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DESIGN AND REASSESSMENT OF TUBULAR JOINTS
FOR OFFSHORE STRUCTURES

CONFIDENTIAL AT

CHAPTER 3: STATIC STRENGTH

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DESIGN AND REASSESSMENT OF TUBULAR JOINTS FOR OFFSHORE STRUCTURES

CHAPTER 3: STATIC STRENGTH

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NOMENCLATURE

D	chord outside diameter (mm)
d	brace outside diameter (mm)
e	joint eccentricity
f_a	axial stress
f_b	bending stress (in-plane, y and out-of-plane, z)
f_{bi}	in-place bending stress
f_{bo}	out-of-plane bending stress
F_t	chord material ultimate tensile strength (N/mm^2)
F_y	chord material yield stress (N/mm^2)
$F(\ )$	function of ( )
g	gap between braces for K/YT joints (mm)
g_o	out-of-plane gap between braces
K_a	approximate relative length for inclined brace intersection
K'_a	exact relative length factor for inclined brace intersection
K_b	approximate relative section factor for inclined brace intersection
K_{bi}	approximate in-plane relative section factor for inclined brace intersection
K_{bo}	approximate out-of-plane relative section factor for inclined brace intersection
L	length of chord between end plates (mm)
L_{can}	length of chord can, generally < L (mm)
L_f	Distance between brace centrelines on chord surface
M	moment (kNm)
M_i	in-plane moment
M_k	characteristic moment at chord surface
M_{ki}	characteristic in-plane moment at chord surface
M_{ko}	characteristic out-of-plane moment at chord surface
M_o	out-of-plane moment
M_u	ultimate moment at chord surface
m	mean
N	population
P	axial brace load
P, P_1, P_2, P_3	axial load

NOMENCLATURE CONTINUED

P_k	characteristic axial load
P_u	ultimate axial load
Q_f	chord stress factor
Q_g	multiplier on joint capacity to account for gap
Q_q	load and geometry factor in API and AWS
Q_u	strength factor for various joint and load types
Q_β	$\frac{0.3}{\beta(1-0.833\beta)}$ for $\beta \geq 0.6$, 1.0 for $\beta < 0.6$
R	chord radius
t, t_1, t_2	brace wall thickness (mm)
T	chord wall thickness (mm)
T_{can}	thickness of chord can (mm)
A	chord utilisation ratio
V	shear stress
x	θ function in K'_a
y	β function in K'_a
z	statistical constant
α	nondimensionalised chord length ratio
β	diameter ratio d/D
γ	chord slenderness parameter D/2T
δ	displacement
ζ	gap parameter g/D
λ	multiplier used within Q_f parameter
η	$\beta/\sin\theta$
θ	intersection angle
θ_c	intersection angle for compression loaded brace
θ_t	intersection angle for tension loaded brace
θ_{ov}	intersection angle for overlapping brace (overlapping joints)
θ_{th}	intersection for through brace (overlapping joints)
std dev	standard deviation
τ	thickness parameter t/T
ϕ	angular separation between planes of braces
IPB	in-plane bending
OPB	out-of-plane bending

1. INTRODUCTION

1.1 Scope

This chapter considers methods for determining the static strength of simple and complex tubular joints typically used in steel jacket offshore structures.

All known relevant data are collated in comprehensive databases. These include experimental and numerical data and cover all the parameters which might influence joint static strength.

The databases are used to review and assess current codified design guidance and other relevant published formulae. Both design and reassessment aspects are addressed and where necessary additional and/or alternative improved guidance are proposed.

1.2 Joint Definition and Notation

Within the context of this guide, tubular joints are formed by the intersection of non-coaxial circular brace and circular chord members. To satisfy this criterion the outside diameter of the brace may not exceed the outside diameter of the chord, and in line with industry practice the thickness of the brace member does not generally exceed the thickness of the chord member.

It is assumed that a simple tubular joint is an unreinforced, non-overlapping, uniplanar welded tubular intersection. The term 'complex joint' covers intersections with ring-stiffeners or grout (composite) reinforcement, a casting, or where braces are overlapped or multiplanar. Configurations and detailed definitions for various joint types are given in the relevant sections.

The geometric notation and non-dimensional parameters for simple joints are shown in Figure 1.1. SI units are used throughout this chapter; suitable conversions are applied in restating data from other literature.

To maintain consistency in the sign convention used, tension loading is defined as positive and compression loading is defined as negative.

1.3 Failure Modes

The mode of failure of a statically loaded tubular joint depends on the type of joint, the loading conditions and the joint geometrical parameters. Tests carried out on mainly simple joints have identified several types of local and global failures which include:

Local failure of the chord:

L1) Plastic failure of the chord wall in the vicinity of the brace

L2) Cracking leading to rupture of the brace from the chord

L3) Local buckling in compression areas of the chord

Global failure of the chord:

G1) Ovalisation of the chord cross section

G2) Beam bending failure

G3) Beam shear failure between adjacent bracings.

The failure of typical joints often involves combination of the above modes especially L1, L2, L3 and G1 which are the most common. In tension loaded joints, the chord wall around the brace undergoes large plastic deformation and the chord cross section distorts. As the load increases, a crack may initiate in the hot spot region while the joint continues to carry higher loads until the cracking becomes excessive and leads to gross separation of the brace from the chord. Failure in compression loaded joints is usually associated with buckling and/or plastic deformation of the chord wall. Joints made of relatively thin walled sections are particularly susceptible to local buckling. Ovalisation of the chord occurs particularly in tension loaded X joints. Beam bending failure may take place in high α axially loaded T/Y joints while beam shear failure may be critical for gap K joints with large β ratios subjected to balanced axial loading.

For in-plane moment loaded joints failure typically occurs due to fracture through the chord wall on the tension side of the brace and plastic bending and buckling of the chord wall on the compression side.

For out-of-plane moment loaded joints, local buckling of the chord wall near the brace saddle occurs, reducing stiffness. Failure is usually associated with fracture on the tension side of the brace after excessive plastic deformation.

1.4 Failure Criteria

Typical load deformation curves for axially loaded tubular joints are shown in Figure 1.2. Failure criteria which may be used to define the static strength of tubular joints in general are indicated on the curves and commonly referred to as follows:

1. Elastic limit

2. Deformation limit

3. Crack initiation

4. Ultimate or peak load.

The elastic limit criterion is clearly inappropriate for defining failure, because tubular joints have substantial reserve capacity beyond the associated limit load. The most internationally acceptable and widely used criterion for accounting for such reserve strength and defining failure is the ultimate or peak load. However in some cases, eg. in tensile loaded joints, crack initiation may precede and possibly influence the ultimate load. In other cases, such as in moment loaded joints, an ultimate load may only be reached after excessive deformation or it may not be reached at all within the confines of the testing rig. Accordingly, it is often argued that the crack initiation and/or deformation limit criteria may be considered as valid alternatives to the ultimate load criterion as discussed below.

a) Deformation limit

The main arguments for the use of a deformation limit include:

- Absence of a peak load on the load deformation curve of certain tubular joint tests.
- Possible differences between the usable joint capacity within a frame and the capacity recorded in an isolated test may become large if the latter is associated with excessive deformation while such deformation may never be reached during the collapse of the frame. In addition, the second order effects accentuated by large deformation may render the capacity predicted in isolated tests less reliable.

The main argument against using a deformation limit is that it might be regarded as a serviceability criterion which is not admissible within an ultimate limit states concept

There is no international agreement regarding either the magnitude or the relevance of a deformation based failure criterion. The best known and possibly the most widely used deformation limits, especially in American studies, are those of Yura (1980):

For axially loaded joints:

$$\text{displacement limit} = \frac{2 F_y l}{E} \qquad (1)$$

For moment loaded joints:

$$\text{rotation limit} = \frac{8}{3}\frac{F_y}{E}\frac{l}{d} \qquad (2)$$

where l = Brace length
d = Brace diameter
F_y = Chord yield strength
E = Elastic modulus of steel

The limit expressed in Equation 1 is based on the American Institute of Steel Construction building design guidance. For axial loading it is assumed that a branch member reaches its practical deformation limit when the strain along its entire length is four times the yield strain. It is further assumed that the comparable practical limit of local joint deformation at each branch end is twice the branch yield deformation. For an individual test, the deformation limit is determined by assuming a branch length equal to thirty times the branch diameter.

The limit expressed in Equation 2 is defined as the joint rotation corresponding to the angle at the end of a simply supported beam which is uniformly loaded to four times the first yield strain. A beam length of thirty times the branch diameter is used to establish the limit (Yura, 1980).

b) Crack initiation

This failure criterion applies primarily to tension tests where joints continue to carry loads after cracks have initiated, and ultimately fail at higher loads than those corresponding to first evidence of cracking. Although the concept of using the 'first crack' load as joint capacity instead of the ultimate load was first proposed in the late seventies (Yura, 1980), it has been either accepted without detailed evaluation or completely dismissed as a serviceability criterion.

Some normally overlooked aspects of the crack initiation criterion are outlined below:

1) Scale and frame dependency

The effects of scale, ie. specimen absolute dimensions, on crack initiation and propagation between the first crack load and ultimate load, are yet to be evaluated. In addition, the differences in joint restraints between isolated tests and real frames may result in the isolated joint response being unrepresentative of frame behaviour. As a result, the relevance of tension test data to the behaviour of full scale joints in frames is questionable.

2) Accuracy of first crack data

Assuming that the crack initiation criterion is valid, its use in the analysis of the tension test database is likely to be influenced by the inaccuracies inherent in determining and interpreting the first evidence of cracking in the relatively few tests where cracking was monitored and recorded.

3) Interaction of first crack and ultimate load criteria

The crack initiation criterion cannot be considered a serviceability criterion, because if first crack data and/or the related ultimate load results are dependent on scale, addressing the effects of cracking becomes an inherent part of determining the ultimate strength.

The above suggests that a lower bound conservative approach to estimating the static strength of tension loaded joints is desirable until the effects of cracking on ultimate strength have been evaluated more rigorously. However, it should be noted that tests on small scale specimens suggest that cracking does not have a significant impact on joint behaviour until the crack has propagated through the thickness.

1.5 Design Approach

Codified design guidance for the assessment of the static strength of tubular joint is generally based on one of the two following broad approaches:

1. Working stress design (WSD), or permissible (or allowable) load design.

2. Load and Resistance Factor Design (LRFD), or ultimate limit states or partial factor design.

The governing principle in the first approach (WSD) is that the nominal loads should not exceed an allowable value which is the nominal failure load reduced by a safety factor. Thus a typical design equation is of the form:

$$\frac{\text{Nominal strength}}{\text{safety factor}} > \text{Sum of applied loads}$$

In the second design approach (LRFD), a number of partial safety are used to account for uncertainties associated with load and resistance aspects. A typical design equation may be expressed as follows:

$$\text{Resistance factors} * \text{Nominal strength} > \text{Sum of factored external loads}$$

where the nominal strength and loads may be the same as in the (WSD) approach, but each terms is multiplied by its respective safety factor.

1.6 General Form of Strength Equations

Examination of the design codes and published formulae yields the following list of variables which may affect the strength of a tubular joint:

1.	Chord outside diameter	D
2.	Brace outside diameter	d
3.	Chord wall thickness	T
4.	Gap (for K, YT and KT joints only)	g
5.	Included angle between chord and brace	θ
6.	Chord length	L
7.	Chord material yield strength	F_y

The chord and brace diameters are taken here to relate to outside tubular dimensions. Details of the geometric notation are given in Figure 1.1.

Additional parameters relating to geometric and material properties affect the strength of complex joints.

The static strength for a particular load case can be expressed in the general form

$$P_u \text{ or } M_u = F(D, d, T, g, \theta, F_y, L)$$

where P_u and M_u are ultimate axial and moment capacities respectively.

The effect of brace wall thickness on joint strength has been examined by Kanatani (1966) and is shown to have little effect on joint strength.

The number of parameters can be reduced by introducing non-dimensional geometric ratios as follows:

$$\alpha = 2L/D \quad \beta = d/D \quad \gamma = D/2T \quad \zeta = g/D$$

P_u or M_u may therefore be expressed as:

$$F(\alpha, \beta, \gamma, \zeta, \theta, F_y).$$

The accepted non-dimensional forms of the ultimate capacities P_u and M_u are:

Axial loading: P_u/F_yT^2

Moment loading: M_u/F_yT^2d

The term (F_yT^2) is based on a ring analogy and can be related to the theoretical yield strength of a ring model with similar diameter, thickness and yield stress to those of the chord (Wardenier, 1982). The term (F_yT^2) can also be associated with the theoretical expression for failure in the chord under the action of a point load (Yura et al 1980).

The calculation of joint strength is usually based on consideration of axial and moment load components perpendicular to the chord axis. These are $P_u Sin\theta$ and $M_u Sin\theta$ for the axial and moment load cases respectively. Therefore the following expressions are often considered as a basis for derivation of joint strength.

Axial : $$\frac{P_u \sin\theta}{F_y T^2} = F(\alpha, \beta, \gamma, \zeta, \theta)$$

In-plane bending : $$\frac{M_u \sin\theta}{F_y T^2 d} = F(\alpha, \beta, \gamma, \zeta, \theta)$$

Out-of-plane bending : $$\frac{M_u \sin\theta}{F_y T^2 d} = F(\alpha, \beta, \gamma, \zeta, \theta)$$

Examination of design codes leads to the identification of other parameters which may affect strength. These are:

K_a or K'_a	relative length factors
K_b, K_{bi} or K_{bo}	relative section factors
Q_β	sometimes referred to as the geometric modifier

In all cases these parameters are functions of β and θ and their validity can be tested by investigation of their applicability to the general equations.

The above equations for joint strength are expressed using the nominal brace load format which is adopted in the majority of current design codes. An alternative format which was used in earlier design codes is the punching shear stress format. This is expressed in terms of the punching stress V_p, which is assumed to be uniformly distributed over the punching shear area in the chord and calculated as follows:

$$V_p = \tau \, f \, \sin\theta$$

where V_p = acting punching shear
τ = ratio of brace thickness to chord thickness
f = nominal axial, in-plane or out-of-plane bending stress in the brace.

1.7 Historical Development of Static Strength Equations

Over the last three decades, tubular joint research programmes, carried out mainly in Japan, the USA and Europe, have provided a large database of test results. Early test programmes were aimed at investigating the effects of parameters such as β and γ ratios on the strength of simple joints. Such basic investigations were followed by programmes which targeted issues of increasing complexity such as the influence on joint strength of:

- Joint configuration (e.g. T/Y, X and K joints)
- Brace load type (i.e. axial compression and tension, in-plane and out-of-plane bending)
- Chord loading and multi-axis brace loading (i.e. combinations of axial and bending loads)

The size of test specimens also increased from relatively small scale models with chord diameter around 100 mm or less to larger models providing a better representation of the actual scale of tubular joints.

The increasing availability of wide ranging test data enabled empirical design guidance to be developed as lower bound, mean or characteristic capacity equations, based on different interpretations of test data. Such equations were formulated using the punching shear stress format and/or the nominal brace load format (see Section 1.6).

Up until the early 1980's, most American and European design codes followed the lead of the API RP2A (1969 and following editions) and adopted the punching shear stress format. These codes include: AWS D1.1-84 (1984), BSI BS6235 (1982), NPD (1977) and DnV (1977).

A number of comprehensive critical reviews of the worldwide tubular joint database were published in the period 1980-1985. These studies resulted in a significant evolution in the ultimate strength technology for tubular joints and initiated dramatic changes in tubular joint design codes. The most prominent of these reviews which are examined below include: Yura et al (1980), Wardenier (1982), Kurobane et al (1980-1984), UEG Design Guide (1985) and the UK Department of Energy (DEn/HSE, 1990). The codes which adopted the results of these reviews include: API RP2A, the DEn/HSE Guidance Notes, CIDECT and IIW design codes.

Yura et al, 1980

Yura et al presented, in a 1980 OTC paper, lower bound capacity equations for the static strength assessment of simple tubular joints using the brace nominal load approach. These equations were based on the results of 137 static strength tests on simple T, Y, X and K joints. This relatively small test database was established after screening the data available in the late 1970's. Only joints with chord diameters greater than 140 mm and measured material properties were admitted. Furthermore, the failure load was taken as the lowest of: maximum load attained during the test, first crack load, or load at an excessive deformation limit.

The equations of Yura et al were introduced as new design equations in the 14th Edition of API RP2A-WSD (1984), in which, the brace nominal load approach was adopted as an alternative to the punching shear stress concept for determining the static strength of tubular joints. The designer was allowed to use either of the two approaches, which were intended to give equivalent results. These changes, introduced in a permissible load format have been maintained in all subsequent API RP2A-WSD editions up to and including the 20th Edition published in 1993.

The basic joint strength equations of the WSD versions of API RP2A (14th Edition to date) have been largely maintained in the first Edition of the Load and Resistance Load Factor code API RP2A-LRFD published in 1993. However, unlike the WSD versions, the LRFD equations are based only on the nominal brace load format, i.e. the equivalent punching shear stress equations have been dropped from the code.

UEG Design Guide (1985)

Part B of this guide includes a thorough review of design guidance and test data on the static strength of tubular joints. Following the example set by Yura et al, the worldwide test database, as in early 1984, was screened and a reduced database consisting of 290 test results was established. This total included 223 joints subjected to uni-axial brace loading, 55 joints tested with additional chord loading and 12 joints subjected to multi-axial brace loading. With regard to tests performed under uni-axial brace loading, only joints with chord diameters greater than 110 mm and measured material properties were accepted. However, unlike the approach adopted by Yura et al for tension tests, the first crack load was considered to correspond to a serviceability criterion and not to the ultimate strength which was defined as the maximum load achieved during the test. The analysis of the UEG database enabled mean and characteristic equations to be derived and design guidance to be proposed according to limit state principles using the brace nominal load approach. The background to the new equations was published earlier by Billington et al (1982).

Department of Energy (DEn/HSE 1990)

In the period (1985-1986), Wimpey Offshore, on behalf of the UK Department of Energy, carried out a comprehensive data assessment similar to that reported in the UEG Design Guide. Test results available in January 1986 were screened and a database consisting of a total of 346 test results was established. This total included 211 joints subjected to uni-axial brace loading, 61 joints tested with additional chord loading and 74 joints subjected to multi-directional brace loading. The screening procedure for the uni-axial brace tests was similar to that adopted in the UEG work but the minimum acceptable chord diameter was set to 125 mm. The database was then analysed and new static strength design formulae were developed in a form suitable for use with limit state design codes, along the same lines of the UEG equations. An equivalent permissible load approach was also proposed for consistency with the Department of Energy Guidance notes. The proposed equations published together with the background analysis in 1990, were incorporated in the latest edition of the DEn/HSE Guidance Notes (1990). A comparison of these equations with the lower bound capacity formulae recommended in the 15th edition of API RP2A-WSD (1984), was undertaken by Lloyd's Register of Shipping and reported in 1986. This study concluded that: 'The joint strengths predicted using the new guidance generally show less scatter and better agreement with the available test results than do those calculated using API (15th)'.

Kurobane et al (1980-1984)

One of the main screening criteria used in the databases, leading to the API, UEG and DEn equations, was the size of the chord diameter. The cut-off point below which specimens were rejected was chosen tentatively and led to the omission of a large number of small scale test results. Most of these were produced by Japanese workers including Kurobane and his research team.

Contrary to the size screening criterion associated with the API, UEG and DEn/HSE databases, Kurobane, working within the IIW circles, accepted small scale test results, e.g. tests with chord diameters of 100 mm or even 60 mm, and assembled a large database of 674 tubular joint tests. The analysis of this relatively large database enabled Kurobane and his team to derive mean and characteristic design equations based on the nominal brace load approach. The latest set of Kurobane's equations was adopted by the IIW and CIDECT and issued by these two organisations in their latest onshore codes (IIW, 1989 and CIDECT, 1991).

Wardenier (1982)

Wardenier and his team, based in the Netherlands, also contributed to the enlargement of the tubular joint database and to the IIW and CIDECT design codes. Wardenier's book, entitled 'Hollow Section Joints' (1982), is an important contribution to tubular joint technology. It includes a comprehensive critical review and analysis of all data on the static strength of tubular joints in addition to detailed comparisons of various design equations which were available in the early Eighties.

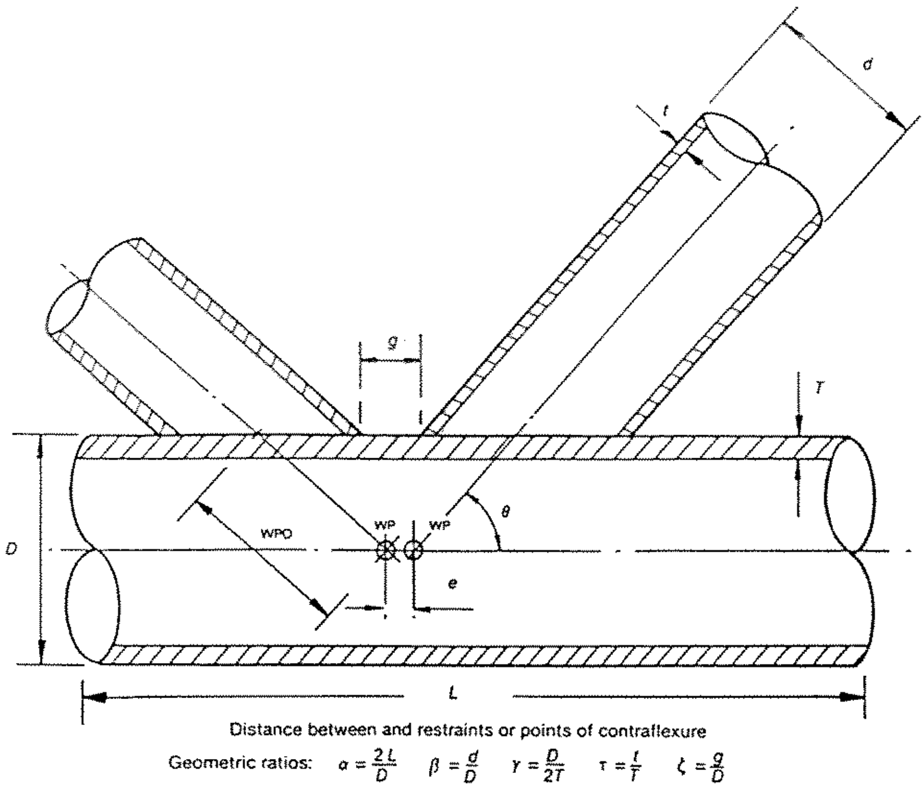


Figure 1.1 Geometric notation for simple joint

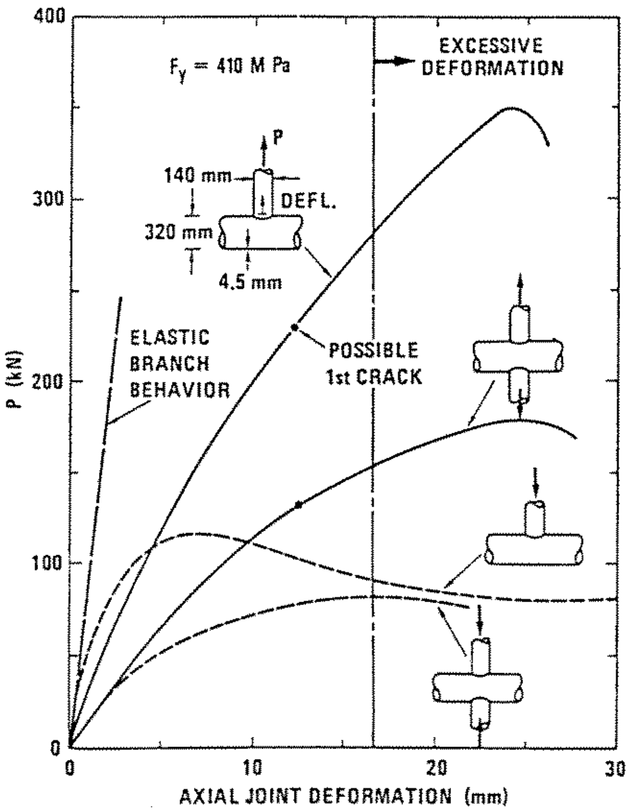


Figure 1.2 Typical load-deformation curves for axially loaded joints

2. METHODS FOR DETERMINING STATIC STRENGTH

Current design guidance for the static strength of tubular joints is almost entirely based on experimental data obtained from model tests on steel specimens. The main reason for this dependence on the experimental approach has been the inability of numerical methods in the 1970s and early 1980s to compete with laboratory model testing in terms of both reliability and cost effectiveness. However, this condition has started to change in favour of numerical methods in general and the nonlinear finite element technique in particular since the mid 1980s. Such a change has become possible due to the increasing availability of powerful computers at affordable costs and to the success of both numerical analysts and software developers in refining and optimising the underlying analytical and numerical theories and their practical implementation.

The following sections highlight the parameters which might influence the accuracy and relevance of static strength data obtained using either experimental or numerical methods. Recommendations on conducting static strength investigations, interpretation of data and reporting of the results are also given.

2.1 Experimental Methods (steel models)

This section examines laboratory based techniques for assessing the static strength of tubular joints. Particular emphasis is placed on identifying the key factors which affect the reliability and relevance of the data generated from steel models.

In the early days of the offshore industry, model tests using steel specimens provided the only practical means to study the static strength of tubular joints. Since then steel model tests have continued to be regarded as the most trusted source for reliable data. However, practical considerations have often driven researchers to scale down steel specimens in order to reduce the size and cost of both specimens and testing rigs. In addition there has been considerable variation in testing technique between different studies which alongside the scale effect and other factors may have led to inaccuracies and inconsistencies in the results.

The following guidelines for conducting tests, interpretation of data and reporting of results are recommended:

a) Specimen geometry

- Subject to the limitations of jacks and reaction frames, the model should be as large as possible. Although the minimum 'acceptable' chord sizes associated with some European and American databases are debatable, the inaccuracies and anomalies attributed to small scale specimens, eg. with $D <$ 100mm, are less likely to occur with larger specimens.
- Apart from absolute size considerations, geometric scaling should be rigorously observed for all dimensions and details of the specimen.

- The length of brace(s) and chord should be such that any effect of the end conditions on capacity of the specimen is minimised.

- Actual measured rather than nominal dimensions should be used in data interpretation.

b) Specimen material and manufacture

- The model should be constructed from steel having stress-strain properties similar to those of typical offshore material.

- The static tensile properties of both the chord and brace(s) should be measured. These are more relevant than the dynamic properties because joint tests are conducted in a quasi-static manner. However, since only the dynamic tensile properties of most available test data are known and in order to maintain consistency in the static strength database, the dynamic tensile properties of both the chord and braces should also be measured.

- As a minimum the chord and brace(s) yield and ultimate tensile strength should be reported for all joints. The brace yield properties are particularly important for assessing brace failure. Ideally the measured full stress-strain curves should be reported. In addition, measurements should be made using several coupons which, in the case of longitudinal tensile specimens, should be taken around the circumference, at least for fabricated tubes.

- The model should be fabricated to standard offshore procedures, which are different to those for onshore construction (eg. with regard to overlapping joints). Weld sizes should be scaled down appropriately to the model thickness. However oversized weld fillets on small scale steel joints may be unavoidable without grinding. In order to allow the effects of fabrication procedures including the welding process and weld size to be assessed, these should be documented fully.

c) Specimen loading and restraint

There is little consensus amongst parties involved in both the testing and analysis of tubular joints regarding which members should be supported in joints with multiple members, and the boundary conditions (ie. fixed or pinned) to be adopted for the supported members. In the absence of other guidelines, the supported members should be chosen to reflect the principal loadpaths through the joint when in position on the structure. Section (2.2.5) on effects of boundary conditions and chord length on predictions from finite element analyses, provides data which are equally relevant to model tests.

d) Reporting of joint deformation and failure modes

- Observed failure modes and load deformation curves, including points at which physical changes like cracking or buckling occur, should be reported for all specimens. The criteria used to determine failure (eg. first peak or deformation limit) must be stated.

- If failure involves cracking, the method used to detect crack initiation must be documented. The extent of crack extension during the test should be recorded as accurately as possible and reported.

2.2 Numerical Methods

The most successful and probably the most promising numerical tool for the static strength assessment of tubular joints is the finite element method. General purpose finite element packages which can handle both material and geometric nonlinearities and which contain large libraries of sophisticated finite elements have become increasingly available. This, is in line with decreasing hardware and computing costs has produced a rapid growth in the use of nonlinear numerical methods. As a result, a large number of recent investigations and applications, associated with tubular joint static capacity, have relied on the finite element technique. In several instances, it has been proven that the finite element based numerical approach can match the accuracy of the experimental approach while offering the investigator several additional advantages which include:

- The ability of the finite element technique to handle complex joints of any geometrical shape, under any type of loading or restraints.

- The flexibility that the technique offers in terms of allowing the effects of any parameter to be evaluated independently, whether it is related to a geometrical or a material property. As a result, systematic parametric studies can be conducted at relatively modest costs.

- Unlike laboratory tests where parameters such as displacements and strains can only be recorded at limited sampling positions with no scope for obtaining additional data once the model is tested, a finite element analysis can provide comprehensive data on any variable at almost any part of the joint.

However, alongside its advantages, the finite element technique has a number of limitations including:

- The results are modelling sensitive. The user has to make several decisions which can have significant effects on both the accuracy and efficiency of the analysis. The most important decisions concern:

  - The choice of element type

   - Mesh density and layout
   - Boundary conditions
   - Loading and solution strategy.

- Calibration of finite element solutions against results obtained using other reliable techniques, such as laboratory testing, is essential for gaining confidence in the numerical results.

- Simulation of crack development and extension is still beyond the capability of most finite element packages. This weakness makes the of results of analyses involving cracking failure, eg. in tension loaded joints, difficult to interpret.

General background information on development of the finite element method with regard to tubular joints is given in Chapter 4, Section 2.2. In the following sections, general recommendations on performing and interpreting nonlinear finite element analyses of tubular joints are provided. Detailed reviews and evaluations of numerical results from various tubular joint studies are reported alongside the relevant experimental test data later in this chapter.

2.2.1 Choice of element type and weld modelling

A large number of different element formulations are available which may be used for the analysis of tubular joints. The most appropriate of these are curved thin and thick shell elements and three-dimensional solid elements. Shell elements are very efficient for modelling the bending of shells and are often used to model the complete tubular joint. However, in shell element analyses where only the tube mid-surface is modelled, the weld geometry at the intersection region cannot be represented accurately. As a result, the weld influence is either ignored or approximated by, for example, a single row of elements diagonally linking the brace and chord as shown in Figure 2.1 (van der Vegte, 1991)

Three-dimensional solid elements give improved modelling in the intersection region but are generally inferior to shell elements for shell bending modelling. If three-dimensional solid elements are used for modelling the complete tubular joint, the cost of the analysis can increase substantially. An efficient compromise solution is to use solid elements to represent the weld at the intersection region and shell elements to model the remaining parts of the tubular joint. However, unless adequate constraints are applied at the solid-shell element interface or transition elements are used to ensure element compatibility, numerical problems may arise (Cofer, 1992 and Wilmshurst, 1993).

While the effects of element type and weld modelling may be quantified for a particular joint geometry and loading condition using a specific finite element program, the results of such studies do not necessarily apply to other joint geometries or to different loading conditions analysed using either the same or a different finite element program. In the absence of comprehensive systematic investigations which include validation against reliable experimental data, only general statements on the merits of element type and weld modelling with regard to analytical predictions of static strength can be made:

- Quadrilateral shell elements and three-dimensional brick elements are likely to produce superior predictions to triangular shell elements and three-dimensional prism elements respectively. When possible, triangular elements and prism elements should only be used for mesh grading.

- Quadratic elements (eg. 8 noded shells and 20 noded bricks) provide more accurate modelling than linear elements (eg. 4 noded shells and 8 noded bricks).

- Thick shell element models and three-dimensional solid element models predict stiffer joint responses and higher capacities than thin shell element models.

- In shell element models, accounting for the weld, using either approximate shell representation or more accurate three dimensional modelling, generally results in higher capacities than if the weld is omitted.

- In modelling β=1.0 joint configurations using shell elements, considerations should be given to realistic representation of the brace/chord intersection at the saddle allowing for weld cut back. The effect is particularly important for an X joint where, in practice, a physical gap exists between the opposite brace weld toes, whereas the theoretical intersection of the brace and chord centrelines at the chord horizontal plane of symmetry does not create a gap. It may therefore be appropriate to adopt a smaller brace diameter (eg. equal to the nominal brace diameter minus the brace thickness) to give a β value close to but not equal to unity, thereby generating a realistic gap.

2.2.2 Model validation and use

Whilst it is essential to validate the performance of any finite element model against reliable data, it is important to appreciate the relevance and limitations of such validation. If a certain model is found to perform well in predicting the ultimate strength for a specific joint geometry and loading type, this does not necessarily justify the assumption that the model can perform equally well for other joint geometries or loading types. Both the failure mode and failure location may change when considering other joint geometries and/or different loading conditions. As a result, extra care must be exercised when interpreting the results of analyses outside the range of the initial validation study.

2.2.3 Geometric nonlinearity and large strains

Since the deformation of a tubular joint at high load levels is often sufficiently large to modify the response of the joint to additional loading, geometric nonlinearities must be accounted for in the analysis.

In general, tubular joints fail at relatively small strain levels. Therefore consideration of large strains is not normally essential.

2.2.4 Material nonlinearity

Appropriate representation of the material properties must be included in the analysis including the yield strength, rate of strain hardening and the ultimate tensile strength. Whilst properties of the chord are the most relevant in determining joint capacity, assigning realistic properties to the brace is essential for predicting premature brace failure. Otherwise the brace properties can be manipulated in order to ensure joint failure. Static tensile properties are more relevant than the corresponding dynamic properties especially for comparison with joint tests because these are conducted in a quasi-static manner (see Section 2.1.1). True stress-strain tensile data are more relevant than nominal engineering stress-strain data. The former can be estimated from the latter, assuming that the volume remains constant during uniform plastic elongation, as follows:

$$\sigma_t = \sigma_n \ (1 + \epsilon_n)$$

$$\epsilon_t = LN \ (1 + \epsilon_n)$$

where σ_t and σ_n are the true and nominal stresses respectively, while ϵ_t and ϵ_n are the corresponding true and nominal strains respectively.

Although material properties are technically orthotropic, adopting isotropic modelling has generally proven adequate.

2.2.5 Boundary conditions and chord length

Depending on joint geometry, joint type and loading conditions, the boundary conditions and chord length adopted in the analysis of a tubular joint can have significant effects on the predicted capacity. Although such effects have been highlighted by recent finite element studies which provide valuable data, the data are generally limited and in some cases inconclusive.

Boundary conditions and chord length effects arise from several causes which include:

- Locality of the chord end plates which affect chord ovalisation. A short chord with stiff end plates suppresses ovalisation and causes higher capacity, eg. in analyses of T/Y and DT/X joints.

- In joints where both chord ends are supported, both the length of the chord between its support points and the applied boundary conditions (ie, fixed or pinned) affect the overall chord in-plane beam bending. Joint failure is more likely to occur in axially loaded high β T/Y joints if the chord is short with fully fixed ends, while with longer pin-ended chords joint failure may be preceded by overall chord failure (van der Valk, 1988)

- The capacity of K joints subjected to balanced axial loading may be affected by both the loading and boundary conditions (Bolt et al, 1992). Parameters which can influence the predicted capacity include:

  - Whether one or both chord ends are supported
  - Whether one or both braces are supported or loaded
  - Brace in-plane rotational restraints
  - Whether the direction of the applied load remains colinear with the brace axis in analyses allowing in-plane brace rotation.

2.2.6 Loading and solution strategy

In single brace joints, it is recommended to use displacement control or the arc length algorithm. These are more efficient than load control and, in cases where the load-deformation curve reaches a peak, they allow the post-peak response to be predicted. In multibrace joints where displacements of the braces in relation to each other are not known in advance, the arc length algorithm may be the only feasible technique to predict post-peak behaviour.

Note: In the arc length algorithm, the loading is assumed to be proportional, that is all the load magnitudes vary with a single scalar parameter. The basis of the method is to use the load magnitude as an additional unknown and to control the increments taken along the load-displacement response curve.

2.2.7 Evaluation of results and interpretation of failure modes

Unlike a laboratory test where the modes of failure can be readily observed, extensive post-processing of the results from a finite element analysis is required in order to interpret the model response. Such an evaluation serves two essential purposes:

1) Ensuring that the analysis is acceptable in that the intended input parameters, such as loading and boundary conditions, have been prescribed accurately (by the analyst) and executed satisfactorily (by the program).

2) Interpreting the results by reducing the considerable volume of numerical output into various forms of graphical data such as plots of the model deformed shape, contour plots or load-deformation curves. The failure load and mode may then be determined. However, this may not be an easy task since there are many possible complex failure modes which often interact. In particular, if crack tearing is involved, which cannot be accounted for by most current finite element programs, or if the load-deformation curve does not reach a peak or a plateau, different failure criteria may have to be considered to determine a usable joint capacity (see Section 1.5).

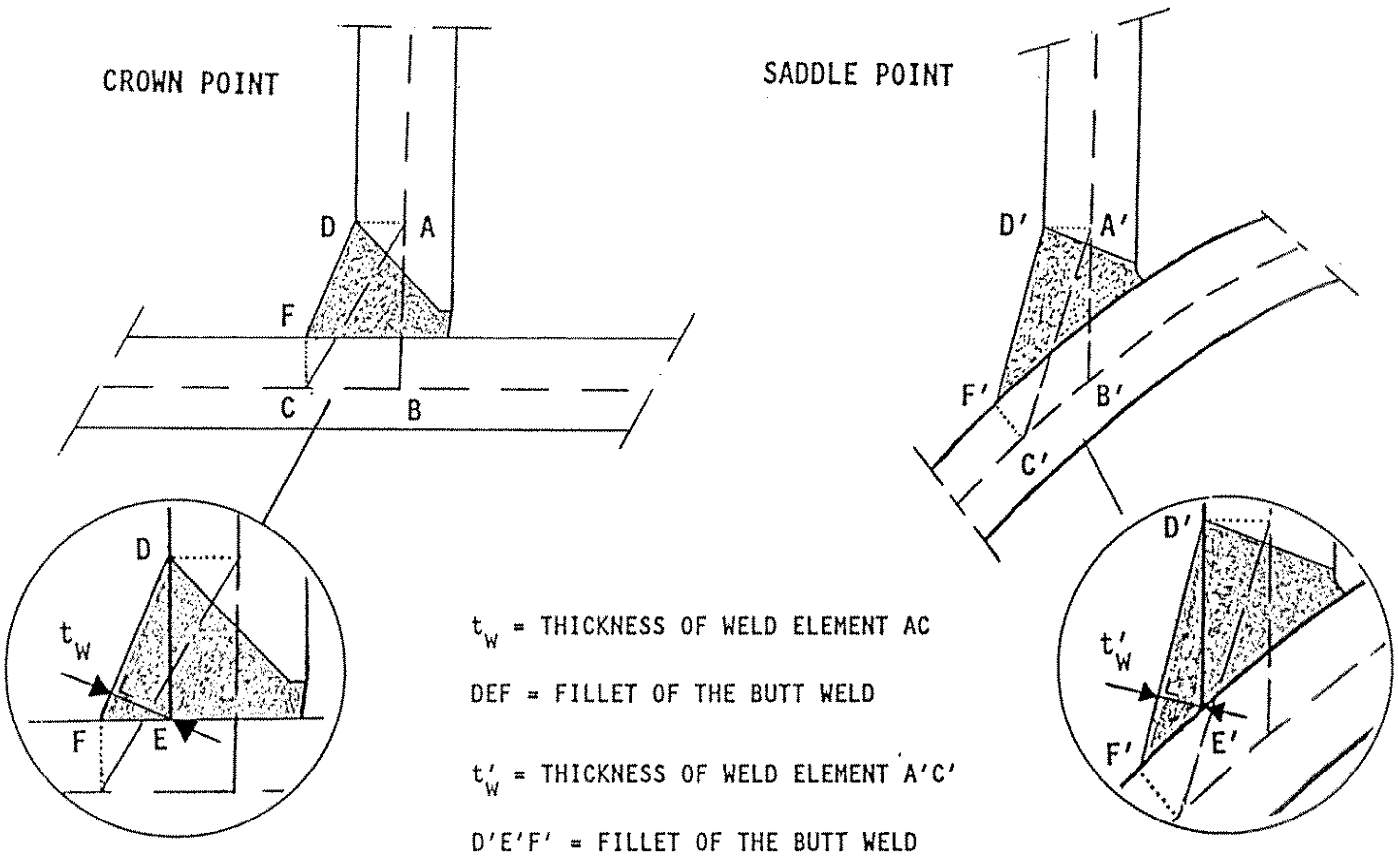


Figure 2.1 Approximate modelling of welds (van der Vegte, 1991)

3. STATIC STRENGTH OF SIMPLE JOINTS

3.1 Introduction

A detailed evaluation of the static strength design of simple tubular joints is presented in this section. Principal design codes and recently published non-codified formulae are reviewed in Sections 3.2 and 3.3, respectively. The newly constructed BOMEL simple tubular joint database, used to evaluate key design codes and published formulae is described in Section 3.4. Results of this evaluation study are reported fully in Section 3.5. Finally, conclusions and recommendations are summarised in Section 3.6.

3.2 Review of Existing Design Codes

3.2.1 General

Several design codes are currently available to aid the designer in assessing the static strength of tubular connections. Some are aimed specifically for use in offshore structures (eg. API, HSE), while others are produced primarily for onshore constructions (eg. CIDECT). This section outlines key features of a number of principal design codes, describes the basic format of their strength equations, and highlights differences between the codes with respect to these strength equations.

The codes considered in this section can be split into two broad categories depending on their design format. The first category includes codes which are based on working stress design (WSD) or permissible (allowable) design formats. For simplicity, these are referred to hereafter as WSD codes. They include:

WSD:
- API RP2A-WSD (1993)
- AWS (1994)
- DnV (1993)
- HSE (1990)

The second category includes codes which are based on load and resistance factor design (LRFD), ultimate limit states or partial factor design formats. For simplicity, these are referred to hereafter as LRFD codes. They include:

LRFD:
- API RP2A-LRFD (1993)
- AWS (1994)
- CIDECT (1991)
- CSA (1992)
- DnV (1993)
- NPD (1990)

The API, AWS and DnV codes are listed under both categories because they provide design guidance based on WSD and LRFD formats, allowing the designer to adopt either of the design approaches.

For the purposes of this section the following nomenclature pertaining to joint strength in either WSD or LRFD format has been adopted.

WSD Codes

P_a = allowable axial strength (includes a global safety factor)
M_a = allowable bending strength (includes a global safety factor)

LRFD Codes

P_f = factored axial design strength (includes partial safety factors)

M_f = factored bending design strength (includes partial safety factors)

For joint strength to be adequate, the following should be satisfied:

In WSD codes: $P_a \geq$ nominal applied loading.

In LRFD codes: $P_f \geq$ factored loading (ie. including partial safety factors for dead, environmental and live loading).

Basic form of static strength equations

Most design equations contain the following basic parameters:

(i) **F_y, T and sinθ**: These are the chord yield strength, the chord thickness and the brace angle. T is always represented by a T^2 term.

(ii) Q_u: The joint strength parameter dependent upon joint geometric configuration and the loading mode.

(iii) Q_f: The joint strength reduction factor to account for existing chord load.

Several design equations include additional parameters for evaluation of joint strength. These are discussed in the relevant sections.

The general format and main features of each code are described in Section 3.2.2. Differences between the codes with regard to basic assessment parameters are discussed in Section 3.2.3.

3.2.2 Scope and key features of existing design codes

3.2.2.1 API RP2A 'Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design 20th Edition (1993); and Load and Resistance Factor Design (LRFD) First Edition (1993)

Format/definition of joint strength

WSD and LRFD based on a lower bound interpretation of test data.

Background/source of equations

Commentary sections (*Section C4.3* in API-WSD and *Commentary E* in API-LRFD); Yura el al (1980)

Expressions of joint strength

$$P_a = \frac{F_y T^2}{GSF*\sin\theta} Q_u Q_f \quad \text{(Axial)}$$

$$M_a = \frac{F_y T^2}{GSF*\sin\theta} Q_u Q_f (0.8d) \quad \text{(Bending)}$$

GSF is a global safety factor equal to 1.7 and 1.28 for normal and severe loading conditions, respectively

The above expressions are adopted in API-WSD. Similar expressions are used in API-LRFD, except that, P_a and M_a are replaced by $Ø_j*P_{uj}$ and $Ø_j*M_{uj}$, where $Ø_j$ is a joint resistance factor equal to 0.9 or 0.95 depending on joint type and loading; and P_{uj} and M_{uj} are obtained by removing the global safety factor (GSF) from the expressions of P_a and M_a, respectively.

Scope of Guidance in API-WSD

Section 4.1 specifies the minimum strength of joints in relation to the effective strength of the connected members.

Section 4.2 includes general comments on effects of restraint and shrinkage associated with welds.

Section 4.3.1 on 'simple joints' covers the following items: Joint classification; determination of allowable joint capacity using either the punching shear stress format or the nominal load format (intended to give equivalent results), including evaluation of Q_u, Q_f, brace load interaction and joint detailing.

Sections 4.3.2-4.3.5 cover, respectively, overlapping joints, congested joints, load transfer across chords, and other complex joints.

Scope of Guidance in API-LRFD

Sections E.1-E.2 and E.3.1-E.3.5 are virtually identical, with regard to both scope and content, to *Sections 4.1-4.2 and 4.3.1-4.3.5* of API-WSD respectively. The only differences are that the guidance in API-LRFD is presented according to the LRFD format, joint design equations are given in terms of the nominal load format only, ie. the equivalent punching shear stress approach has been dropped, and the brace load interaction equation is slightly different to the arcsin expression of API-WSD.

Notes

It is noted in *Sections 4.3.1 and E.3.1* that '*joints with brace to chord diameter ratio approaching 1.0 will exhibit different failure mechanisms and strength properties than the empirically based formulae contained herein* (in API-WSD and API-LRFD). *At present, insufficient experimental evidence exists to quantify the degree of increased strength. Therefore reasonable alternative methods may be used in the design of such joints*'.

The commentary Sections in both API-WSD and API-LRFD cover: basis of simple joint equations, joint classification, load transfer across chords, and other joints.

3.2.2.2 Canadian Standards Association 'Steel Structures - Offshore Structures' (1992)

Format/definition of joint strength

Limit states design based on '*best fit*' to empirical data. No further explanation of the term 'best fit' is given in either the code or in the accompanying Commentary Document.

Background/source of equations

Section 11 in CSA SP S473.1-1992 'Commentary to CSA Standard CAN/CSA-S473-92, Steel Structures'

Expressions of joint strength

$$P_f = \emptyset_j \frac{F_y T^2}{\sin\theta} Q_u Q_f \quad \text{(Axial)}$$

$$M_f = \emptyset_j \frac{F_y T^2}{\sin\theta} Q_u Q_f d \quad \text{(Bending)}$$

In the document, P_f is expressed as C_r (for compression) and T_r (for tension); M_f is expressed as M_r.

$\emptyset_j$ is the resistance factor of the joint, which varies depending on joint type and loading.

Scope of Guidance

Section 11.1.1 covers the following items: Joint classification; joint types; minimum resistance of joints in relation to resistance of the connected members; and joint detailing.

Section 11.1.2 on 'simple joints' provides guidance on joint detailing (in relation to gap size in K joints); determination of joint resistance using the nominal load format, including evaluation of Q_u, Q_f and brace load interaction; and load transfer across chords.

Sections 11.1.3-11.1.6 cover, respectively, overlapping joints, complex joints, congested joints and grouted joints.

Notes

Further brief guidance on the aforementioned subjects is provided in the Commentary Document CSA SP S473.1-1992.

3.2.2.3 **CIDECT 'Design Guide for Circular Hollow Section (CHS) Joints under Predominantly Static Loading' (1991)**

Format/definition of joint strength

Ultimate limit states based on a characteristic strength interpretation of test data, corresponding to 95% confidence (IIW, 1989).

Background/source of equations

IIW Doc XV-701-89 (1989); IIW Doc XV-461-80 (1980); and IIW Doc XV-488-81 (1981)

Expressions of joint strength

$$P_f = \frac{F_y T^2}{\sin\theta} Q_u Q_f \quad \text{(Axial)}$$

$$M_f = \frac{F_y T^2}{\sin\theta} Q_u Q_f d \quad \text{(Bending)}$$

In the document, P_f and M_f are expressed as N^* and all partial coefficients are embodied in the Q_u and Q_f terms. Q_u is expressed directly in terms of β and γ, and Q_f is designated as f(n').

The characteristic joint strength may be obtained by multiplying the design strength (P_f or M_f) by γ_m, the material and joint partial safety factor, which is equal to 1.1 for all joint types (IIW, 1989)

Scope of Guidance

Section 2 describes key steps of the design procedure of tubular structures (primarily onshore), and provides practical guidance on optimising the design process including consideration of static strength, joint detailing, economy in fabrication and maintenance.

Section 4 entitled 'joint design under predominantly static loading' includes equations for determination of the design strength of simple joints and provides further guidance on optimising their design including measures to improve the efficiency of the connected bracings (see notes below). In addition, guidance on design of axially loaded multiplanar joints is given based largely on recent finite element analyses. This guidance is in the form of correction factors which relate the strength of multi-planer joints to that of uni-planar joints. A simple approach is also proposed to relate the strength of a number of nonconforming uni-planar joints to the strength of common simple configurations.

Notes

This code is intended primarily for design of onshore structures. The same joint design equations are also adopted in Eurocode 3 Annex K (1992) and in the International Institute of Welding design guide (1989).

In addition to satisfying the above joint strength equations, relating mainly to resistance due to chord plastification, the code requires that punching shear checks are carried out. It is noted that the latter design criterion is likely to be critical for joints with thick chords (low γ ratio), and generally in combination with low β ratio.

Design charts intended to speed up joint sizing and help check computer calculations are given in terms of β, γ and the joint efficiency parameter C_e. This is defined in terms of the joint axial strength divided by the brace yield capacity (for axially loaded joints), and in terms of the joint moment strength divided by the brace plastic moment capacity (for moment loaded joints).

With regard to tension strength, the following is noted: 'The ultimate strength under tensile loading is usually higher than under compression loading, however, it is not possible to take advantage of this strength due to large deformations or due to premature cracking'.

3.2.2.4 DnV - Rules for Design, Construction and Inspection of Offshore Structures (1993)

Format/definition of joint strength

Allowable Stress Method (WSD) or Partial Coefficient Method (LRFD) based on a characteristic strength interpretation of test data. This is based on the 5th or 95th percentile of the test results, whichever is the most favourable.

Background/source of equations

According to Ellinas et al (1993), the DnV equations are based on the test results and equations of Gibstein (1973 and 1975). Such information could not be found in the Code.

Expressions of joint strength

$$P_a = \frac{F_y T^2}{GSF * \sin\theta} Q_u Q_f \quad \text{(Axial)}$$

$$M_a = \frac{F_y T^2 d}{GSF} Q_u Q_f \quad \text{(Bending)}$$

GSF is a global safety factor equal to 1.85 [=1/(0.6 x 0.9)] and 1.39 [1/(0.8 x 0.9)] for normal and severe loading conditions, respectively.

The above expressions are for WSD. Similar expressions are adopted for LRFD, except that, P_a and M_a are replaced by P_f and M_f, and the global safety factor (GSF) is substituted by a partial material safety factor equal to 1.3.

Scope of Guidance

Recommendations on design of tubular joints are given in *Part 3, Chapter 1, Section 6, Part E.*

Section E100 covers joint detailing including comments on overlapping joints, congested joints and stiffened joints.

Section E200 'Static strength of simple welded tubular joints' provides guidance on determination of the characteristic joint strength for use with either WSD or LRFD design formats, including joint classification, chord load effects, and brace load interaction.

Sections E300 - E500 cover, respectively, multiplanar joints (allows the use of the equations of uniplanar joints but discusses measures to ensure conservatism), overlapping joints, and complex joints.

Notes

The characteristic strength of simple joints under axial loading is limited by the chord shear strength. The Code provides an equation to perform this check which is also adopted in the CIDECT Design Guide.

3.2.2.5 Health and Safety Executive (HSE) - 'Offshore Installations - Guidance on Design, Construction and Certification', Fourth Edition (1990)

Format/definition of joint strength

WSD based on a characteristic strength interpretation of test data (defined as the value below which not more than 5% of the results of an infinite number of tests would fall)

Background/source of equations

The underlying experimental database and the evaluation process which led to mean and characteristic equations are reported in a DEn/HSE Report entitled 'Background to new static strength guidance for tubular joints in steel offshore structures' (OTH 89 308, 1990).

Expressions of joint strength

$$P_a = \frac{F_y T^2 K_a}{GSF*\sin\theta} Q_u Q_f$$

$$M_a = \frac{F_y T^2 d}{GSF * \sin\theta} Q_u Q_f$$

In the document, P_a and M_a are expressed as P_c and M_c respectively

GSF is a global safety factor equal to 1.7 and 1.28 for normal and severe loading conditions, respectively

Scope of Guidance

Section A21.2.4 in Appendix A21 provides guidance on the following items: Determination of design loads; joint classification; determination of the characteristic capacity of simple joints, including evaluation of Q_u and Q_f; validity ranges of the simple joint design equations; approaches for estimating the strength of nonconforming joints; safety factors; brace load interaction; allowable shear stress at transverse sections in the chord; and joint detailing. In addition, comments are made on overlapping joints but no design equations are given quoting a lack of data as the reason. However the user is referred to the Background Document and the UEG Design Guide for an assessment of the available test data.

Notes

This code includes an additional factor K_a which takes into account the length of perimeter of the brace footprint on the chord, causing an increase in predicted capacity for angles less than 90° (K_a = 1.0 for θ = 90°). This term is only present in the axial load joint capacity equations and not in those for determining capacity where the joint is subject to moment loading.

3.2.2.6 Norwegian Petroleum Directorate 'Guidelines on the Design and Analysis of Steel Structures' (1990)

Format/definition of joint strength

LRFD based on a characteristic strength format.

Background/source of equations

Not stated in the document.

Expressions of joint strength

$$P_f = \frac{F_y T^2}{\gamma_m * \sin\theta} Q_u Q_f \quad \text{(Axial)}$$

$$M_f = \frac{F_y T^2 d}{\gamma_m * \sin\theta} Q_u Q_f \quad \text{(Bending)}$$

In the document, P_f is expressed as N and M_f is expressed as M_{ip} or M_{op}.

γ_m is a partial material safety factor equal to 1.15.

Scope of Guidance

Section 3.5.1 covers joint detailing including comments on overlapping joints,and stiffened joints.

Section 3.5.2 'Static strength of tubular joints' provides guidance on: Determination of the strength of simple joints, including chord load effects, and brace load interaction; design of overlapping joints; and comments on complex joints.

Notes

Guidance on design of conical transitions are given in *Section 3.5.3*.

3.2.2.7 **American Welding Society (AWS) 'Structural Welding Code - Steel'. ANSI/AWS D1.1-94 (1994)**

Format/definition of joint strength

Allowable stress design (ASD or WSD) based on the punching shear stress format, and LRFD based on the nominal load format.

Background/source of equations

Section C10.5 in *Appendix C10* (includes a number of references to a number of publications mainly of P. W. Marshall)

Expressions of joint strength (ASD)

Expressions of the allowable punching stress, which incorporate a safety factor of 1.8, are given in terms of F_y, γ, Q_q and Q_f.

Expressions of joint strength (LRFD)

$$P_f = \phi \frac{F_y T^2}{\sin\theta} (6\pi\beta Q_q) Q_f \quad \text{(Axial)}$$

$$M_f = \phi \frac{F_y T^2}{\sin\theta} \frac{d}{4} (6\pi\beta Q_q) Q_f \quad \text{(Bending)}$$

Φ is the resistance factor which is equal to 0.8 for all joint types.

The above expressions, introduced in the 1992 Edition of the code, are derived from, and intended to be equivalent to, the earlier punching shear criteria (the Q_q and Q_f parameters are the same as in the ASD punching shear equations).

Scope of Guidance

Section 10.5.1 on design of circular T, Y, and K joints, provides guidance on determination of joint capacity using either the punching shear stress format or the nominal load format, including evaluation of Q_q, Q_f, brace load interaction, allowable shear stress in the chord, general collapse (see below), weld sizing, material considerations for base metal selection, overlapping joints, joint classification, and multiplanar joints.

Notes

In addition to the above criteria relating to local joint failure, is required that general collapse (*general ovalising plastic failure in the cylindrical shell of the main member*) is investigated especially in cross joints and joints subjected to crushing loads. An expression for the allowable transverse chord load due to compressive brace loading in unreinforced cross joints is given. In ASD format, this is equal to the API allowable compression capacity for compression loaded X joints with a global safety factor of 1.8 rather than 1.7. With regard to joints reinforced by a joint can, an expression for determining the allowable brace load is provided which has been adopted in both API-WSD and API-LRFD.

A key difference between this and other codes is the use of a chord ovalising parameter α in the Q_q factor. For simple joints, the parameter α is assigned different values depending on joint type and loading. However, its key merit is that it allows results from uniplanar joints to be extended to multiplanar joints (see Section 3.2.3.8).

In the Commentary Section, it is noted that the LRFD (with a resistance factor of 0.8) is nominally equivalent to the ASD (with a safety factor of 1.8) for structures having 40% dead load and 60% service loads.

3.2.3 Comparisons of key design parameters

This section presents a systematic comparison of the codes considered in Section 3.2.2 with regard to the static strength design of simple tubular joints. The following aspects are considered:

1) Joint classification
2) Safety factors
3) Chord yield strength
4) The Q_u factor
5) Chord load effects (Q_f factor)
6) Brace load interaction
7) Validity ranges of design equations
8) Joint detailing
9) Load transfer across chords

When possible, in order to ease comparison, the information is presented separately for WSD and LRFD codes, and the API nomenclature is used.

3.2.3.1 Joint classification

Most codes provide guidance on joint classification for use in connection with design for static strength. Simple joints may be classified as T/Y, DT/X (cross), or YT/K joints on the basis of both joint configuration and joint loading. Figures 3.2.1 and 3.2.2, reproduced from API-WSD (1993) and HSE (1990), respectively, show typical examples of joint classification. Guidance in other codes is broadly similar and is typified by the following clauses (quoted from HSE, 1990) which are based on the UEG Design Guide (1985).

'Each joint should be considered as a number of independent chord/brace intersections and the capacity of each intersection should be checked against the design requirement set out in paragraph (i). Each plane of a multiplanar joint should be subjected to separate consideration and classification.

Each chord/brace intersection should be classified as Y, K, or X according to their configuration and load pattern for each load case. Examples of joint classification are shown in Figure A21.6 (Figure 3.2.2) and should be used with the following guidelines:

(i) For two or three brace members on one side of the chord, the classification is dependent on the equilibrium of the axial load component in the brace members. If the resultant shear on the chord member is essentially zero, the joint should be allocated a K classification. If this requirement is not met, the joint can be downgraded to Y classification as shown in Figure A21.6 (Figure 3.2.2). However, for braces which carry part of their load as K joints and part as Y or X joints, interpolation based on the portion of each in total may be valid. The procedure for interpolation in these cases should be agreed with the certifying authority.

(ii) For multibrace joints with braces on either side of the chord as shown in the example DYDT joint in Figure A21.6 (Figure 3.2.2), care should be taken in allocating the appropriate classification. For example, a K classification would be valid if the net shear across the chord is essentially zero. In contrast, if the loads in all the braces are tensile (eg. at a skirt pile connection), even an X classification may be unsafe due to the increased ovalising effect. Classification for these cases should be agreed with the certifying authority.'

3.2.3.2 Safety factors

<u>WSD Codes (API, AWS, DnV and HSE)</u>

In WSD Codes, the allowable joint strength incorporates a global safety factor. Estimates of joint strength, based on either a lower bound or a characteristic representation of relevant data, are usually divided by the global safety factor to obtain the joint design (or allowable) strength. If this is larger than the nominal (or characteristic) applied load, the static strength design criterion is considered satisfied. The global safety factors for the API, AWS, DnV and the HSE codes are as follows:

	API	AWS*	DnV	HSE
Normal loading conditions	1.7	1.8	1.85	1.7
Severe loading conditions	1.28	---	1.39	1.28

* The safety factor is embodied in the equations based on the punching shear stress format

Table 3.2.1. Safety factors in Working Stress Design codes

<u>LRFD Codes (API, AWS, CIDECT, CSA, DnV, NPD)</u>

In LRFD Codes, the joint design strength incorporates a partial safety factor (may consist of a number or constituent safety factors). Estimates of joint strength, based on either a lower bound or a characteristic representation of relevant data, are usually multiplied by the partial safety factor to obtain the joint design strength. If this is larger than the factored applied load (incorporating other partial safety factors), the static strength design criterion is considered satisfied. The partial safety factors for the API, AWS, CIDECT, CSA, DnV and the NPD codes are as follows:

API: $Ø_j$, referred to as the joint resistance factor, is equal to 0.90 for tension loaded T/Y and X joints, and to 0.95 for other cases.

AWS: ϕ, referred to axs the joint resistance factor, is equal to 0.8.

CIDECT: $(1/\gamma_m)$ is equal to 0.91 (=1/1.1) for all joint types (IIW, 1989). γ_m, referred to as the material and joint partial safety factor, is embodied in the CIDECT design equations.

CSA: $Ø_j$, referred to as the joint resistance factor, is as follows:

	K(Gap)	T/Y	X	K(Lap)
Tension	0.72	0.52	0.89	0.72
Compression	0.72	0.91	0.91	0.72
IPB	0.87	0.75	0.62	---
OPB	0.70	0.59	0.61	---

DnV: $(1/\gamma_m)$ is equal to 0.77 (=1/1.3). γ_m is referred to as the material coefficient.

NPD: $(1/\gamma_m)$ is equal to 0.87 (=1/1.15). γ_m is referred to as the material coefficient.

3.2.3.3 Chord yield strength

Some codes place limits on the maximum value of F_y, the yield strength of the chord, that can be used in design equations for quantifying the static strength of tubular joints. Such limits are specified as a maximum absolute value of F_y and/or as a maximum value of the ratio F_y/F_t, as shown in the table below.

Code	Max. F_y (N/mm^2)	Source: Sec. No. in Code	Max. F_y/F_t	Source: Sec. No. in Code
API-WSD	---		2/3	4.1
API-LRFD	---		2/3	E.1
AWS	415	10.2.5.3	2/3	10.5.1.1
CIDECT	---		---	
CSA	450	5.4.2*	0.85	5.4.3*
DnV	---		0.85	Pt.3 Ch.1 Sec.6 A304
HSE	400	A21.2.4 g	0.7	A21.2.4 e
NPD	---		---	

* Specified in connection with material requirements rather than static strength of tubular joints

Table 3.2.2 Limitations on yield strength of the chord

3.2.3.4 Expressions of the Q_u factor

Table 3.2.3 shows the Q_u factor for each joint geometric and loading type for all the codes considered in Section 3.2.1 except the AWS, whose equations include a Q_q factor of a different format to the Q_u factor. The Q_q expressions are presented at the end of this section. Most Q_u factors are dependent solely upon a function of the joint β ratio (d/D). However, some of the Q_u expressions of the CSA, CIDECT and DnV codes imply that γ ratio (D/2T) has also an influence on the strength for many joint configurations . For joints loaded by IPB all codes except the API suggest some dependence on γ. Finally all the equations for K joints subjected to balanced axial loading include the gap factor Q_g, which is a function of the surface gap between the braces, g. The applicability of these factors is discussed further in Section 3.5 where the simple joint database is used to evaluate most of the design equations.

It should be noted that the Q_u factors do not necessarily represent the same function in all the design equations which may contain additional factors, ie. the Q_u expressions are not necessarily equivalent and they should not be compared without consideration of the full design equations. However, for most codes Q_u may be expressed as follows:

- $Q_u = P^* \sin\theta / F_y T^2 Q_f$ (for axial loading)

  where P^* is either P_a* GSF (WSD codes) or P_f/Φ_j (LRFD codes). One exception is the Q_u expression of the HSE code which in addition contains K_a in the denominator of P^*.

- $Q_u = M^* \sin\theta / F_y T^2 Q_f d$ (for bending loading)

  where M^* is either M_a* GSF (WSD codes) or M_f/Φ_j (LRFD codes). One exception is the Q_u expression of the API code which in addition contains 0.8 in the denominator of M^*.

The gap factor Q_g

The gap factor Q_g (≥ 1.0) is as follows:

<u>API-WSD, API-LRFD, and NPD</u>

$$Q_g = 1.8 - 0.1g/T \text{ for } \gamma \leq 20$$
$$= 1.8 - 4g/D \text{ for } \gamma > 20$$

<u>CSA and DnV</u>

$$Q_g = (2.4 + 1.8\ g/D) / (2.4 + 7.0\ g/D)$$

<u>CIDECT</u>

$$Q_g = 1 + \frac{0.024\,\gamma^{1.2}}{\exp(0.5\,g/T - 1.33) + 1}$$

<u>HSE</u>

$$Q_g = 1.7 - 0.9\,(g/D)^{1/2}$$

Code	T/Y compression	T/Y tension	DT/X compression	DT/X tension	K/YT balanced axial	IPB	OPB
API-WSD & API-LRFD	$3.4 + 19\beta$		$(3.4 + 13\beta)Q_\beta$	$3.4 + 19\beta$	$(3.4 + 19\beta)Q_g$	$3.4 + 19\beta$	$(3.4 + 7\beta)Q_\beta$
DnV	$7.5\beta\ \gamma^{1/2}$	$(2.3 + 6\beta)\gamma^{1/2}$	$\frac{(7+5.7\beta)}{(1.45-\beta)}$ DT only	$1.7\left[\frac{7+5.7\beta}{1.45-\beta}\right]$ DT only	$7.5\beta\gamma^{1/2}Q_g$ * $(1-0.26\cos^2\theta_c)$ * $(1+6.1\beta)/(4.2\beta)$	$6\beta\ \gamma^{1/2}$ T only	$6.55\beta^{0.52}\gamma^{0.1}$ T only
HSE	$(2 + 20\beta)\sqrt{Q_\beta}$	$(8 + 22\beta)$	$(2.5 + 14\beta)Q_\beta$	$(7 + 17\beta)Q_\beta$	$(2 + 20\beta)Q_g\sqrt{Q_\beta}$	$5\beta\ \gamma^{1/2}\ \sin\theta$	$(1.6 + 7\beta)Q_\beta$ (Y/K) $(1.6 + 7\beta)\sqrt{Q_\beta}$(X)
CSA	$7.5\beta\ \gamma^{1/2}$	$(2.3 + 6\beta)\gamma^{1/2}$	$(2.2 + 17.3\beta)Q_\beta$	$1.7\left[\frac{7+5.7\beta}{1.45-\beta}\right]$	$7.5\beta\gamma^{1/2}Q_g$ * $(1-0.26\cos^2\theta_c)$ * $(1+6.1\beta)/(4.2\beta)$	$3.4 + 19\beta$ (K) $6\beta\ \gamma^{1/2}$ (T,Y & X)	$\frac{3.56}{(1-0.81\beta)}$
CIDECT	$1.1(2.8 + 14.2\beta^2)\ \gamma^{0.2}$		$1.1\left[\frac{5.2}{1-0.81\beta}\right]$		$1.1(1.8 + 10.2\beta)\gamma^{0.2}Q_g$	$(1.1)4.85\gamma^{1/2}\beta$	$1.1\ \frac{2.7}{(1-0.81\beta)}$
NPD	$2.5 + 19\beta$		$(2.7 + 13\beta)Q_\beta$		$0.90(2 + 21\beta)Q_g$	$5.0\gamma^{1/2}\beta$	$\frac{3.2}{(1-0.81\beta)}$

Table 3.2.3 Q_u factors for assessment of static strength of tubular joints

The geometric modifier Q_β

Some of the Q_u expressions of API (WSD &LRFD), AWS, CSA, HSE, and NPD include the Q_β factor which is often referred to as the geometric modifier. It is defined as:

$$Q_\beta = 1.0 \text{ for } \beta \le 0.6$$

$$Q_\beta = \frac{0.3}{\beta(1-0.833\beta)} \text{ for } \beta > 0.6$$

Q_q expressions (AWS)

The AWS equations are unique in that they include the chord ovalising parameter α which allows the simple joint equations to be extended to the more complex multiplanar configurations. The nominal load version of the AWS equations is described in Section 3.2.2. All the factors which make up these equations have already been outlined in the previous sections except the Q_q factor which may be considered equivalent to the Q_u factor in other codes. The Q_q expressions, common to both the punching shear and nominal load equations, are as follows:

$$Q_q = \left(\frac{1.7}{\alpha} + \frac{0.18}{\beta}\right) Q_\beta^{0.7(\alpha-1)} \quad \text{for axial loads}$$

and

$$Q_q = \left(\frac{2.1}{\alpha} + \frac{0.6}{\beta}\right) Q_\beta^{1.2(\alpha-0.67)} \quad \text{for bending loads}$$

For simple joints, the chord ovalising parameter α is as follows:

1.7 for axially loaded T and Y joints
2.4 for axially loaded X joints
1.0 + 0.7 g/d
$1.0 \le \alpha < 1.7$
for K joints subject to balanced loading
0.67 for in-plane bending
1.5 for out-of-plane bending.

3.2.3.5 Chord load effects (Q_f factor)

Formulations of the Q_f factor are given below for both WSD and LRFD codes. Symbols and formulae used in the codes have been standardised, taking where possible the API nomenclature as a basis (see Section 3.5.10 for evaluations of the parameter Q_f and of the available data).

WSD Codes (API, AWS, DnV and HSE)

In most codes the formulation of the Q_f factor is very similar to that of API-WSD, which is as follows:

$$Q_f = 1.0 - \lambda \gamma A^2$$

where
λ = 0.030 for brace axial loading
= 0.045 for brace in-plane bending (0.044 in AWS)
= 0.021 for brace out-of-plane bending (0.018 in AWS)

$$A = \frac{\sqrt{f_{ax}^2 + f_{ipb}^2 + f_{opb}^2}}{(F_y / GSF)}$$

f_{ax}, f_{ipb} and f_{opb} are the nominal axial, in-plane bending, and out-of-plane bending stresses in the chord, respectively; and GSF is a global safety factor usually equal to the factor used in connection with joint allowable strength. Values of GSF are as follows:

GSF	API	AWS	DnV	HSE
Normal loading conditions	1.7	1.7	1.85	1.7
Severe loading conditions	1.28	---	1.39	1.28

Table 3.2.4 Global safety factors in WSD codes for use in Q_f

In the HSE formulation, the parameter A is effectively similar to that of API-WSD except that it is expressed in terms of chord loads rather than chord stresses as shown below:

$$A = \frac{\sqrt{(0.23PD)^2 + M_{ipb}^2 + M_{opb}^2}}{0.72 D^2 T F_y / GSF}$$

where P, M_{ipb}, and M_{opb} are the nominal applied chord loads; D and T are the chord diameter and thickness, respectively.

LRFD Codes (API, AWS, CIDECT, CSA, DnV, NPD)

The formulation of the Q_f factor is broadly similar to that of API-WSD except that while in WSD Codes a global safety factor (GSB) is applied only to the chord yield strength, in LRFD Codes, partial safety factors are applied to the chord yield strength and to the chord nominal applied stresses, thus: f_{ax}, f_{ipb} and f_{opb} are the factored axial, in-plane bending, and out-of-plane bending stresses in the chord, respectively; and φ_q is a partial safety factor (referred to as the yield stress resistance factor in API-LRFD). Values of φ_q are as follows:

$$A = \frac{\sqrt{f_{ax}^2 + f_{ipb}^2 + f_{opb}^2}}{\varphi_q F_y}$$

	API	AWS	DnV	NPD
φ_q	0.95	1.0	0.77	0.8

Table 3.2.5 Partial safety factors in LRFD codes for use in Q_f

In the CSA formulation the A parameter is expressed in terms of chord loads rather than chord stresses as follows:

$$A = \sqrt{\left(\frac{C_{fo}}{C_{ro}}\right)^2 + \left(\frac{M_{fo}}{M_{ro}}\right)^2_{IPB} + \left(\frac{M_{fo}}{M_{ro}}\right)^2_{OPB}}$$

where C_{fo} is the greater of the compressive forces on either side of the joint; M_{fo} is the factor applied in-plane-bending or out-of-plane bending moment in the chord; C_{ro} and M_{ro} are the factored chord strengths under compression and bending loads, respectively.

The CIDECT formulation is significantly different with Q_f expressed as follow:

$$1 + 0.3n' - 0.3(n')^2 \quad \text{where} \quad n' = \frac{f_{op}}{F_y}$$

f_{op} is defined as the compression prestress in the chord, ie. it is the resultant stress due to chord loads in excess of those associated with equilibrium. However, no further guidance on evaluation of f_{op} is given.

All codes state that Q_f must not exceed 1.0 and that it is equal 1.0 if all extreme fibre stresses in the chord are tensile. The NPD additionally states that if $\beta \geq 0.9$, $Q_f = 1.0$.

3.2.3.6 Brace load interaction

All codes adopt a similar approach to deal with combinations of axial and bending brace loads, generally by means of an interaction equation of the form:

$$f_1(P^r)^x + f_2[(M_{ip}{}^r)^y \ , \ (M_{op}{}^r)^z] \leq 1.0$$

where P^r, $M_{ip}{}^r$ and $M_{op}{}^r$ are ratios of applied design loads to design strengths, respectively for, axial, in-plane bending, and out-of-plane bending loads; and f_1 and f_2 are simple functions based on approximate interaction models and/or empirical interaction data (see Section 3.5.11 for evaluations of common interaction equations and of the available data).

In WSD Codes, the design strengths (denominators in P^r, M_{ip}^r and M_{op}^r) incorporate a global safety factor. However, in LRFD Codes, both the design loads (numerators in P^r, M_{ip}^r and M_{op}^r) and design strengths incorporate partial safety factors.

The interaction equations are given below for both WSD and LRFD codes. Symbols used in the codes have been standardised in order to ease comparison.

WSD Codes

API-WSD and DnV

$$\left|\frac{P}{P_a}\right| + \frac{2}{\pi}\arcsin\sqrt{\left(\frac{M}{M_a}\right)^2_{IPB} + \left(\frac{M}{M_a}\right)^2_{OPB}} \leq 1.0$$

The argument under the square root sign must not exceed 1.0, otherwise the arcsin term is undefined.

AWS

$$\left(\frac{\text{acting } V_P}{\text{allow. } V_P}\right)^{1.75}_{axial} + \left(\frac{\text{acting } V_P}{\text{allow. } V_P}\right)_{bending} \leq 1.0$$

HSE

$$\left|\frac{P}{P_a}\right| + \left(\frac{M}{M_a}\right)^2_{IPB} + \left|\frac{M}{M_a}\right|_{OPB} \leq 1.0$$

where P and M are the nominal (or characteristic) applied axial and moment loads, respectively, and P_a and M_a are the corresponding allowable design strengths.

LRFD Codes

API-LRFD

$$1-\cos\left(\frac{\pi}{2} * \frac{P}{P_f}\right) + \sqrt{\left(\frac{M}{M_f}\right)^2_{IPB} + \left(\frac{M}{M_f}\right)^2_{OPB}} \leq 1.0$$

AWS

$$\left(\frac{P}{P_f}\right)^{1.75} + \left(\frac{M}{M_f}\right) \leq 1.0$$

CIDECT and CSA

$$\left[\frac{P}{P_f}\right] + \left[\frac{M}{M_f}\right]^2_{IPB} + \left[\frac{M}{M_f}\right]_{OPB} \leq 1.0$$

DnV

$$\left|\frac{P}{P_f}\right| + \frac{2}{\pi} \arcsin \sqrt{\left[\frac{M}{M_f}\right]^2_{IPB} + \left[\frac{M}{M_f}\right]^2_{OPB}} \leq 1.0$$

NPD

$$\left[\frac{P}{\gamma_m * P_f}\right] + \left[\frac{M}{\gamma_m * M_f}\right]^2_{IPB} + \left[\frac{M}{\gamma_m * M_f}\right]_{OPB} \leq \frac{1}{\gamma_m}$$

($1/\gamma_m$) is equal to 0.87 (=1/1.15). γ_m is referred to as the material coefficient (see Section 3.2.3.2 on safety factors)

In the above equations P and M are the factored applied axial and moment loads, respectively, and P_f and M_f are the corresponding factored design strengths.

3.2.3.7 Validity ranges of design equations

Most codes state ranges of applicability of their equations for the static strength design of simple joints. Such limits are given in relation to joint geometrical parameters (eg. β, γ and θ), and/or joint material property (eg. F_y and F_t). In general, application of the design equations to joints lying outside the stated limits is not recommended since it may lead to unsafe joint design. In such cases, most codes recommend other means for estimating joint strength for example using finite element analysis or laboratory tests.

Limits on a number of geometrical parameters of simple joints are summarised in Table 3.2.6. In general, these limits reflect the range of parameters in the test databases on which the equations are based. The API, AWS and NPD codes do not state any similar limits. Limits on material properties relating to the yield strength are reviewed in Section ???.

Code	Joint	β	γ	θ
CIDECT	Y axial K bal. axial X axial	0.2-1.00 0.2-1.00 0.2-1.00	≤25 ≤25 ≤20	30°-90° 30°-90° 30°-90°
	All M_{ip} All M_{op}	same as axially loaded joints same as axially loaded joints		
CSA & DnV	T tension T comp. Y tension Y comp. K bal axial	0.20-1.00 0.25-0.85 0.20-0.85 0.25-0.85 0.25-0.85	9-30 10-20 10-30 10-30 10-55	90° 90° 30°-90° 30°-90° $\theta_c \geq 30°. \theta_t \leq 90°$
CSA	X tension X comp. All M_{ipb} All M_{opb}	0.25-0.55 0.20-1.0 0.20-0.90 0.30-0.90	10-20 10-25 7-30 13-28	Not stated Not stated Not stated Not stated
DnV	DT tension DT comp. T M_{ipb} T M_{opb}	0.25-0.85 0.20-1.0 0.25-0.90 0.30-0.90	10-20 10-25 7-30 13-28	90° 90° 90° 90°
HSE	All simple joints under axial or moment loads	0.15-1.00	9-50	30°-90°

Table 3.2.6 Geometric limits of equations for simple joints

3.2.3.8 Joint detailing

Most codes provide guidance on joint detailing (Figure 3.2.3). These commonly cover minimum length of joint reinforcement on the chord side (joint can) and brace side (brace stub), minimum gap between nonoverlapping braces, and maximum offset of working points (intersections of brace and chord centrelines). Such an offset may be used to satisfy the minimum gap requirement or to reduce the required length of heavy wall in the chord. The guidance of API-WSD, API-LRFD, CSA, DnV, HSE, and NPD are summarised in Table 3.2.7. It can be seen clearly that except the CSA, most codes adopt similar limits to those of API-WSD. CIDECT and AWS are not covered in Table 3.2.7 since they provide little guidance on such joint detailing. The HSE's guidance is restricted to general comments but the reader is referred to the Background Document (OTH 89 308) for a summary of practices on joint detailing.

Code	Minimum Extension of chord reinforcement	Minimum extension of brace reinforcement	Minimum gap between non-overlapping braces	Maximum offset of working points
API-WSD & API-LRFD	D/4 or 305mm (greater of)	d or 610mm (greater of)	51mm	± D/4
CSA	D/4 or 300mm (greater of)	$10t_1$ or 600mm (greater of)	$2t_2$ or 75mm [b] $2t_2$ or 50mm [c] (greater of)	---
DnV	D/4 or 300mm (greater of)	d or 600mm (greater of)	50mm	± D/4
HSE	Back. Doc.	Back. Doc.	Back. Doc.	± D/4
NPD	D/4 or 300mm (greater of)	d or 600mm (greater of)	50mm	---

t_1 is the increased brace wall thickness
t_2 is the wall thickness of the thicker brace
[b] applies if the diameters of both braces are ≥ 650mm
[c] applies if the diameter(s) of one or both braces are < 650mm

Table 3.2.7 Limits on: Length of joint reinforcement, gaps and offset of working points in K joints

3.2.3.9 Load transfer across chords

Joints in which load is transferred across the chord may fail by general collapse. This is defined in the AWS *Clause 10.5.1.2* as 'general ovalising plastic failure in the cylindrical shell of the main member', and is reported to be particularly severe in cross joints and in joints subjected to crushing loads. It is suggested that such joints may be reinforced by increasing the main member thickness, or by use of diaphragms, rings or collars.

For X (cross) joints reinforced by a joint can having an increased thickness T_c, and length L, AWS limits the allowable brace axial load to the following:

$$P_a = P_{a(1)} + \frac{L}{2.5D}\left[P_{a(2)} - P_{a(1)}\right] \quad \text{for} \quad L < 2.5D$$

$$P_a = P_{a(2)} \quad \text{for} \quad L \geq 2.5D$$

where $P_{a(1)}$ is evaluated using the nominal chord thickness
$P_{a(2)}$ is evaluated using the joint can thickness T_c

The same approach is applicable to LRFD equations with the allowable joint strengths replaced by factored design strengths.

Similarly, API (WSD & LRFD) require that general collapse is considered in the design of X (cross) joints, launch leg joints, and other joints in which load is transferred across the chord. For such joints with $\beta < 0.9$, API adopts similar equations to those recommended by AWS for designing joint cans in X joints.

Of the other codes the CSA also contains these provisions in relation to tension loaded T, Y and X joints incorporating joint cans. The CIDECT, DnV, HSE and NPD codes do not give any guidance on quantifying the strength of canned joints.

3.3 Review of Other Published Formulae

3.3.1 General

As well as those provided by or referred to in the design codes summarised in Section 3.2, several design formulae for static strength are given in the literature. Most of the formulae published prior to 1985 are reviewed in the UEG Design Guide including those of Reber (1972), Pan et al (1976), Lee et al (1976), Yura et al (1980), IIW SC XV-E (1981), Graf et al (1981), and Billington et al (1982).

More recently, New test data have been generated leading to enlargement of the worldwide test database. In addition, nonlinear finite element analysis has been used extensively to perform parametric studies aimed at investigating specific factors or at filling gaps in the experimental database. These developments enabled new static strength formulae to be derived and, in some cases, incorporated in design codes. Some of the new formulae are reviewed below, while others are considered in the relevant sections.

3.3.2 Yura et al (1980)

This paper published in 1980 gives a review of test data on the static strength of tubular joints. After preliminary discussion of the database and the equation format, this paper systematically addresses axially loaded T, Y and DT joints, axially loaded K joints and moment loaded joints. In each section there is a review of joint performance characteristics, a presentation of new formulae and a statistical analysis of the accuracy of the database.

The formulae given are based on lower bounds to the test data and form the basis of recommendations given first in the 15th Edition of API RP2A and in all the following editions.

3.3.3 DEn/HSE OTH 89 308 (1990)

This document reports in detail the background analysis which led to derivation of the static strength equations of the DEn/HSE Guidance Notes (1990). The mean strength equations implied in the document are summarised below. The design equations are described in Section 3.2.

Joint Type	Loading	Mean Strength Equation
T/Y	Compression	$P_u \sin\theta / F_y T^2 = (1.61+24.89\beta) \sqrt{Q_\beta} K_a Q_f$
T/Y	Tension	$P_u \sin\theta / F_y T^2 = (11.7+32.26\beta) K_a Q_f$
DT/X	Compression	$P_u \sin\theta / F_y T^2 = (2.98+15.45\beta) Q_\beta K_a Q_f$
DT/X	Tension	$P_u \sin\theta / F_y T^2 = (9.2+22.63\beta) Q_\beta K_a Q_f$
K	B. Axial	$P_u \sin\theta / F_y T^2 = (2.37+23.60\beta) \sqrt{Q_\beta} K_a Q_g Q_f$ $Q_g = 1.67-0.86 \sqrt{(g/D)} \geq 1.0$
T/Y, DT/X	IPB	$M_u / F_y T^2 = (6.20\beta-0.27) d \sqrt{\gamma} Q_f$
T/Y, K	OPB	$M_u \sin\theta / F_y T^2 = (1.88+8.64\beta) d Q_\beta Q_f$
DT/X	OPB	$M_u \sin\theta / F_y T^2 = (1.88+8.64\beta) d \sqrt{Q_\beta} Q_f$

Table 3.3.1 Mean strength equations (DEn/HSE OTH 89 308, 1990)

3.3.4 Yura (1993)

Yura, whose work forms the basis of static strength guidance in API RP2A (API-WSD 15th Edition to date and API-LRFD), has produced a new set of static strength formulae which may be considered as an update of his earlier equations (Yura et al, 1980).

The new equations, which are based on an enlarged database (in comparison with the database reported in 1980), were communicated privately to BOMEL in 1995.

The general format of the equations is as follows:

$P_u = Q_u (F_y T^2 / \sin\theta)\ Q_f$ (axial loading)

$M_u = Q_u (d F_y T^2 / \sin\theta)\ Q_f$ (moment loading)

Expressions of Q_u representing mean and lower bound joint strength are given in tables 3.3.2 and 3.3.3 respectively. Different Q_u formulae are recommended for tension loaded T/Y and DT/X joints, depending on whether the first crack criterion or the ultimate load criterion is used to define joint failure (see Section 1.4). In addition a new factor dependent on γ and β is used in the formulae for tension loaded DT/X joints. This is designated as Q_γ and defined as follows:

$$Q_\gamma = \gamma/8.6 \text{ for } \beta > 0.9$$
$$1.0 \text{ for } \beta \leq 0.9$$

Formulae of the gap factor Q_g and the chord load factor Q_f are similar to those in API-RP2A. The Q_f formulae were proposed by Yura and co-workers at the University of Texas (Boone et al, 1982).

With regard to brace loading interaction effects, a simplified version of the Hoadley and Yura polynomial equation (1985), which has been adopted in the HSE Guidance Notes (1990) is recommended.

Joint Type	Loading	Mean Strength	N	SD
T/Y	Compression	$3.1+20.9\beta$	37	0.107
T/Y	Tension	$0.5\sqrt{\gamma}(3.1+20.9\beta)$	22	0.138
DT/X	Compression	$(3.4+15.3\beta)Q_\beta$	45	0.093
DT/X	Tension	$36\beta\ Q_\gamma$	36	0.18
YT/K	B. Axial	$1.3(3.1+20.9\beta)\ Q_g$	88	0.172
All	IPB	$6\beta\sqrt{\gamma}$, but not$<0.8(3.4+19\beta)$	40	0.121
All	OPB	$3.56/(1-0.81\beta)$	27	0.088

Table 3.3.2 Mean strength Q_u factors (Yura, 1993)

Joint Type	Loading Failure Criterion	Lower Bound Strength
T/Y	Compression	$2+21\beta$
T/Y	Tension (1st crack)	$2+21\beta$
T/Y	Tension (ultimate)	$3+32\beta$
DT/X	Compression	$(3.4+13\beta)\ Q_\beta$
DT/X	Tension (1st crack)	$25\beta\ Q_\gamma$
DT/X	Tension (ultimate)	$30\beta\ Q_\gamma$
YT/K	B. Axial	$1.05(2+21\beta)\ Q_g$
All	IPB	$5\beta\sqrt{\gamma}$, but not $< 0.8(3.4+19\beta)$
All	OPB	$3.2/(1-0.81\beta)$

Table 3.3.3 Lower bound Q_u factors (Yura, 1993)

3.3.5 Healy and Zettlemoyer (1993)

The authors report the findings of a non linear FE study of the in-plane bending strength of T/Y joints. A total of 37 joints covering wide ranges of β (0.3-0.95), γ (8.0-40.0), and θ (45°-90°) were analysed, with a particular emphasis on ensuring the achievement of joint failure rather than brace failure. A statistical regression of the results enabled the following equation representing the mean strength of the joints to be developed:

$$M_u = \frac{17.354\,\tau^{0.05} F_y^{0.91} \beta^{2.06} \gamma^{1.47} T^{3.04}}{\sin\theta^{0.82}}$$

Eliminating the $\tau^{0.05}$ term and introducing a number of simplifications including rounding the powers of other terms allowed the authors to derive the following simplified expression:

$$M_u = \frac{9.5 F_y \beta^2 \gamma^{1.5} T^3}{\sin\theta}$$

This equation is reported to increase the coefficient of variation from 6% (previous equation) to only 8%.

The new equation was then used to evaluate the in-plane bending test database for T/Y, DT/X, and YT/K joints. This had been updated and rigorously screened by the authors. The static yield strength was used in this evaluation rather than the traditionally adopted dynamic yield strength. The authors argue that such a choice is justified since joint tests are conducted in a quasi-static manner. For cases where no static yield data were measured, the dynamic yield data were converted into approximate static data using a correction factor of 0.93.

The new equation was found to represent a lower bound to the valid experimental data. The scatter of which was not considered so large as to suggest that a separate IPB equation is required for each joint type. It should be noted that a rearrangement of the terms in the new equation shows that, except for the slightly different lead constant, it is similar to the IPB equations of a number of the codes reviewed in the previous section as shown below:

Proposed IPB Equation : $M_u \sin\theta = (C) F_y T^2 \beta\sqrt{\gamma} d$

where the lead constant C is equal to 4.75, 4.85, 6.0, 6.0, and 5.0, respectively, in the equations of Healy/Zettlemoyer, CIDECT, CSA, DnV, and NPD.

3.3.6 Lee et al (1995)

The authors report the findings of a non linear FE study of the out-of-plane bending strength of T joints. Preliminary investigations showed that the tensile to yield strength ratio (F_t/F_y), and γ ratio affect joint strength. The latter parameter was found to be influential especially at high β values. α ratio was also investigated but found to have a negligible effect for values exceeding 10. A parametric study was then performed on 16 T joints covering wide ranges of β (0.37-1.0) and γ (10.0-40.0). The results, together with previous experimental data, were curve-fitted to produce the following equation representing the mean of all data:

$$M_u = \frac{F_y T^2}{\sin\theta} 4.18 \gamma^{0.51\beta^2} d \left[0.14 \frac{F_u}{F_y} + 0.77 \right]$$

Experimental Y joint data were excluded from this analysis as the authors note these cause considerable scatter. Hence the above formula is stated as only being applicable to T joints. It should be noted that no information is given on screening of the experimental database.

3.4 Database on Static Strength of Simple Joints

3.4.1 General

The tubular joint static strength database used in this project is an expanded and comprehensive re-screened version of the databases underlying offshore structural design guidance. In this section the background to the database is presented together with the basis of the screening criteria adopted.

For offshore structures worldwide, considerable importance is placed on the resistance provisions of API-RP2A (1993). For tubular joints the lower bound capacity equations are based on the results of just 137 static strength tests as documented by Yura et al (1980). During the early 1980s the database was recompiled in the UK and some 211 test results were used to derive mean and characteristic capacity equations to form the basis of the Department of Energy (DEn) Guidance Notes (1990) now under the jurisdiction of the Health and Safety Executive (HSE). The background is described in a separate document (DEn, OTH 89 308, 1990). The larger DEn database is attributable not only to the availability and awareness of more test results but also to differences in the screening criteria and the minimum acceptable specimen size in particular. This importance is even more marked when reference is made to the work of Kurobane and his team at Kumamoto University in Japan. By accepting chord diameters as small as 60mm, a database of 674 axially loaded joint tests was obtained and the resulting mean and characteristic equations now underlie current IIW (1989) and CIDECT (1991) Design guidance.

These latter codes and the Japanese work are directed primarily to onshore construction and the realism of weld size effects for such small specimens is questioned in relation to large offshore structural connections. Despite this immediate observation, it was recognised that UK/US researchers had perhaps not included all relevant data from Japan. Furthermore, more research programmes, particularly from Delft University of Technology in The Netherlands, had contributed significantly to the understanding of tubular joint behaviour, thereby demanding a re-evaluation of database screening criteria. In the early 1990s the HSE endeavoured to establish a new database with new screening criteria. A total of 634 static strength results for simple joints (T/Y, DT/X, YT/K) under either axial tension/compression, in-plane or out-of-plane bending were compiled. Screening criteria were proposed and comments obtained from experts worldwide. The final screening included the use of a minimum acceptable chord diameter of 115mm, in addition to other traditional criteria. The screening process reduced the available data points to 293 in number.

As part of rigorous international activity to develop an ISO code, BOMEL were provided with the full (unscreened) database to verify. This thorough re-examination of all source material and values within the database has revealed a number of anomalies and omissions which indicate the enormity and complexity of the database collation activity. Nevertheless these differences have been resolved with the HSE database contractor and the newly constructed BOMEL database is the most comprehensive and accurate available, being the combined result of years of research and benefiting from a rigorous QA/validation procedure. The full database contains 680 raw test results with a minimum chord diameter of 100mm. The screening process outlined below reduced the available results to 423 in number.

3.4.2 Screening criteria

The criteria eliminating results from the screened dataset are as follows:

Wall thickness ratio, τ

The limit on this brace to chord thickness ratio has been set to 1.2 to ensure that brace failure for a joint configuration is not suppressed. Offshore practice demands $\tau \leq 1.0$.

Chord slenderness ratio, γ

No limit has been imposed on this parameter. The maximum and minimum values in the database are approximately 48 and 8, respectively. However the vast majority of the data are around the middle of the practical range.

Chord length parameter α

Initially a flexible approach was adopted with regard to this parameter due to the uncertainties surrounding the chord length data. The boundary conditions vary depending on joint type, joint loading and available testing equipment. As a result it is not easy to define a minimum acceptable chord length based on a consistent definition of the 'effective' length. In addition, the existence of flanges and/or other supports which may or may not affect joint failure makes the screening even more difficult. While this parameter requires further investigation possibly using a recent approach based on numerical results generated at TU Delft, the minimum α in the current screened database is 4.3.

Tensile properties

Where chord yield data were not measured and only minimum specified yield strengths were given, the results are screened out but may be considered to provide a lower bound for the data. For general assessment the maximum measured 'dynamic' chord yield stress is 506 MPa but data with higher values are retained for the assessment of HSS joints. Data on the tensile strength of the chord and yield strength of the brace have been included. Where these were not reported for each specimen in a certain test programme, approximate values have been estimated based on tensile data for other specimens in the same test programme. Where 'dynamic' and 'static' chord yield data were reported, the 'dynamic' values were used in order to maintain consistency with the majority of the data where only 'dynamic' properties were given. 'Static' values have been estimated, based on an extensive analysis of a large set of tubular joints and tubular members data (Appendix A3.7), and used for conducting member capacity checks. Tests where the joint capacity is lower than the capacities of the brace members, have been rejected.

Chord and brace thicknesses

All joints in the full and screened databases have thicknesses larger than 2.0mm.

Gaps in K joints

Only K joints where the nominal gap is not equal to zero and is larger than the brace thickness have been accepted.

Load-deformation data

Available data on load-deformation characteristics have been carefully studied. Where there is no evidence that a peak or plateau was reached in compression loaded joints, the tests are screened out and treated as providing lower bound data. Tension data were accepted regardless of whether a peak was reached or not because joint failure is governed by cracking. If a load-deformation curve shows both a plateau and a maximum capacity, the load corresponding to the plateau is adopted because in the majority of cases, it is found to coincide approximately with the first crack load.

Minimum chord diameter

With reference to minimum chord diameter the justification for retaining only 100mm and above chord diameters is as follows:

- There are very few DT/X tests with chord diameter lower than 100mm, and in most of these the load-deformation curves do not reach a peak.

- There are no known T/Y tests with chord diameter lower than 100mm.

- Most of the data for chord diameters lower than 100mm are for Japanese K joints tested under balanced axial loading. However, the vast majority of these have $\gamma \approx 11$ and $F_y/F_t \approx 0.9$. Therefore, they do not represent typical offshore joints. In addition, the effects of oversized weld on capacity of small gap K joints increase significantly when the chord diameter is below 100mm.

- Carefully assembled databases on compression loaded X joints and K joints under balanced axial loading, representing wide ranges of chord diameters, have been analysed. This has revealed that there is no clear cut-off limit for chord diameter below which a size effect can be identified (see Figure 3.4.1). The evidence for such a limit is clouded by the scatter of the small as well as the large scale data. It would appear that the effects of other parameters such as chord length, chord boundary conditions, chord slenderness and yield properties may be as large as the so-called size effect.

- Omission of the data for diameters between 100 and 115mm could reduce the size of the compression loaded DT and K joint databases significantly and could mask the effects of important parameters covered only by the small scale data.

The screening criteria are rigorous, reflecting industry understanding of tubular joint behaviour and the evidence is presented by the full database itself. The screened database used within this project therefore represents the leading state-of-the-art in this field.

3.4.3 Scope of the simple joint database

The screened database is shown in Appendix A3.1 and comprises:

98	T	joints under axial compression
12	Y	joints under axial compression
75	DT	joints under axial compression
3	X	joints under axial compression
118	K	joints under balanced axial loading
8	YT	joints under balanced axial loading
14	T	joints under axial tension
32	DT	joints under axial tension
15	T	joints under in-plane bending
2	Y	joints under in-plane bending
7	DT	joints under in-plane bending
6	K	joints under in-plane bending
19	T	joints under out-of-plane bending
1	Y	joints under out-of-plane bending
5	DT	joints under out-of-plane bending
4	K	joints under out-of-plane bending
4	YT	joints under out-of-plane bending

giving a total of 423 joints.

The data listed do not cover the complete ranges of joint configuration, geometry and loading, and the number of each type bears little relation to the number in service. As noted in the following sections, this lack of data leads to the introduction of a number of key assumptions in formulating design guidance. Of particular concern is the lack of data for a number of joint and loading types as outlined below:

Axially loaded T/Y and DT/X joints: Most data in the compression datasets are for T and DT joints with only a few data for Y and X joints, while all data in the tension datasets are for T and DT joints. This general lack of Y/X data limits the assessment of design codes particularly with regard to the influence of θ and the relative length factor, K_a, present in the HSE formulation. A wide range of β ratios are present in the compression datasets, allowing a thorough assessment of the influence of this parameter. However the maximum β ratio in the tension dataset for T joints is 0.76, which limits the scope of assessment for β ratios approaching 1.0.

Axially loaded YT/K joints: All the data are for the balanced axial load case, ie. where the net force perpendicular to the chord is essentially zero. Although a large volume of data is available, most from small scale specimens, there are relatively very few tests for $\beta > 0.8$. A wide range of angle configurations is covered with some non symmetric K joints (ie. θ_1 and $\theta_2 \neq 90°$; and $\theta_1 \neq \theta_2$) as well as some YT joints (ie. $\theta_1 = 90°$, $\theta_2 \neq 90°$), but the majority of data are for $\theta_1 = \theta_2 = 60°$.

Moment loaded joints: Most of the data are for T joints with relatively very few data covering Y/X joints. This restricts the scope of assessing the effects of brace angle on IPB and OPB strengths. Data on YT/K joints are also limited with only six and four K joint tests for the IPB and OPB cases respectively, and no IPB tests for the YT configuration.

It should be noted that addition of the largely Japanese small scale data (100mm < D < 115mm) has enhanced mainly the data for compression loaded DT and K joints. The limitations outlined above in relation to Y and X joints for all loading types had been largely noted in the UEG Design Guide (1985). Although this awareness led to generation of new data to cover some of the gaps, especially through the JISSP Programme, problems have been identified in connection with some of the old as well as the new data. These problems concerning validity of some parameters, eg. chord length and/or boundary conditions, have cast doubt over some data or led to the omission of a significant volume of data from the latest screened database. The net result is that important gaps still exist. However, the new analytical data generated using non linear finite element analyses and the potential for production of more analytical data in the future, are likely to compensate for the limitations of the experimental database as is shown in the following sections.

3.5 Assessment of Design Equations for Simple Joints

3.5.1 General

The screened simple joint database is used in the following sections to evaluate the static strength equations of six principal codes. These are API-RP2A, CSA, DnV, HSE, CIDECT, and NPD. The data are assessed in terms of the ratio of measured joint strength, P_{meas} (axial) or M_{meas} (moment), to predicted joint strength, P_{pred} (axial) or M_{pred} (moment). Axial refers to either compression or tension, and moment refers to either in-plane bending or out-of-plane bending. P_{pred} and M_{pred} are evaluated after removing global and partial safety factors from the equations of each of the codes. The resulting equations are reproduced in full in the relevant sections together with plots of P_{meas}/P_{pred} or M_{meas}/M_{pred} versus key nondimensional geometric parameters, especially β, for most of the codes considered. In addition, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of P_{meas}/P_{pred} and M_{meas}/M_{pred} are given for all six codes.

Depending on joint loading and type, the joints are divided into three main groups and a number of subgroups as follows:

Compression loaded joints

- Compression loaded T/Y joints (Section 3.5.2)
- Compression loaded DT/X joints (Section 3.5.3)
- YT/K joints subject to balanced axial loading (Section 3.5.4)

All axially loaded YT/K joints were tested under balanced axial loading, ie. tension in one brace and compression in the other with the net force perpendicular to the chord approximately equal to zero. Under these conditions and unless the braces are of significantly different geometry, failure is always associated with the compression loaded brace. The failure data are therefore given in terms of the load in the compression brace and the joints are identified as compression loaded joints.

Tension loaded joints

- Tension loaded T/Y joints (Section 3.5.5)
- Tension loaded DT/X joints (Section 3.5.6)

Since failure of tension loaded joints may be associated with either crack initiation or the attainment of an ultimate load (Section 1.4), data defined according to both these criteria are reported in the database. The ultimate load data are analysed in Sections 3.5.5 and 3.5.6, while the relatively limited first crack (crack initiation) data are considered for both T/Y and DT/X joints in Section 3.5.7.

Moment loaded joints

- Joints subject to in-plane-bending (Section 3.5.8)
- Joints subject to out-of-plane bending (Section 3.5.9)

The value of moment used throughout this document is that at the intersection of the brace and chord rather than at the chord centreline. This is more representative of the position at which failure occurs. In the analysis of structures it is normal to base the calculation of member end moments on the distance between chord centrelines. This results in higher end moments than those which occur in practice and thus the use of formulae based on failure moment at the intersection of the brace and chord leads to a slightly conservative design.

Effects of combined loading on joint strength including brace load interaction and chord load are considered in Sections 3.5.10 and 3.5.11.

3.5.2 Compression loaded T/Y joints

Scope

This section considers test results for a total of 110 joints consisting of 98 T joints and 12 Y joints (Appendix A3.1).

Formulae implied by existing design codes

Formulae given in the API, CIDECT, CSA, DnV, and HSE codes are reproduced in Table 3.5.1 (global and partial safety factors are excluded). Examination of these allow the following observations to be made:

- There are differences in the implied effects of some geometric parameters on strength. In particular, γ is included only in the equations of CSA, DnV and CIDECT. The power assigned to γ in the latter code is different to the power adopted in the CSA and DnV formulations. The API, HSE and NPD codes imply that γ has no effect on nondimensional strength. In addition, all the codes imply that α (ratio of chord length to chord radius) has no effect on strength.

- The CSA and DnV formulae are identical, while there is relatively little difference between the API and DnV equations.

- The length factor K_a, which accounts for the length of the brace footprint on the chord surface implying higher strengths for joints which inclined braces, is included in the HSE formulation only. This is also unique in that it includes also the geometric modifier, Q_β (raised to power 0.5), which implies higher strength at large values of β.

API	$(3.4+19\beta)\dfrac{F_yT^2}{\sin\theta}$
CSA & DnV	$7.5\beta\gamma^{1/2}\dfrac{F_yT^2}{\sin\theta}$
HSE	$(2+20\beta)\sqrt{Q_\beta}\ \dfrac{F_yT^2}{\sin\theta}K_a$
CIDECT	$1.1(2.8+14.2\beta^2)\gamma^{0.2}\dfrac{F_yT^2}{\sin\theta}$

Table 3.5.1 Static strength formulae for compression loaded T/Y joints

Evaluation of design equations

Using the above equations the ratio P_{meas}/P_{pred} has been evaluated for all the available data and plotted versus β in Figure 3.5.1. In addition, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio P_{meas}/P_{pred} are given for all the codes in Table 3.5.2. Based on these results the following may be noted:

N=110	Mean	Std dev	CoV
API	1.21	0.31	0.26
CIDECT	1.17	0.17	0.14
CSA	1.01	0.21	0.20
DnV	1.01	0.21	0.20
HSE	1.22	0.19	0.16
NPD	1.30	0.31	0.24

Table 3.5.2 P_{meas}/P_{pred} for compression loaded T/Y joints

- The Standard deviation of the API and NPD predictions are both equal to 0.31, while those of the CSA and DnV are lower (both equal 0.21). However, lower values are associated with the HSE and CIDECT predictions (0.19 and 0.17 respectively), with the latter having also the smallest CoV at 0.14.

- The API formula, based on a lower bound interpretation of test data, overpredicts joint strength slightly at low β ratios, especially for values close to 0.4. However, this trend is reversed at higher β (>0.8). In particular the API predictions appear to be overly conservative at β=1.0 where there is significant scatter.

- The CIDECT predictions, based on a characteristic representation of the data, appear to provide approximately a constant level of conservatism across the β range with relatively little scatter.

- The identical CSA and DnV formulae appear to provide a mean strength representation of the data (mean of P_{meas}/P_{pred} is 1.01). However, they overpredict the strength of most of the joints at β ratios close to 0.4.

- The HSE formula, based on a characteristic representation of test data, offers one of the best representation but it is relatively more conservative at β ratios exceeding 0.75.

Effect of γ (= D/2T)

As noted earlier the codes differ in their treatment of dependence of joint strength on γ ratio. The approach adopted in the CSA/DnV formula which includes the term $\sqrt{\gamma}$ is evaluated in Figure 3.5.2. This is a plot of actual $\sqrt{\gamma}$ versus $P_{meas}\sin\theta/(7.5\beta F_y T^2)$ which is the value of $\sqrt{\gamma}$ implied by the CSA/DnV formula. Whilst there is some evidence of an increase in nondimensional strength as $\sqrt{\gamma}$ increases, this trend is clouded by the scatter. Furthermore the data where $\sqrt{\gamma}$ is greater than 6.0 exhibit a decrease rather than an increase in nondimensional strength, which cast doubt over the validity of the implied effect of $\sqrt{\gamma}$.

Effect of K_a (approximately = $(1+1/\sin\theta)/2$)

For Y joints the effect of the brace/chord angle θ is twofold. Firstly the brace load is resolved into two perpendicular directions and only the component perpendicular to the chord is considered. Thus the term $\sin\theta$ appears in virtually all design equations for axially loaded joints. Secondly, the length of the interaction (brace footprint on the chord surface) is increased, as the brace/chord angle becomes acute (θ<90°), by a factor K_a. Only the HSE formulae for axially loaded T/Y, DT/X and YT/K joints incorporate the parameter K_a. The implied increase in nondimensional strength can be significant especially for θ=45° and θ=30° where K_a is equal to 1.21 and 1.5 respectively. To investigate the validity of this approach, experimental and numerical data for T and Y joints, which are nominally identical except for the brace/chord angle, are reproduced in Tables 3.5.3 and 3.5.4 from a recent paper by Bolt and Crockett (1993). These data show clearly that good correlation of the Y joint and T joint data could be achieved by using the term $\sin\theta$ only. When, in addition, the parameter K_a is included the T and Y data appear to diverge.

It should be noted that although the above evidence suggests that adoption of the K_a parameter is not valid, its use is implicit in the development of the HSE axial strength equations. If K_a had not been included coefficients of the other parameters in the equations would have been different. It is therefore not appropriate to simply replace K_a with unity.

β	Ratio of $P_Y \sin\theta$ to P_T	Ratio of $P_Y \sin\theta / K_a$ to P_T
0.40 0.67 0.90	1.044 0.983 0.903	0.874 0.823 0.756
Average	0.977	0.818
P_Y and P_T are the strengths of a Y joint (θ=41°) and a T joint, respectively, which are nominally identical except with regard to θ.		

Table 3.5.3 Comparison of analytical joint strengths with and without account of K_a.

β	γ	Ratio of $P_Y \sin\theta$ to P_T	Ratio of $P_Y \sin\theta / K_a$ to P_T
0.8 0.8 1.0	20 32 32	1.043 1.017 1.028	0.864 0.843 0.852
Average		1.029	0.853

Table 3.5.4 Comparison of experimental joint strengths with and without account of K_a (JISSP Data).

<u>Effect of α (=2L/D)</u>

Possible effects of the parameter α on the static strength of axially loaded T/Y joints have traditionally been ignored mainly due to the general lack of data. As a result, none of the existing design codes includes α in the strength formulae for T/Y joints. In order to shed some light on this issue, failure mechanisms which may imply an α effect and the available data are examined below, in addition to findings from recent finite element investigations.

Compression loaded T/Y joints fail normally due to plastification and/or buckling of the chord wall in the vicinity of the brace/chord intersection, especially for joints with low β ratios. However, as β ratio increases, a larger proportion of the brace compression load contributes to global bending in the chord than to local deformation of the chord wall around the brace footprint. Thus, local and global failure mechanisms interact and failure may no longer be associated with local punching into the chord as for low β joints.

The above analysis becomes more complicated if the chord is short, since the restraints applied to the chord ends (eg. via welded flanges) may increase the stiffness and reduce ovalisation of the chord cross section leading to higher joint strength. This is more likely for high β ratios for the reasons outlined above (ie. because brace loads are resisted by both the local and global stiffnesses of the chord). Therefore, the combination of a short chord (low α) and high β enhances joint strength, while this effect is less likely for low β joints which are influenced less by the chord boundary conditions.

As the chord length and α increase, with the brace load kept constant, the associated maximum bending moment in the chord increases. Thus, the ratio of axial brace load to maximum bending moment in the chord decreases. As a result the plastic moment capacity of the chord may be reached prior to joint failure. This is more likely for high β ratios, where true joint failure may not be achieved or at least it is likely to interact with beam bending failure in the chord.

In compiling the experimental database all the available information on chord length and chord boundary conditions were documented. However this information was not always reported or the boundary conditions were not described with sufficient detail in the original references. As a result, it was not always possible to determine reliable estimates of the effective chord length, or of the associated chord bending moment at the section adjacent to the joint. This limitation has precluded the analysis of the experimental data with regard to failure of the chord member (beam bending failure), and the use of the results in the screening process since such actions are debatable and might lead to erroneous findings. Equally, The inconsistencies in reporting the chord length and boundary conditions are bound to influence the relevance of the associated α values and affect the reliability of investigations based on these values.

Despite the above reservations, a preliminary investigation of the effect of α is performed in order to illustrate approximately the scatter in the test data. The ratio P_{meas}/P_{pred} for the HSE formulation is plotted versus α in Figure 3.5.3. A considerable degree of scatter is evident especially for $\alpha<7.0$. As noted above, in addition to the boundary conditions, β ratio has an important influence on the interaction between beam bending failure in the chord and joint failure. In order to investigate this further, the data in Figure 3.5.3 are split into three groups depending on β ratio. It can be seen that most of the joints with $6<\alpha<7$ which have higher capacities than the rest of the data, have also large β ratios (>0.5) confirming that the combination of low α (short chord length) and high β enhances strength. However, this trend is not evident for joints with α below 6.

A better insight into chord length effect may be gained by considering analytical data where most of the uncertainties surrounding experimental data could be eliminated or at least minimised. Such data were reported by Van der Valk (1988) who undertook non-linear finite element analyses of T joints subject to axial compression. Several β and γ ratios were considered and α ratio was varied between 6 and 18. The nondimensional joint strengths shown in Table 3.5.5 for γ=20 indicate that lower α enhances joint strength considerably for β ratios exceeding 0.6.

β	α = 6	α = 12	α = 18
0.2	5.91	5.66	5.42
0.4	10.87	10.09	9.17
0.6	17.60	15.18	13.19
0.8	27.09	21.25	16.60
1.0	39.33	24.54	16.20

Table 3.5.5 Non-dimensional capacities of compression loaded T joints (Van der Valk 1988).

Effect of scale

In order to shed some light on effects of specimen size on the strength of compression loaded T/Y joints, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio P_{meas}/P_{pred} have been evaluated for the following groups of joints (Table 3.5.6):

i) joints with chord diameter < 115mm
ii) joints with chord diameter > 115mm
iii) All joints

In addition, the above groups are illustrated on Figures 3.5.1. Based on these results, the following observations, where data from Groups i and ii are referred to as small scale and large scale data respectively, may be made:

	Number of all joints = 110 Number of joints with D > 115mm = 92 Number of joints with D < 115mm = 18								
	Mean			Std dev			CoV		
Diam.	All	>115	<115	All	>115	<115	All	>115	<115
API	1.21	1.21	1.19	0.31	0.34	0.15	0.26	0.28	0.13
CSA	1.01	0.99	1.08	0.21	0.22	0.08	0.20	0.22	0.07
HSE	1.22	1.22	1.20	0.19	0.20	0.16	0.16	0.16	0.13

Table 3.5.6 P_{meas}/P_{pred} for compression loaded T/Y joints: Scale effect

- Figures 3.5.1 suggest that the small scale data are well within the scatter of the large scale data.
- Table 3.5.6 shows that for the API and HSE formulae, the mean of the small scale data is slightly lower than that based on the large scale data. For the CSA formula, the opposite is true, implying that small scale specimens exhibit higher nondimensional strength. The standard deviations and CoVs associated with the small scale data are lower than those based on the large scale data suggesting a larger degree of scatter in the latter group.

It may therefore be concluded that the above evidence does not support the notion of a scale effect relating to Group i, and that consideration of data from this group alongside the large scale data is justified.

Conclusions

The CIDECT and HSE formulations provide the best representations of the data. However further refinements of existing design equations are required, especially with regard to consideration of the chord length parameter α.

3.5.3 Compression loaded DT/X joints

Scope

This section considers test results for a total of 78 joints consisting of 75 DT joints and 3 X joints (Appendix A3.1).

Formulae implied by existing design codes

Formulae given in the API, CIDECT, CSA, DnV, and HSE codes are reproduced in Table 3.5.7 (global and partial safety factors are excluded). Examination of these allow the following observations to be made:

- Unlike the formulae for T/Y joints, None of the DT/X formulae includes the parameter γ. Rather, the latter formulae imply that β is the only parameter that influences nondimensional strength.
- The formulae of API, CSA, HSE and NPD adopt a similar format of the Q_u factor which consists of a linear function of β multiplied by the geometric modifier Q_β. In particular there are relatively little differences between the Q_u expressions of the API, HSE and NPD.
- Similarly to the T/Y formulae, the K_a factor is included only in the DT/X formula of the HSE.

API	$(3.4+13\beta)Q_\beta \dfrac{F_y T^2}{\sin\theta}$
CSA	$(2.2+17.3\beta)Q_\beta \dfrac{F_y T^2}{\sin\theta}$
DnV	$\left[\dfrac{7+5.7\beta}{1.45-\beta}\right] F_y T^2$
HSE	$(2.5+14\beta)Q_\beta \dfrac{F_y T^2}{\sin\theta} K_a$
CIDECT	$1.1\left[\dfrac{5.2}{1-0.81\beta}\right]\dfrac{F_y T^2}{\sin\theta}$

Table 3.5.7 Static strength formulae for compression loaded DT/X joints

Evaluation of design equations

Using the above equations the ratio P_{meas}/P_{pred} has been evaluated for all the available data and plotted versus β in Figures 3.5.4. In addition, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio P_{meas}/P_{pred} are given for all the codes in Table 3.5.8. Based on these results the following may be noted:

N=78	Mean	Std dev	CoV
API	1.14	0.11	0.10
CIDECT	1.12	0.12	0.10
CSA	1.04	0.10	0.09
DnV	1.09	0.14	0.13
HSE	1.19	0.10	0.08
NPD	1.23	0.11	0.09

Table 3.5.8 P_{meas}/P_{pred} for compression loaded DT/X joints

- The standard deviations and CoVs for all codes are in the ranges 0.10-0.14 and 0.08-0.13 respectively. In addition, they are lower than the corresponding values for T/Y joints, ie. the scatter in the DT/X data is less than in the T/Y data. One possible reason for this difference is that DT/X joints are not susceptible to beam bending failure in the chord.

- There is relatively little difference between the standard deviations and CoVs of the API, CSA, HSE and NPD codes. This is not surprising since they adopt formulae which are broadly similar. However, the smallest CoVs and subsequently the least scatter are those of the CSA and HSE predictions.

- The API formula, appears to provide a lower bound representation of most of the test data. However, it is slightly more conservative at β=1.0, where the scatter is much lower than that of T/Y joints apparently due to the introduction of the parameter Q_β into the DT/X formula.

- The CSA formula appears to provide a mean representation of the data for β>0.4, but it is more conservative for other values of β.

- The DnV formula provides approximately a mean representation of the large scale data (D>115mm) for β<0.8, but it is very conservative for β=1.0.

- The HSE predictions appear to incorporate a constant level of conservatism across the β range.

Effect of K_a (approximately = $(1+1/\sin\theta)/2$)

A useful insight into the validity of the K_a factor may be obtained by considering data on DT and X joints reported by Kaiho (1977). The joints are excluded from the DT/X simple joint database because they have cans, but they are retained for future evaluation of effects of joint can. Table 3.5.9 shows nominally identical DT and X joints (θ=90° and 60° respectively) from the Kaiho programme which differ only with respect to the brace/chord angle. The cans do not affect the ratio of $P_X\sin\theta$ to P_{DT} since they have identical geometries in the DT and X joints. Similarly to the findings relating to the validity of K_a in T/Y formulae, the data in Table 3.5.9 suggest that the use of $\sin\theta$ only achieves better correlation between the DT and X data than that resulting from the inclusion of K_a. However, the use of K_a only provides the best correlation.

Specimen DT	Specimen X	Ratio of $P_X\sin\theta$ to P_{DT}	Ratio of $P_X\sin\theta/K_a$ to P_{DT}	Ratio of P_X/K_a to P_{DT}
CC90-3	CC60-11	0.92	0.85	0.99
CC90-4	CC60-12	0.89	0.82	0.95
CC90-7	CC60-13	0.95	0.88	1.02
CC90-8	CC60-14	0.94	0.87	1.00
Average		0.925	0.855	0.99
P_{DT} and P_X are the strengths of the CC90 and CC60 specimens which have β=1.0 and differ only with regard to θ.				

Table 3.5.9 Comparison of experimental joint strengths with and without account of K_a.

Effect of scale

In order to shed some light on effects of specimen size on the strength of compression loaded DT/X joints, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio P_{meas}/P_{pred} have been evaluated for the following groups of joints (Table 3.5.10):

i) joints with chord diameter < 115mm
ii) joints with chord diameter > 115mm
iii) All joints

Number of all joints = 78
Number of joints with D > 115mm = 41
Number of joints with D < 115mm = 37

	Mean			Std dev			CoV		
Diam.	All	>115	<115	All	>115	<115	All	>115	<115
API	1.14	1.12	1.16	0.11	0.13	0.08	0.10	0.11	0.07
CSA	1.04	1.02	1.07	0.10	0.10	0.09	0.09	0.10	0.08
HSE	1.19	1.16	1.22	0.10	0.10	0.09	0.08	0.09	0.07

Table 3.5.10 P_{meas}/P_{pred} for compression loaded DT/X joints: Scale effect

In addition, the above groups are illustrated on Figures 3.5.4. Based on these results, the following observations, where data from Groups (i) and (ii) are referred to as small scale and large scale data respectively, may be made:

- Figure 3.5.4 suggest that the small scale data lie generally close to the upper bound of the large scale data implying that the former group exhibits higher strength than the latter. However, the vast majority of the small scale specimens have long chords which are known to contribute to enhancing the measured strength.

- Similarly to Figures 3.5.4, Table 3.5.10 indicates that the mean of the small scale data is approximately 5% higher than that of the large scale data. However, the standard deviations and CoVs associated with the former group are lower than those based on the latter suggesting a greater degree of scatter in the large scale data.

The above evidence would appear to support the notion of a scale effect relating to Group (i). However, consideration of other factors which affect the measured strength of DT/X joints, such as chord length and boundary conditions (eg. whether or not flanges were welded to the chord ends), may reveal that these factors contribute to the observed enhancement in joint strength more than the scale effect.

Conclusions

The HSE and CSA formulations provide the best representations of the data.

3.5.4 YT/K joints subject to balanced axial loading

Scope

This section considers test results for a total of 126 joints consisting of 118 K joints and 8 YT joints. All these were tested under balanced axial loading, ie. tension in one brace and compression in the other with the net force perpendicular to the chord approximately equal to zero (Appendix A3.1).

Formulae implied by existing design codes

Formulae given in the API, CIDECT, CSA, DnV, and HSE codes are reproduced in Table 3.5.11 (global and partial safety factors are excluded). Examination of these allow the following observations to be made:

API	$(3.4+19\beta)\dfrac{F_y T^2}{\sin\theta} Q_g$
CSA & DnV	$7.5\beta\gamma^{1/2}\dfrac{F_y T^2}{\sin\theta_c} Q_g$ * $(1-0.26\cos^2\theta_c)$ * $(1+6.1\beta)/(4.2\beta)$
HSE	$(2+20\beta)Q_\beta^{1/2} K_a \dfrac{F_y T^2}{\sin\theta} Q_g$
CIDECT	$1.1(1.8+10.2\beta)\gamma^{0.2}\dfrac{F_y T^2}{\sin\theta} Q_g$
The Q_g formulae are reported in Table 3.2.3	

Table 3.5.11 **Static strength formulae for YT/K joints subject to balanced axial loading**

- The design codes generally imply that when the gap between braces at the intersection is large, a joint with a YT/K configuration should be treated as a number of separate simple T or Y joints. As the gap reduces, the strength of the joint usually increases in comparison with a nominally identical compression loaded T or Y joint. The increase is often quantified using the gap factor Q_g which is a function of the gap ratio. This is a nondimensional expression of the gap as either g/D (designated as ζ and adopted in the API (γ>20), CSA/DnV, and HSE formulae), or g/T (sometimes referred to as g' and adopted in the API ($\gamma\leq$20) and CIDECT formulae).

- The formulae of the API and HSE imply that the strength of YT/K joints subject to balanced axial loading becomes equal to that of compression loaded T/Y joints, when the gap factor Q_g is equal to 1.0 (for high values of g). Thus Q_g represents the ratio of strength of YT/K joints to that of Y/T joints. However, this is not the case in the YT/K formulae of CSA/DnV, CIDECT or NPD. The API expression of Q_g implies that the threshold gap size corresponding to Q_g=1.0 is g=8T for $\gamma\leq$20 and g=0.2D for γ>20. The corresponding threshold gap size in the HSE formulation is g=0.6D. For gaps smaller than these threshold values Q_g is > 1.0.

- The CIDECT formulation is unique in that it accounts for both gap and overlapping joints. Estimates of joint strength are obtained by inserting a positive value of g (for gap joints) or a negative value of g for overlapping joints, in the same formula. In the CSA formulation, the formulae used for gap and overlapping joints are identical except with regard to the Q_g factor. The other codes adopt a completely different approach to deal with overlapping joints based on engineering mechanics (Section 4).

- There are differences in the implied effects of some geometric parameters on strength. In particular, formulations of the gap factor Q_g differ significantly from one code to another. In addition, γ is included only in the equations of CSA, DnV and CIDECT. In the latter code γ is also incorporated in the Q_g expression, while in the corresponding API expression, there is only an indirect reference to γ. The HSE and NPD codes imply that γ has no effect on nondimensional strength.

<u>Evaluation of design equations</u>

Using the above equations the ratio P_{meas}/P_{pred} has been evaluated for all the available data and plotted versus ζ (=g/D) in Figure 3.5.5. In addition, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio P_{meas}/P_{pred} are given for all the codes in Table 3.5.12. Based on these results the following may be noted:

- The least degree of scatter appears to be associated with the CIDECT and CSA/DnV formulations (Standard deviations equal to 0.15 and 0.14 respectively). The scatter in the predictions of the remaining codes is slightly larger especially for $g/D \leq 0.2$.

- The API and HSE formulae appear to provide lower bound representations of the vast majority of the data. The CIDECT formula provides a similar representation of all the data. The mean of P_{meas}/P_{pred} for the CSA/DnV formula is 1.03 implying a mean representation of the data especially for $g/D \leq 0.35$.

- The scatter associated with the YT/K data appears to be larger than that of other joint configurations. This may be attributed to a number of factors including:

  <u>Boundary conditions</u>: YT/K joints have been tested in many different ways, with the balanced load case generally falling into two broad categories (Figure 3.5.6). In the first category, compression loading is applied to one brace and reacted out at the other brace and one chord end, whilst the other half of the chord is unsupported and does not transfer any load. In the second category, both ends of the chord are supported and balanced axial loading is applied to the braces to be reacted out at both chord ends. It can be envisaged that different joint capacities may be recorded depending on the loading and restraint conditions, especially if the critical compression brace intersects the unsupported half of the chord. Numerical data on the effects of boundary conditions on the capacity of K joints are reported by Bolt et al (1992).

Gap size data: Where the nominal gap is small (eg. for g/D ≤ 0.1 in small scale specimens) the weld size may have a significant influence on the actual size of the gap. Oversized welds reduce the effective gap size which is likely to lead to slightly higher joint strength than the strength which would correspond to the nominal pre-welding gap. However, for the majority of tests, only data on the size of the pre-welding gap are reported. As a result, the effect of the actual post-welding gap cannot be investigated and discrepancies in the ratio of actual to nominal gap size are likely to contribute to the scatter in the data.

N=126	Mean	Std dev	CoV
API	1.35	0.18	0.14
CIDECT	1.38	0.15	0.11
CSA	1.03	0.14	0.14
DnV	1.03	0.14	0.14
HSE	1.22	0.19	0.15
NPD	1.56	0.22	0.14

Table 3.5.12 P_{meas}/P_{pred} for K Joints subject to balanced axial loading

Effect of γ (=D/2T)

As noted earlier, the codes differ in their treatment of joint strength dependence on γ ratio. The approach adopted in the CSA/DnV formulation which includes the term $\sqrt{\gamma}$ is investigated in Figure 3.5.7. This is a plot of actual $\sqrt{\gamma}$ versus the value of $\sqrt{\gamma}$ implied by the CSA/DnV formula (ie. the measured strength divided by the CSA/DnV formula excluding the $\sqrt{\gamma}$ term). While there is evidence of an increase in strength with $\sqrt{\gamma}$ for $\sqrt{\gamma} < 4$, it could also be noted that there is no increase at larger $\sqrt{\gamma}$ values (>4) which lie below the (x=y) line. It is speculated that a horizontal line around an abscissa value of 4.5 would fit the data equally well indicating no γ effect. The evidence of dependence upon gamma is therefore questionable partly due to the large degree of scatter.

Effect of K_a (approximately = $(1+1/\sin\theta)/2$)

A useful insight into the validity of the K_a factor may be obtained by considering data on YT/K joints, which differ only with respect to the brace/chord angle (Togo 1967). Data for compression brace angles in the range, θ_c = 90°- 30°, are available. These are summarised in Table 3.5.13 and, similarly to the findings relating to the validity of K_a in T/Y and DT/X formulae, suggest that the use of $\sin\theta$ only achieves better correlation between the YT and K data than that resulting from the inclusion of K_a and $\sin\theta$. However, the use of K_a only provides the best correlation.

Specimen YT/K	Ratio of $P_K \sin\theta$ to P_{YT}	Ratio of $P_K \sin\theta / K_a$ to P_{YT}	Ratio of P_K / K_a to P_{YT}
θ_c=75°	0.97	0.95	0.98
θ_c=45°	0.89	0.74	1.04
θ_c=30°	0.77	0.51	1.03
Average	0.88	0.73	1.02
P_K and P_{YT} are the strengths of specimens with θ_c<90 and θ=90 respectively (Series K-I-3.2-E-20-θ_c-1,2&3)			

Table 3.5.13 Comparison of experimental joint strengths with and without account of K_a.

Effect of scale

In order to shed some light on effects of specimen size on the strength of compression loaded YT/K joints, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio P_{meas}/P_{pred} have been evaluated for the following groups of joints (Table 3.5.14):

i) joints with chord diameter < 115mm
ii) joints with chord diameter > 115mm
iii) All joints

In addition, the above groups are illustrated on Figures 3.5.5. Based on these results, the following observations, where data from Groups (i) and (ii) are referred to as small scale and large scale data respectively, may be made:

	Number of all joints = 126 Number of joints with D > 115mm = 39 Number of joints with D < 115mm = 87								
	Mean			Std dev			CoV		
Diam.	All	>115	<115	All	>115	<115	All	>115	<115
API	1.35	1.44	1.31	0.18	0.22	0.15	0.14	0.16	0.11
CSA	1.03	0.95	1.06	0.14	0.19	0.10	0.14	0.20	0.10
HSE	1.22	1.23	1.22	0.19	0.21	0 18	0.15	0.17	0.15

Table 3.5.14 P_{meas}/P_{pred} for K Joints subject to balanced axial loading: Scale effect

- Figures 3.5.5 suggest that the small scale data are broadly within the scatter of the large scale data.

- Table 3.5.14 shows that depending on whether the API, CSA or HSE formula is considered, the mean of the small scale data is either lower or higher than that of the large scale data. this implies that the evidence of a scale effect is questionable and clouded by the scatter. The standard deviations and CoVs associated with the small scale data are lower than those based on the large scale data suggesting a larger degree of scatter in the latter group.

It may therefore be concluded that the above evidence does not support the notion of a scale effect relating to Group i, and that consideration of data from this group alongside the large scale data is justified.

Conclusions

There is a significant degree of scatter in the representations of data by all the formulae. However, the CIDECT formulation may be considered to offer the best fit because it includes approximately a constant margin of safety across the ζ (=g/D) range. The HSE formulation may also be considered to provide a reasonable representation of the data.

3.5.5 Tension loaded T/Y joints

Scope

This section considers test results for a total of 14 tension loaded T joints. No Y joint data exist in the screened database and the largest β ratio is 0.76, ie. there are no data for the β=1 configuration. Ultimate load data were recorded for all the 14 joints, while crack initiation (or first crack) data were available for only eight joints (Appendix A3.1).

The following analysis is based on the ultimate load data. The first crack data are analysed together with those of DT joints in Section 3.5.7.

Formulae implied by existing design codes

Formulae given in the API, CIDECT, CSA, DnV, and HSE codes are reproduced in Table 3.5.15 (global and partial safety factors are excluded). Examination of these allow the following observations to be made:

- A major cause of differences between the formulae for tension loaded joints is whether they are based on the first crack or ultimate load criteria (Section 1.4). The ultimate load criterion is adopted in the CSA, DnV and HSE codes. The first crack criterion would appear to have been adopted first in the API Code, then in the CIDECT and NPD codes. This is not manifested explicitly by specific formulae representing first crack data. Rather, the tension strength of T/Y and DT/X joints according to the API, CIDECT and NPD formulae is limited to that of nominally identical compression loaded joints, presumably because compression strength appears to be close to or lower than tension strength if this is based on the first crack criterion. Furthermore the API formulae imply that the strength of DT/X joints is lower under tension than under compression for $\beta > 0.6$.

- The comments made in relation to the T/Y compression formulae, including differences in the implied effects of the geometric parameters γ and K_a but excluding the parameter Q_β, are equally applicable to the T/Y tension formulae.

API	$(3.4 + 19\beta)\ \dfrac{F_y T^2}{\sin\theta}$
CSA & DnV	$(2.3 + 6\beta)\gamma^{1/2}\ \dfrac{F_y T^2}{\sin\theta}$
HSE	$(8 + 22\beta)\ \dfrac{F_y T^2 K_a}{\sin\theta}$
CIDECT	$1.1(2.8 + 14.2\beta^2)\gamma^{0.2}\ \dfrac{F_y T^2}{\sin\theta}$

Table 3.5.15 Static strength formulae for tension loaded T/Y joints

Evaluation of design equations

Using the above equations the ratio P_{meas}/P_{pred} has been evaluated for all the available data and plotted versus β in Figure 3.5.8 (P_{meas} is the failure load based on the ultimate load criterion. Similar analyses based on the first crack data are reported for both T and DT joints in the Section 3.5.7). In addition, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio P_{meas}/P_{pred} are given for all the codes in Table 3.5.16. Based on these results the following may be noted:

- The CSA/DnV formulation, which includes a $\sqrt{\gamma}$ term, provides the closest representation of the data (standard deviation and CoV equal to 0.16 and 0.19 respectively). The HSE predictions are more conservative and exhibit more scatter. However, the database, restricted to T joints, is relatively small and does not represent the full β range. In particular there are no tests for the β=1 configuration.

- Given the uncertainties surrounding determination of tension strength and the problems associated with beam bending failure in the chord and short chord length effects, the relatively limited scatter in the CSA/DnV predictions is quite surprising (standard deviation is lower than the corresponding value for compression loaded joints). However, it is difficult to make direct comparisons of the statistical data relating to the compression and tension databases since tension data are much fewer than the compression data and the associated failure mechanisms are significantly different.

- The plots and statistical data of P_{meas}/P_{pred} for the API, CIDECT and NPD formulations, represent effectively the ratio of P_{meas} (measured tension strength based on the ultimate load criterion) to P_{pred} (assuming compression loading). Therefore, the high values of P_{meas}/P_{pred} (means in the range 2.35-2.60) are not surprising.

N=14	Mean	Std dev	CoV
API	2.40	0.58	0.24
CIDECT	2.35	0.52	0.22
CSA	1.20	0.19	0.16
DnV	1.20	0.19	0.16
HSE	1.59	0.38	0.24
NPD	2.60	0.64	0.24

Table 3.5.16 P_{meas}/P_{pred} for tension loaded T/Y joints

Effect of γ (=D/2T)

The validity of adopting a $\sqrt{\gamma}$ term in the CSA/DnV formulation is investigated in Figure 3.5.9. This is a plot of actual $\sqrt{\gamma}$ versus the value of $\sqrt{\gamma}$ implied by the CSA/DnV formula (ie. the measured strength divided by the CSA/DnV formula excluding the $\sqrt{\gamma}$ term). A trend for tensile strength to increase with $\sqrt{\gamma}$ is noticeable suggesting that the CSA/DnV approach is adequate. However, this conclusion, based on a relatively small database, should be reevaluated if more data become available.

Conclusions

The CSA/DnV formulation provides the best representation of the data.

3.5.6 Tension loaded DT/X joints

Scope

This section considers test results for a total of 32 tension loaded DT joints. No X joint data exist in the screened database. Ultimate load data were recorded for all the 32 joints, while crack initiation (or first crack) data were available for only 12 joints (Appendix A3.1).

The following analysis is based on the ultimate load data. The first crack data are analysed together with those of T joints in Section 3.5.7.

Formulae implied by existing design codes

Formulae given in the API, CIDECT, CSA, DnV, and HSE codes are reproduced in Table 3.5.17 (global and partial safety factors are excluded). In addition to the comments on the formulae for tension loaded T/Y and DT/X joints made in Section 3.5.5 in relation to the effects of tension failure criteria, the following may be noted:

- The DnV formulae imply that the tension strength of DT joints is equal to 1.7 times their compression strength.
- The formulae of all codes imply that the parameter γ does not influence the tension strength of DT/X joints.

API	$(3.4+19\beta)\,\frac{F_yT^2}{\sin\theta}$
CSA	$1.7\left[\frac{7+5.7\beta}{1.45-\beta}\right]\frac{F_yT^2}{\sin\theta}$
DnV (DT only)	$1.7\left[\frac{7+5.7\beta}{1.45-\beta}\right]F_yT^2$
HSE	$(7+17\beta)\,Q_\beta\,\frac{F_yT^2}{\sin\theta}K_a$
CIDECT	$1.1\left[\frac{5.2}{1-0.81\beta}\right]\frac{F_yT^2}{\sin\theta}$

Table 3.5.17 Static strength formulae for tension loaded DT/X joints

Evaluation of design equations

Using the above equations the ratio P_{meas}/P_{pred} has been evaluated for all the available data and plotted versus β in Figure 3.5.10 (P_{meas} is the failure load based on the ultimate load criterion. Similar analyses based on the first crack data are reported for both T and DT joints in Section 3.5.7). In addition, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio P_{meas}/P_{pred} are given for all the codes in Table 3.5.18. Based on these results the following may be noted:

- Given the uncertainties surrounding determination of tension failure loads, the CSA/DnV and HSE formulations appear to provide reasonable representations of the data (means equal to 1.39 and 1.55 respectively). However, the scatter is significant and the predictions are more conservative at β=1.0.
- The statistical data of P_{meas}/P_{pred} for the CIDECT and NPD formulations, represent effectively the ratio of P_{meas} (measured tension strength based on the ultimate load criterion) to P_{pred} (assuming compression loading). Therefore, the high values of P_{meas}/P_{pred} (means equal to 2.40 and 2.62 respectively) are not surprising. P_{pred} according

to the API formula, which does not include the Q_β factor, is even lower than the values for compression loaded joints for β>0.6. This explains partly the excessive conservatism of the API formulation at β=1.0 and the very high standard deviation and CoV equal to 1.04 and 0.47 respectively.

N=32	Mean	Std dev	CoV
API	2.22	1.04	0.47
CIDECT	2.40	0.57	0.24
CSA	1.39	0.38	0.28
DnV	1.39	0.38	0.28
HSE	1.55	0.41	0.27
NPD	2.62	0.62	0.24

Table 3.5.18 P_{meas}/P_{pred} for tension loaded DT/X joints

Conclusions

The CSA/DnV formulation provides the best representation of the data.

3.5.7 Crack initiation in tension loaded T/Y and DT/X joints

The formulae implied by existing codes for the design of tension loaded T/Y and DT/X joints are evaluated, using data based on the ultimate load criterion, in the two previous sections. A similar evaluation is performed in this section using data based on crack initiation in tests on eight and 12 T and DT joints respectively (Appendix A3.1). The formulae of the API, CSA and HSE codes are only considered. These are described in detail in the previous two sections.

The ratio P_{meas}/P_{pred} has been evaluated for all the available data and plotted versus β in Figure 3.5.11 (P_{meas} is the failure load based on the crack initiation criterion). In addition, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio P_{meas}/P_{pred} are given for the combined T and DT data in Table 3.5.19. Based on these results the following may be noted:

N=20	Mean	Std dev	CoV
API	1.52	0.58	0.38
CSA	0.85	0.25	0.29
HSE	1.01	0.26	0.26

Table 3.5.19 P_{meas}/P_{pred} for tension loaded T/Y and DT/X joints P_{meas} is based on crack initiation

- The API, CSA, and HSE formulae appear to provide, respectively, a lower bound, an upper bound and a mean representations of the data. This is not surprising given the bases of these formulae (see Sections 3.5.5 and 3.5.6).

- The scatter in the crack initiation data is broadly similar to that associated with the ultimate load data. In addition, the levels of scatter in the T and DT data are in general comparable.

- Given that only the API formulation is based on the strength of compression loaded joints, the above evidence suggests that formulae for compression loaded joints may provide approximately lower bound representations of crack initiation data. However, this observation requires further validation.

3.5.8 Joints subject to in-plane-bending moments

Scope

This section considers test results for in-plane moment loaded joints. The available data consist of 15 T joints, 2 Y joints, 7 DT joints, and 6 K joints (Appendix A3.1).

Formulae implied by existing design codes

Formulae given in the API, CIDECT, CSA, DnV, and HSE codes are reproduced in Table 3.5.20 (global and partial safety factors are excluded). Examination of these allow the following observations to be made:

API	$(3.4 + 19\beta)\,0.8d\,\frac{F_y T^2}{\sin\theta}$
CSA K only	$(3.4 + 19\beta)\,d\,\frac{F_y T^2}{\sin\theta}$
CSA T/Y & DT/X	$6\beta\gamma^{1/2} d\,\frac{F_y T^2}{\sin\theta}$
DnV T only	$6\beta\gamma^{1/2} d\,\frac{F_y T^2}{\sin\theta}$
HSE	$5\beta\gamma^{1/2} d\,F_y T^2$
CIDECT	$(1.1)\,4.85\,\beta\gamma^{1/2} d\,\frac{F_y T^2}{\sin\theta}$

Table 3.5.20 Static strength formulae for in-plane moment loaded joints

- Each of the API, CIDECT, HSE and NPD codes gives one formula for in-plane moment strength irrespective of joint type (T/Y, DT/X or YT/K).

- The CSA gives one formula for T/Y and DT/X joints, but recommends a different formula for K joints which is based on a Q_u formulation similar to that of the API.

- The DnV formula is restricted to T joints only (as implied by a diagram in the code). However, it is noted that if more accurate information is not available, the formula may also be applied to inclined braces.

- The equations of CSA (T/Y and DT/X), CIDECT, DnV (T only), and NPD are similar except that the leading constant differs slightly from one code to another. The HSE formula is also similar but does not permit resolution of moments, applied to inclined braces, into perpendicular components (no $\sin\theta$ term in the full HSE equation).

- The formulations of the API and CSA (K joints) imply that γ does not influence the nondimensional strength. However, all the other formulations suggest the opposite and include the term $\sqrt{\gamma}$ in their Q_u expressions.

- The codes do not imply that the direction of in-plane-bending moments, when applied to inclined braces, affect joint strength. The likeliest reason for this lack of guidance is that the majority of data, on which the formulae were based, are for T joints where the question of direction of applied moment does not arise. However, limited data generated in the JISSP Programme for Y and K joints, and recent finite element analyses of Y joints, suggest the following:

    - A moment causing the inclined brace of a Y joint to rotate in the direction of the acute brace angle can lead to failure at a load significantly lower than that under a moment applied in the opposite direction when β and γ are high (Healy and Zettlemoyer, 1993).

    - Moments causing the inclined braces of a series of K joints (β=1.0, θ_c=45° and θ_t=45°) to rotate in the same direction led to failure at a load which was 17% lower than that achieved under moments causing rotation in the opposite directions towards the gap. However, the opposite was observed for similar joints with β=0.5, where the difference in failure loads was approximately 10% (DEn OTH 89 297, 1989).

<u>Evaluation of design equations</u>

Using the above equations the ratio M_{meas}/M_{pred} has been evaluated for all the available T/Y, DT and K data and plotted versus β in Figure 3.5.12, where the data are labelled according to joint type (ie. T, Y, DT or K). In addition, statistical data in the form of mean, standard deviation and coefficient of variation

(CoV) of the ratio M_{meas}/M_{pred} are given separately for each joint type in Table 3.5.21. Based on these results the following may be noted:

- The plots show that the ratios M_{meas}/M_{pred} for two Y joints from the JISSP Programme (β = 0.8 and 1.0) are very high in comparison with the rest of the data, ie. the joints exhibit exceptionally high strengths. The reason for this apparent anomaly is twofold. First, these joints were tested under moments in the direction opposite to that of the acute angle (see above), and second, they had short chords (α= 6.2) with flanges welded to the chord ends, which may have increased the stiffness and reduced deformation of the chord leading to higher joint strength. Given the small population in the T/Y database (N=17), the relatively large standard deviations and CoV of the T/Y data may be partly attributed to the effects on these two Y joints.

- With the exception of the above JISSP Y tests, the formulations of the CSA, DnV, CIDECT and NPD appear to provide similar representations of the data with relatively little scatter. This is confirmed by the insignificant differences between the standard deviations (and CoVs) associated with the four formulations. Furthermore, the DT and K data are well within the scatter of the T data which supports the adoption of a single in-plane-bending formula for all joint types by most codes (eg. CIDECT and NPD).

- The scatter associated with the HSE representation of the Y and K data is larger than that of CIDECT. The two formulations are broadly similar except that the HSE does not allow resolution of moments when these are applied to inclined braces. Healy and Zettlemoyer who undertook a comprehensive evaluation of the experimental data and generated finite element data on T/Y joints with θ in the range 45°-90° (Section 3.3), suggest that the format adopted in the CIDECT equation is adequate. In addition, they recommend an equation which, except for a slightly different leading constant, is identical to the CIDECT formula.

	T/Y N=17			DT/X N=7			YT/K N=6		
	Mean	SD	CoV	Mean	SD	CoV	Mean	SD	CoV
API	1.43	0.52	0.37	1.29	0.20	0.16	1.29	0.12	0.10
CIDECT	1.10	0.23	0.21	1.03	0.05	0.05	1.05	0.11	0.10
CSA	0.98	0.20	0.21	0.91	0.04	0.05	1.03	0.10	0.10
DnV	0.98	0.20	0.21	--	--	--	--	--	--
HSE	1.26	0.47	0.37	1.10	0.05	0.05	1.58	0.17	0.10
NPD	1.17	0.24	0.21	1.10	0.05	0.05	1.12	0.12	0.10

Table 3.5.21 M_{meas}/M_{pred} for in-plane moment loaded joints

Effect of γ (=D/2T)

In addition to the above evidence that formulations which include the $\sqrt{\gamma}$ provide good representations of the data, the effect of this term is investigated further in Figure 3.5.13. This is a plot of actual $\sqrt{\gamma}$ versus the value of $\sqrt{\gamma}$ implied by the CIDECT formula (ie. the measured strength divided by the CIDECT formula excluding the $\sqrt{\gamma}$ term). With the exception of the two aforementioned two Y tests from the JISSP Programme ($\sqrt{\gamma} \approx 5.6$), a trend for in-plane-bending strength to increase almost linearly with $\sqrt{\gamma}$ is clearly noticeable suggesting that the CIDECT approach is adequate.

Effect of ζ (=g/D) in K joints

Limited data generated in the JISSP Programme on four K joints with ζ equal to 0.1 and 0.15 (β=0.5) suggest that the measured strength of the joints with ζ=0.1 was almost equal to that of the joints with ζ=0.15.

Conclusions

The CIDECT formulation (and the nearly similar formulae of CSA/DnV) provides the best representation of the data. The HSE approach which does not allow resolution of moments, when these are applied to inclined braces, is not supported by the available data.

3.5.9 Joints subject to out-of-plane-bending moments

Scope

This section considers test results for out-of-plane moment loaded joints. The available data consist of 19 T joints, 1 Y joint, 5 DT joints, 4 YT joints, and 4 K joints (Appendix A3.1).

Formulae implied by existing design codes

Formulae given in the API, CIDECT, CSA, DnV, and HSE codes are reproduced in Table 3.5.22 (global and partial safety factors are excluded). Examination of these allow the following observations to be made:

- Each of the API, CIDECT, CSA and NPD codes gives one formula for out-of-plane moment strength irrespective of joint type (T/Y, DT/X or YT/K).

- The HSE gives one formula for T/Y and YT/K joints, and recommends an almost identical equation for X joints which differs only with regard to the power assigned to the parameter Q_β (0.5 for X joints and 1.0 for T/Y and YT/K joints). This implies that, when β approaches 1.0, the strength of X joints does not increase as steeply as the strength of T/Y and YT/K joints.

API	$(3.4+7\beta)Q_\beta(0.8d)\dfrac{F_yT^2}{\sin\theta}$
CSA	$\dfrac{3.56\,d}{1-0.81\beta}\;\dfrac{F_yT^2}{\sin\theta}$
DnV T only	$6.55\,\beta^{0.52}\gamma^{0.1}\,d\,\dfrac{F_yT^2}{\sin\theta}$
HSE T/Y & K	$(1.6+7\beta)Q_\beta\,d\,\dfrac{F_yT^2}{\sin\theta}$
HSE DT/X	$(1.6+7\beta)\sqrt{Q_\beta}\;d\,\dfrac{F_yT^2}{\sin\theta}$
CIDECT	$1.1\,\dfrac{2.7\,d}{1-0.81\beta}\;\dfrac{F_yT^2}{\sin\theta}$

Table 3.5.22 Static strength formulae for out-of-plane moment loaded joints

- The DnV formula is restricted to T joints only (as implied by a diagram in the code). However, it is noted that if more accurate information is not available, the formula may also be applied to inclined braces.

- The equations of CSA, CIDECT, and NPD are similar except that the leading constant differs slightly from one code to another.

- There are clear differences in the implied effects of the parameter β and in the format of the Q_u factor.

- Only the DnV formulation implies that γ has an influence on the nondimensional strength. However, the power assigned to γ is only 0.1 which suggests a relatively small γ effect.

Evaluation of design equations

Using the above equations the ratio M_{meas}/M_{pred} has been evaluated for all the available T/Y, DT and K data and plotted versus β in Figure 3.5.14, where the data are labelled according to joint type (ie. T, Y, DT or K). In addition, statistical data in the form of mean, standard deviation and coefficient of variation (CoV) of the ratio M_{meas}/M_{pred} are given separately for each joint type in Table 3.5.23. Based on these results the following may be noted:

	T N=20			DT N=5			YT/K N=8		
	Mean	SD	CoV	Mean	SD	CoV	Mean	SD	CoV
API	1.20	0.29	0.24	1.08	0.13	0.12	1.08	0.12	0.12
CIDECT	1.25	0.25	0.20	1.10	0.07	0.07	1.13	0.17	0.15
CSA	1.04	0.21	0.20	0.92	0.06	0.07	0.94	0.14	0.15
DnV	1.26	0.45	0.35	--	--	--	--	--	--
HSE	1.29	0.27	0.21	1.27	0.23	0.18	1.13	0.15	0.14
NPD	1.16	0.23	0.20	1.02	0.07	0.07	1.05	0.16	0.15

Table 3.5.23 M_{meas}/M_{pred} for out-of-plane moment loaded joints

- the formulations of the API, CIDECT, CSA, HSE, and NPD appear to provide similar representations of the data with large scatter for $\beta > 0.6$. This is confirmed by the relatively small differences between the standard deviations (and CoVs) associated with the five formulations. Furthermore, the DT and K data are well within the scatter of the T data which supports the adoption of a single out-of-plane-bending formula for all joint types by most codes.

- Similarly to the in-plane-bending data, the plots show that one T and one Y joints from the JISSP Programme ($\beta = 0.8$) exhibit higher strengths than most of the other data. However, this observation could also be made in connection with T joints from other programmes (eg. TNO and Makino/Kurobane). Although, this behaviour could be attributed to the combined effects of short chords and high β ratios, further analysis of the data is required possibly using finite element analysis where the factors causing scatter could be isolated.

- The DnV predictions are excessively conservative for T joints with $\beta > 0.6$. Furthermore, the implication that nondimensional strength is proportional to $\gamma^{0.1}$ (= 1.26 and 1.45 for $\gamma = 10$ and 40 respectively) is not justified, given the large scatter.

- The M_{meas}/M_{pred} ratios (evaluated for the HSE formulae) for the two DT joints with $\beta = 1.0$, are relatively larger than those for the three T and two K joints with similar β ratio. This suggests that the HSE's adoption of a different formula for DT/X joints, implying that when β approaches 1.0, their strength does not increase as steeply as that of T/Y and YT/K joints is not justified.

Conclusions

There are little differences with regard to goodness of fit between the formulae of the API, CSA, HSE, CIDECT, and NPD codes. However, the CSA/CIDECT/NPD format appears to be slightly superior to that of the API and HSE codes.

3.5.10 Chord load effects

Tests on simple T, DT, and K joints indicate that the presence of compressive stresses in the chord, in addition to those required for equilibrium, can cause a significant reduction in joint strength. Such a reduction is quantified in design codes using the factor Q_f which is defined as the ratio of joint strength in the presence of chord stresses to joint strength associated with brace loads only. Examination of the expressions of Q_f in various codes reveals that the formulation proposed by Boone et al (1982) and first adopted by API RP2A in 1984 is widely accepted. One key exception in the formulation proposed in Japanese studies by Kurobane and co-workers (Kurobane et al 1984) and adopted in IIW and CIDECT circles (see Section 3.2.3).

The Q_f expression of Boone et al is based on a series of tests on DT joints with uniform and triangular chord stress distributions. The joints tested under axial, IPB and OPB brace loads have β ratios in the range 0.48-0.67. The Q_f equation developed largely on the basis of these tests suggests the following:

- Reduction is proportional to γA^2 (A, the chord utilisation ratio, is defined in Section 3.2.3).

- Chord stresses due to axial and bending loading are considered to have identical effects, i.e. no distinction is made between uniform stress distributions associated with axial chord loads and bending stress distributions which are characterised by a gradient across the chord cross section. This conservative approach is not based on evidence from tests. Rather it appears to be driven by the lack of data to support alternative treatments.

- For a fixed stress distribution in the chord, brace in-plane bending causes the largest reduction in joint strength. This is followed, respectively, by brace axial loading and brace out-of-plane bending.

- The reduction in joint strength becomes more significant as the chord slenderness parameter, γ, increases, i.e. the chord thickness decreases. This may be attributed to the associated reduction in the bending stiffness of the chord wall which, in the presence of chord compressive stresses, could lead to an acceleration of joint failure, especially in joints that resist brace loading by local chord bending. In addition, once the chord wall has deformed, local P-Δ moments may develop and contribute to joint failure.

If the extreme fibre stresses in the chord are tensile all design codes do not require any reduction in joint strength.

The Q_f expression of Kurobane et al is based on a large database of tests performed mainly on K joints with uniform chord stress distributions and subjected to balanced axial loading. Most of these tests were not considered fully in European and American studies due to difficulties in tracing the original data and possibly to reservations with regard to acceptance of data from small scale specimens.

Database on chord load effects

In order to take advantage of Japanese chord stress data which have become available recently and of data which were not considered in previous studies, a comprehensive database consisting of 113 results from, T, DT, and K/YT joints has been assembled. This is included in full in Appendix A3.2 and summarised in Table 3.5.24.

Reference	Joint Type	Beta (d/D)	Gamma (D/2T)	Brace load	Chord Load	No of Joints
Makino et al (1986)	K	0.61	11.6-23.3	Bal. Axial	IPB	14
	K	0.61	23.3	Bal. Axial	Comp	1
Nakajima et al (1971)	YT	0.29-0.46	13.1-51.0	Bal. Axial	Comp	11
	YT	0.29-0.46	13.4-51.0	Bal. Axial	Comp	11
Kurobane & Makino (1965)	K	0.42	14.6-15.9	Bal. Axial	Comp	15
	K	0.42	15.9	Bal. Axial	Tension	13
Togo (1967)	K	0.48	16.1	Bal. Axial	Tension	9
	K	0.48	16.1	Bal. Axial	Comp	9
Koning & Wardenier (1981)	K	0.31-1.0	17.1-28.6	Bal. Axial	Comp	9
Boone et al (1982)	DT	0.67	25.32	Comp	Comp	2
	DT	0.67	25.32	Comp	Comp+IPB	1
	DT	0.67	25.32	IPB	Comp	1
	DT	0.67	25.32	IPB	Comp+IPB	1
	DT	0.67	25.32	OPB	Comp	1
	DT	0.67	25.32	OPB	Comp+IPB	1
Weinstein & Yura (1986)	DT	0.35, 1.0	25.50	Comp	Comp	2
	DT	0.35	25.50	Comp	Comp+IPB	1
	DT	1.00	25.53	IPB	Comp	1
	DT	1.00	25.53	IPB	Comp+IPB	1
	DT	1.00	25.53	OPB	Comp	1
Sanders & Yura (1987)	DT	1.00	25.53	Tension	Comp	1
JISSP (1989)	T	0.80	20.65	Comp	Comp	1
	T	0.80	20.99	Comp	Comp+IPB	1
	DT	0.80	20.99	Comp	Comp	1
	T	0.80	20.48	IPB	Comp	1
	T	0.80	20.65	IPB	Comp+IPB	1
	T	0.80	21.17	OPB	Comp	1
	T	0.80	20.82	OPB	Comp+IPB	1

Table 3.5.24 Scope of the chord stress database

The following approach has been adopted in assembling and assessing the database.

1. In line with the screening criteria adopted in assembling the simple joint database, joints with a chord diameter smaller than 100mm have not been considered. This has resulted in the exclusion of approximately 14 Japanese tests on K joints with a chord diameter of 61 mm. Omitting these tests is considered acceptable due to the availability of a large volume of other Japanese tests of broadly similar loading and geometrical properties but with chord diameters larger than 100mm.

2. In some programmes, limited tests were performed without chord loading in order to provide base data for use in quantifying the parameter Q_f associated with tests including chord loading. However, in most of the programmes, base data are not available or some parameters relating to material and/or geometric properties of the base tests are different to those of the tests with chord loading. In such cases, base data for each series of tests have been inferred from data generated in the same programme by applying correction factors. These are functions of geometric and/or material properties and are based on static strength equations relevant to the joints under consideration. Key aspects of determining base data for all tests in the database are summarised in Table 3.5.25.

3. Chord stresses are estimated from the axial forces and bending moments applied externally to the chord. In the case of K joints tested under balance axial loading, brace loading generates forces in the chord to satisfy equilibrium. As a result, the total force in the chord, i.e. the sum of external forces and equilibrium forces due to brace loading, may vary along the chord length depending on the chord support conditions in the testing frame and the location with respect to the compression and tension braces. However, within the context of assessing the effects of chord stresses, it may be argued that only stresses due to external chord loading need be considered, since equilibrium stresses are accounted for implicitly in the derivation of basic joint capacity, i.e. in the absence of external chord loading. Ignoring equilibrium stresses is permitted in the IIW and CIDECT codes which are based on the equations of Kurobane et al (1984), but not in the other codes which, similarly to API RP2A, require that all chord stresses are considered. In the present evaluation of the chord stress database, equilibrium stresses have been considered only in connection with the U Series of the Nakajima tests (Nakajima et al 1971), where they are tensile on both sides of the compression brace. In all other cases, where equilibrium stresses are compressive, only stresses due to external chord loading have been considered. This approach is conservative and is partly driven by the uncertainties relating to determination of the equilibrium stresses.

<u>Assessment of data</u>

Evaluation of the database enables the following conclusions to be drawn:

Reference	Specimens, Series	Joint Type	Base Tests	Correction for Parameters	Correction Factor	Notes
Makino et al 1988	KA KB KC KD KE	K K K K K	KA4 KB4 KA4 KA4 KA4	T T F_y, T, γ F_y, T, γ F_y, T, γ	T^2 T^2 $F_yT^2Q_g$ $F_yT^2Q_g$ $F_yT^2Q_g$	 Q_g, CIDECT Q_g, CIDECT Q_g, CIDECT
Nakajima et al 1971	L U	YT YT	L-2.3-4 U-2.4-4	F_y,T,β,γ F_y,T,β,γ	$F_yT^2Q_g(1.8+10.2\beta)$ $F_yT^2Q_g(1.8+10.2\beta)$	Q_g, CIDECT Q_g, CIDECT
Kur-Mak 1965	264-291	K	Av(261,262,263)	T,g	T^2Q_g	Q_g, HSE
Togo 1967	I-III V-VII	K K	Av(IV-1,IV-2,IV-3) Av(IV-1,IV-2,IV-3)	None None	None None	
Koning and Wardenier 1981	32 33 35 36 37 39,40 44,45	K K K K K K K	7 8 10 Av(10,11) Av(12,13) Av(14,15) Av(21,22)	F_y,T,g F_y,T,g F_y,T,g F_y,T,g F_y,T,g F_y,T,g None	$F_yT^2Q_g$ $F_yT^2Q_g$ $F_yT^2Q_g$ $F_yT^2Q_g$ $F_yT^2Q_g$ $F_yT^2Q_g$ None	Q_g, HSE Q_g, HSE Q_g, HSE Q_g, HSE Q_g, HSE Q_g, HSE
Boone et al 1982	AP2,AP5,AM6 IP12,IM11 OP9,OM10	DT DT DT	A1 I7 O8	None None None	None None None	
Weinstein and Yura 1986	AP25 AP46,AM47 IP29,IM30 OP27	DT DT DT DT	Av(A21,A22) Av(A40,A41) I24 Av(O23,O28)	None None None None	None None None None	
Sanders 1987	TP4	DT	Av(T1,T2,T3)	None	None	
JISSP 1989	4.1, 4.2 4.3, 4.4 4.5, 4.6 4.7	T T T DT	1.3 TCC-2 (Stamenk.) 1.13 7 (Gibstein)	F_y,T F_y,T,d,β,γ F_y,T F_y,T,β	F_yT^2 $F_yT^2dQ_u$ F_yT^2 $F_yT^2dQ_u$	 Q_u, HSE Q_u, HSE

Table 3.5.25 Base tests and correction factors used in evaluation of data on chord stress effects

Effect of γA^2 on axially loaded joints: Figure 3.5.15 indicates that under the effects of compressive chord stresses, the capacity of axially loaded joints may be considered to decrease linearly as γA^2 increases. In addition, a curve representing the Q_f equation recommended by Boone et al (University of Texas) can be seen to represent approximately the mean of the experimental Q_f data. However, most of the new Japanese data relating to axially loaded K joints subjected to in-plane bending in the chord (Makino et al 1988) fall well above the analytical Q_f predictions. This finding indicates that a bending stress distribution in the chord, where the stresses are compressive in the region adjacent to the braces, is effectively less detrimental to joint capacity than a uniform compressive stress distribution.

Effect of γA^2 on moment loaded joints: Figure 3.5.16 indicates that under the effects of compressive chord stresses, the capacity of T and DT joints loaded by in-plane or out-of-plane bending may be considered to decrease linearly as γA^2 increases. The Q_f curves recommended by Boone et al would appear to represent approximately the experimental Q_f data. However, the data, which originate from programmes at the University of Texas and the JISSP Programme, are relatively very limited and are characterised by a considerable degree of scatter.

Effect of β ratio: The ratio of test Q_f to predictions evaluated according to the equations of Boone et al are plotted against β ratio in Figure 3.5.17. Despite the significant scatter, it can be seen that, in general and excepting the Makino tests where only bending stresses are applied to the chord, the reduction in joint capacity under the effect of compressive chord stresses is less significant at higher β ratios. This trend characterises specifically most of the data from the University of Texas and the JISSP Programme where a range of β ratios larger than 0.65 are considered. However, in the majority of the other programmes only one value of β or a limited range of low β ratios are considered, which makes the evaluation of the effect of this parameter rather difficult.

With regard to data at β=1, four tests on T and DT joints tested under brace axial or out-of-plane bending loads show no reduction in strength due to chord loading. Two DT joints tested under in-plane bending show approximately 10% reduction or 10% increase in capacity in comparison with the no chord load reference test. With regard to K joints tested under balanced axial loading, the two tests from the Koning and Wardenier Programme (1981) indicate a reduction in capacity of approximately 10% under the effect of compressive chord stresses.

Effect of ratio of bending to axial stress: As noted earlier current code guidance (e.g. API RP2A) does not distinguish between chord stresses due to axial compression and those due to bending moments. This may be due to the lack of data on effects of chord bending stresses particularly when the maximum magnitude of these exceed that of axial stresses. The data on which the API and IIW/CIDECT guidance are based are mainly from tests with uniform compression stresses in the chord. Only a few data with additional bending stresses are available, namely from the University of Texas and the JISSP Programmes, where the resultant stress distribution is of a triangular shape, i.e. the magnitude of the outer fibre bending stress is equal to that of the compressive stress. Recently Makino et al (1988) performed tests on K joints with balanced axial loading applied to the braces and in-plane bending moments applied to the chord. Moments inducing tension and compression bending stresses in the chord in the vicinity of the compression brace were considered. In the first loading case, i.e. tension bending stresses adjacent to the compression brace, the joints failed at loads well above those corresponding to the no chord load case. However, in the second case, i.e. with compressive stresses in the vicinity of the compression brace, the capacity of the joints deteriorated in comparison with the no chord load case.

Evaluation of the latter tests using the Q_f equation of Boone et al produces very conservative estimates (see Figures 3.5.15 and 3.5.17). However, the degree of conservatism can be reduced to levels identical to those achieved with uniform chord stresses if the following alternative expression of A is used:

$$A = \frac{f_a + f_b}{\sqrt{2} * F_y}$$

This expression is suggested by Weinstein and Yura (1986) for assessment of DT joints subjected to out-of-plane bending when the chord bending stress is greater than the chord compressive stress, i.e. when there is tension on one of the extreme fibres. One advantage of this expression is that it leads to similar Q_f predictions for the aforementioned DT tests where bending and axial stresses of equal magnitudes were applied at the chord. Table 3.5.26 shows all the data involving bending stresses in the chord evaluated using both expressions of A.

Reference	Spec.	f_a/F_y	f_b/F_y	Test Q_f / $(1-\lambda\gamma A_1^2)$	Test Q_f / $(1-\lambda\gamma A_2^2)$
Makino et al	KA-1	0.0	-0.6	1.16	1.0
	KA-2	0.0	-0.9	1.82	1.11
	KB-1	0.0	-0.6	1.25	1.07
	KB-2	0.0	-0.9	1.80	1.11
	KC-1	0.0	-0.6	1.08	0.96
	KC-2	0.0	-0.9	1.51	1.08
U. Texas	AM6	-0.3	-0.34	1.03	1.03
	IM11	-0.3	-0.34	0.96	0.96
	OM10	-0.3	-0.34	1.04	1.04
	AM47	-0.31	-0.35	0.95	0.95
	IM30	-0.31	-0.35	0.91	0.91
JISSP	4.2	-0.27	-0.27	1.01	1.01
	4.4	-0.29	-0.29	1.20	1.20
	4.6	-0.27	-0.27	1.31	1.31

A_1 is evaluated using the University of Texas expression
A_2 is evaluated as $(f_a+f_b)/(\sqrt{2}\ F_y)$

Table 3.5.26 Effects of the ratio of axial to bending stresses

<u>Effect of chord tensile stresses</u>: Figure 3.5.18 shows the ratio of test Q_f to predictions evaluated according to the equations of Boone et al, assuming that these are applicable for tensile chord stresses, plotted against the ratio of chord stress to yield stress. Data corresponding to K joints under balanced axial loading with compressive or tensile chord stresses are considered. It can be seen clearly that, with exception of two tests from the Nakajima Programme (1971), tension chord stresses tend to increase joint strength or at least they do not reduce it in comparison with the no chord load case. This finding suggests that the current approach adopted in virtually all codes in relation to effect of tensile chord stresses is adequate. However, recent finite element data for compression

loaded DT joints with β = 1 subjected to tensile and compressive chord stresses indicate that chord tensile stresses reduce the capacity of this joint configuration (van der Valk 1991). Unfortunately, there are no equivalent valid experimental data to verify this analytical finding.

Conclusions:

The API's Q_f equations which are based on work at the University of Texas appear to represent most of the available experimental data adequately. However, the experimental evidence is clouded by a significant degree of scatter which needs to be addressed in order to increase the confidence in the present design approach. Since additional tests are likely to suffer from more scatter, it is recommended to perform limited finite element studies to address key areas of uncertainties which include:

- Effect of β ratio, i.e. whether there is a threshold value above which chord stresses do not reduce joint capacity.
- Effect of chord bending stresses, especially when their magnitude exceeds that of compressive chord stresses.
- Effect of chord loading on capacity of joints loaded by in-plane or out-of-plane brace bending. Current guidance is based on a very limited dataset.
- Effect of tensile chord stresses on joints with β = 1.
- Effect of equilibrium chord stresses, e.g. those which result from brace loading in joints with inclined braces, and whether such stresses can be ignored when determining chord stress effects.

New Japanese data appear to support an alternative expression for the chord utilisation ratio A where the chord bending stress exceeds the chord compressive stress. Application of the current A equation leads to excessively conservative estimates. However, the alternative expression produces conservatism levels which are broadly similar to those associated with uniform compressive chord stresses.

3.5.11 Brace load interaction

The effects of multiple-axis (or multi-directional) brace loading, i.e. combinations of axial, IPB and OPB brace forces, on joint strength are accounted for by using load interaction equations. A number of such equations are available (Section 3.2.3) but only two forms have found wide acceptance, namely, those of the API-WSD arcsin equation and Hoadley's polynomial equation. These and other more recent formulations are outlined below.

API-WSD

The interaction equation in API-WSD is as follows:

$$\left|\frac{P}{P_a}\right| + \frac{2}{\pi}\arcsin\sqrt{\left(\frac{M}{M_a}\right)^2_{IPB} + \left(\frac{M}{M_a}\right)^2_{OPB}} \le 1.0$$

where P and M are applied brace loads and P_a and M_a are allowable joint capacities. The value of the left hand term in the above equation is usually referred to as the 'utilisation ratio', the 'interaction ratio' or the 'unity check' of the joint under consideration. Since the arcsin term is undefined if the argument under the square root sign exceeds 1.0, API-WSD requires that the following is satisfied:

$$\sqrt{\left(\frac{M}{M_a}\right)^2_{IPB} + \left(\frac{M}{M_a}\right)^2_{OPB}} \le 1.0$$

The arcsin interaction equation is based on the plastic section strength of a circular hollow cross section, i.e. it is intended to predict failure of tubular members rather than that of tubular joints. Its use to account for load interaction effects on tubular joints may be justified only on the basis of its representation of tubular joint test data.

API-LRFD

The interaction equation in API-LRFD is as follows:

$$1-\cos\left(\frac{\pi}{2} * \frac{P}{P_f}\right) + \sqrt{\left(\frac{M}{M_f}\right)^2_{IPB} + \left(\frac{M}{M_f}\right)^2_{OPB}} \le 1.0$$

where P_f and M_f are factored joint capacities. Zettlemoyer (1994) notes that the LRFD equation is a rearranged form of the WSD arcsin equation, and that the equations give the same joint 'unity check' only when the assessment point lies on the failure surface (i.e. 'unity check' = 1.0). However, the LRFD equation has the advantage that calculation of a 'utilisation ratio' is always possible even if the argument of the trigonometric term exceeds 1.0.

Hoadley and Yura (1985)

Based on interaction tests on DT joints with β = 0.67 and γ = 25.3, Hoadley and Yura proposed the following polynomial interaction equation as a lower bound representation of the data:

$$\left|\frac{P}{P_a}\right| + \left(\frac{M}{M_a}\right)_{IPB}^{2.1} + \left(\frac{M}{M_a}\right)_{OPB}^{1.2} \leq 1.0$$

The following simplified form of the equation is recommended in both the UEG Design Guide (1985) and the HSE/DEn Guidance Notes (1990):

$$\left|\frac{P}{P_a}\right| + \left(\frac{M}{M_a}\right)_{IPB}^{2} + \left(\frac{M}{M_a}\right)_{OPB}^{1} \leq 1.0$$

Stol et al (1985)

Based on interaction tests on T joints, Stol et al proposed an equation of a similar form to that of Hoadley and Yura but with exponents of the moment terms dependent on both β and γ ratio. The interaction equation was determined as a lower bound representation of the data which included joints with β in the range 0.35-1.0 and γ in the range 8.2-25.5. However, due to suspected premature member failures which cast uncertainties on interpretation of some of the data, the proposed equation was reported to be valid to only a fraction of the aforementioned β and γ ranges.

Swensson and Yura (1987)

After performing interaction tests on DT joints with β = 0.35 and 1.0, and γ = 25.5 (in addition to those of Hoadley and Yura), Swensson and Yura proposed an equation of a similar form to that of Hoadley and Yura but with exponents of the moment terms dependent on β ratio. The proposed equation is reported to provide an improvement in accuracy over the equations of API-WSD and Hoadley and Yura, when the interaction data were nondimensionalised by the experimental reference data, especially for the β = 1.0 DT series. However, evaluation of the impact of the three equations on design is reported to indicate that the savings associated with the proposed equation were not significant except for β = 1.0. Noting that β = 1.0 joints make up only a small proportion of the DT joint population (according to surveys in the UEG Design Guide), Swensson and Yura recommend the Hoadley and Yura equation because of its simplicity.

Interpretation of interaction ratio

Although an interaction check using one of the above equations provides information on the adequacy of a joint design, it does not give an accurate indication of the proximity of the assessment point to the interaction (i.e. failure) surface. A parameter which overcomes this limitation has been developed at the University of Texas (Swensson and Yura 1987) and used in recent American evaluations of interaction equations (e.g. Zettlemoyer 1988 and 1993). The parameter, denoted as X, is defined as the ratio of the distance from the origin to the assessment point (L1) to the distance from the origin to the interaction surface (L2). X is larger than 1.0 if the assessment point is outside the failure surface, i.e. the interaction ratio is larger than 1.0, and vice versa (see Figure 3.5.19).

The parameter X can be evaluated in connection with any interaction equation. However, since most of these have relatively complex forms, iterations are often necessary for determining X. One exception is the simplified version of Hoadley's interaction equation (UEG/HSE version). Assuming that chord load effects are small ($Q_f \equiv 1.0$) and that the brace loads are proportionally applied, Zettlemoyer (1993) notes that X may be determined by solving the following form of the interaction equations:

$$\frac{P}{X*P_a} + \left[\frac{M}{X*M_a}\right]^2_{IPB} + \left[\frac{M}{X*M_a}\right]_{OPB} = 1.0$$

After rearrangement, it can be shown that:

$$X = \frac{B}{2} + \sqrt{\frac{B^2}{4} + C}$$

where

$$B = \left[\frac{P}{P_a} + \left[\frac{M}{M_a}\right]_{OPB}\right] \quad \text{and} \quad C = \left[\frac{M}{M_a}\right]^2_{IPB}$$

Database on brace load interaction

All known available experimental data on brace load interaction have been considered. Previous data from the TNO Programme have been rescreened and new Japanese data including tests on T joints under tension and OPB loads have been sourced and screened. Following the rejection of reference data on compression loaded T joints from the Kingston Polytechnic Programme, the corresponding interaction data on joints tested under combinations of compression and IPB loads, have also been screened out. The full screened database is given in Appendix A3.3, and summarised in Table 3.5.27. Key features of the screening process are outlined below:

- Failure loads from the University of Texas and TNO Programmes were originally defined using the deformation limit criterion of Yura et al (1980). In the majority of cases differences between failure loads determined using the ultimate load criterion (or corresponding to the maximum recorded load) and those determined according to the deformation limit criterion are relatively small. However, in order to maintain consistency between the simple joint database and the interaction database, the ultimate load criterion has been generally adopted as a basis for determining the failure loads.

Reference	Join t Type	Beta (d/D)	Gamma (D/2T)	Brace Load	No of Joints
Makino & Kurobane (1986), & Kurobane et al (1991)	T	0.28	13.4-23.8	Tension+OPB	3
	T	0.53	16.0-23.8	Tension+OPB	3
	T	0.76	23.8	Tension+OPB	1
	T	0.28	23.8	Comp+OPB	1
	T	0.53	13.4-23.8	Comp+OPB	4
	T	0.76	23.8	Comp+OPB	1
	T	1.00	13.4-23.8	Comp+OPB	2
Hoadley & Yura (1985)	DT	0.67	25.3	Comp+OPB	2
	DT	0.67	25.3	Comp+IPB	2
	DT	0.67	25.3	IPB+OPB	2
	DT	0.67	25.3	Comp+IPB+OPB	3
Swensson & Yura (1987)	DT	0.35	25.5	Comp+OPB	2
	DT	0.35	25.5	Comp+IPB	2
	DT	0.35	25.5	IPB+OPB	2
	DT	1.00	25.5	Comp+OPB	3
	DT	1.00	25.5	Comp+IPB	4
	DT	1.00	25.5	IPB+OPB	4
Stol et al (1985)	T	0.35	8.2-14.8	Comp+IPB	2
	T	0.35	24.4-25.5	Comp+OPB	2
	T	0.35	8.2-25.5	IPB+OPB	2
	T	0.35	8.2-25.5	Comp+IPB+OPB	5
	T	0.68	8.2-25.5	Comp+IPB	5
	T	0.68	8.2-25.5	Comp+OPB	6
	T	0.68	8.2-25.5	IPB+OPB	5
	T	0.68	8.2-25.5	Comp+IPB+OPB	4
	T	1.00	14.3-24.5	Comp+IPB	4
	T	1.00	14.3-24.5	Comp+OPB	3
	T	1.00	14.3-24.5	IPB+OPB	2
	T	1.00	14.3-24.5	Comp+IPB+OPB	2

Table 3.5.27 Scope of the database on combined brace loading

- In all the programmes, reference tests were performed under uni-directional brace loading in order to provide base data for evaluation of the interaction tests. However, in some cases especially in the TNO Programme, The chord thickness and/or the chord yield stress of the reference tests were different to those of the associated interaction tests. Such differences were overcome by applying the correction factor ($F_y T^2$) to the reference data.

- Determination of valid failure loads of a number of reference tests in the TNO and Makino/Kurobane programmes was hindered by premature brace failure and by problems relating to the shape of the load deformation curves. Such problems led to omission of the reference tests from the simple joint database. However, in order to make the most of the corresponding interaction data, which in the case of the Japanese Programme involved rare tests under tension and bending brace loading, exceptional measures were taken to determine usable data from the reference tests as follows:

When brace failure was suspected to have occurred prior to joint failure, the maximum recorded load was compared to predictions based on the CSA equations (excluding safety factors) and/or the HSE mean equations. Such comparisons showed that predictions from both codes were in most cases close to or lower than the maximum recorded loads. Therefore, the latter loads were adopted since they produce lower interaction ratios and consequently yield conservative assessments within the context of analysis of the corresponding interaction data. This measure was applied to tests 3, 4 and 70 of the TNO Programme, and tests L-B-T, L-D-T, M-C-T, MA-C-T and L-A-M of the Makino/Kurobane Programme.

The loads corresponding to the point of contraflexure in the load deformation curves of three reference tests in the TNO Programme were used (Tests 13, 14 and 17). These loads were found to exceed the CSA predictions.

Predictions based on the CSA equations were used in the case of only two reference TNO tests because the load deformation curves were either unavailable (Test 2) or had an odd shape (Test 15).

Assessment of data

The screened database has been used to evaluate the polynomial equation of Hoadley and the arcsin equation of API-WSD. Only the experimental reference data, obtained from uni-directional tests, has been used to derive the nondimensional axial and moment ratios in the interaction equations. In practice, the reference data are calculated using parametric equations. Since these are intended to provide conservative estimates of joint strength, the corresponding interaction ratios will be higher than those from the experimental reference data.

The results are shown separately for each of the three experimental programmes in Figures 3.5.20 to 3.5.22. In addition, in the case of the HSE's Equation (simplified version of Hoadley's equation), the parameter X has been evaluated and plotted versus β in Figure 3.5.23. Corresponding statistical data are summarised in Table 3.5.28. All these results allow the following conclusions to be made:

- Hoadley's Equation is more conservative than the API-WSD arcsin Equation, i.e. a larger proportion of failure points lie outside Hoadley's failure surface than outside the API-WSD arcsin failure surface.

- A larger proportion of the failure points from the University of Texas Programme (DT joints) fall outside both failure surfaces than the corresponding proportion from the TNO Programme (T joints). Such phenomenon may be due to the differences in failure mode between DT and T joints. It may also be partly attributed to the effect of loading path, i.e. whether the combined brace loads are applied proportionally (all load components, e.g. compression and OPB, are applied at the same time) or non-proportionally (one or two load components are applied one at a time up to prespecified magnitudes, then a final load component is applied up to failure). The former loading procedure was adopted in all but two of the TNO tests, while the latter loading procedure was adopted in all but three of the University of Texas tests. Although, the available limited evidence indicates that proportional loading causes failure at lower loads than non-proportional loading, further data are required to study this phenomenon.

- Differences between the interaction ratios calculated using the original Hoadley Equation and its simplified version (HSE's Equation) are relatively small. In view of the simplicity of the latter equation especially in relation to evaluation of the parameter X, it is preferred to the original equation on the grounds of practicality rather than accuracy.

- The interaction equations, evaluated in previous studies using data from compression and bending tests, can be used to assess interaction in tests involving brace tension. The failure points of the tension and OPB tests from the Makino/Kurobane Programme fall well outside both failure surfaces. For these tests, the mean value and standard deviation of the parameter X, relating to the HSE's Equations, are 1.57 and 0.28 respectively. The corresponding values for the compression and OPB tests from the same Japanese programme are 1.09 and 0.08. This is not surprising since tension restricts the OPB deflection at the brace/chord intersection, and uni-directional joint capacity is larger under tension than under compression brace loading. Recent finite element analyses performed by Jubran and Cofer (1992) on a range of T and Y joints subjected to tension and IPB, and compression and IPB, confirm that in the presence of IPB, tension strengthens the joint while compression tends to weaken it, which supports the aforementioned experimental data.

- Jubran and Cofer report that the interaction diagrams derived analytically for T and Y joints are essentially similar. This implies that the findings relating to the screened experimental database, which consists of interaction tests on T and DT joints only, are likely to apply equally to joints with inclined braces.

Reference & loading	Mean	Std dev	CoV
Mak / Kur (comp + mom)	1.09	0.08	0.07
Mak / Kur (tens + mom)	1.57	0.28	0.18
U. Texas (comp + mom)	1.13	0.12	0.11
TNO (comp + mom)	1.10	0.14	0.12

Table 3.5.28 Statistical data on the X parameter

Conclusions

- The Hoadley Equation and its derivative (HSE's Version) are more conservative than the API's arcsin equation.

- New experimental data confirm that the available interaction equations, which are formulated to account for compression and moment loads, can be used conservatively to account for interaction of tension and moment loads.

- New finite element data suggest that the available interaction equations, are likely to apply to joints with inclined braces as well as to the T and DT geometries tested so far.

- The Hoadley Equation and its derivative (HSE's Version) are recommended. However, the latter is preferred due to its simplicity.

3.6 Conclusions and Recommendations

On the basis of comprehensive evaluation studies, a number of formulae have been found to offer the best representations of the available experimental data. In most cases, differences between the formulae are relatively small. The choice of the best formulation for each joint type and load type has been often made on the basis of the statistical evidence in addition to other criteria not reflected in the statistical data. Comments on the limitations of various formulae and the evaluation studies are reported in sections 3.5.2 to 3.5.11.

The following is a list of the formulae found to offer the best representations:

- Compression loaded T/Y joints: CIDECT and HSE.
- Compression loaded DT/X joints: HSE and CSA.
- Balanced axially loaded YT/K joints: CIDECT and HSE.
- Tension loaded T/Y joints: CSA/DnV (ultimate strength).
- Tension loaded DT/X joints: CSA/DnV (ultimate strength).
- IPB loaded T/Y, DT/X, and YT/K joints: CIDECT.
- OPB loaded T/Y, DT/X, and YT/K joints: CIDECT, CSA, and NPD.

The CSA/DnV formula for tension loaded T/Y and DT/X joints provide estimates of the ultimate strength based on the ultimate load criterion. Limited test data on load levels corresponding to crack initiation (first crack data) suggest that such loads may be estimated approximately by using formulae for compression loaded joints such as those of API-RP2A or other codes (Section 3.5.7).

With regard to effects of chord load on joint strength, the following has been concluded based on the available data:

- The API's Q_f equations which are based on work at the University of Texas appear to represent most of the available experimental data adequately. However, the experimental evidence is clouded by a significant degree of scatter which needs to be addressed in order to increase the confidence in the present design approach. Since additional tests are likely to suffer from more scatter, it is recommended to perform limited finite element studies to address key areas of uncertainties (see Section 3.5.10).

- New Japanese data appear to support an alternative expression for the chord utilisation factor, A, where the chord bending stress exceeds the chord compressive stress. Application of the current A equation leads to excessively conservative estimates. However, the alternative expression produces conservatism levels which are broadly similar to those associated with uniform compressive chord stresses (Section 3.5.10).

With regard to brace load interaction, the following has been concluded based on the available data (Section 3.5.11):

- The Hoadley Equation and its derivative (HSE's Version) are more conservative than the API's arcsin equation.

- New experimental data confirm that the available interaction equations, which are formulated to account for compression and moment loads, can be used conservatively to account for interaction of tension and moment loads.

- New finite element data suggest that the available interaction equations, are likely to apply to joints with inclined braces as well as to the T and DT geometries tested so far.

- The Hoadley Equation and its derivative (HSE's Version) are recommended. However, the latter is preferred due to its simplicity.

The margins of safety implied by the above formulae differ and are not consistent. Further evaluation studies are required before consistent global or partial safety factors can be recommended for use in design. However, the safety factors recommended in each of the above codes may be used until alternative guidance becomes available (Section 3.2).

Further studies are required to evaluate the effects of a number of parameters on the static strength of tubular joints (eg. α, γ, and F_y) and introduce the necessary changes to existing design guidance.

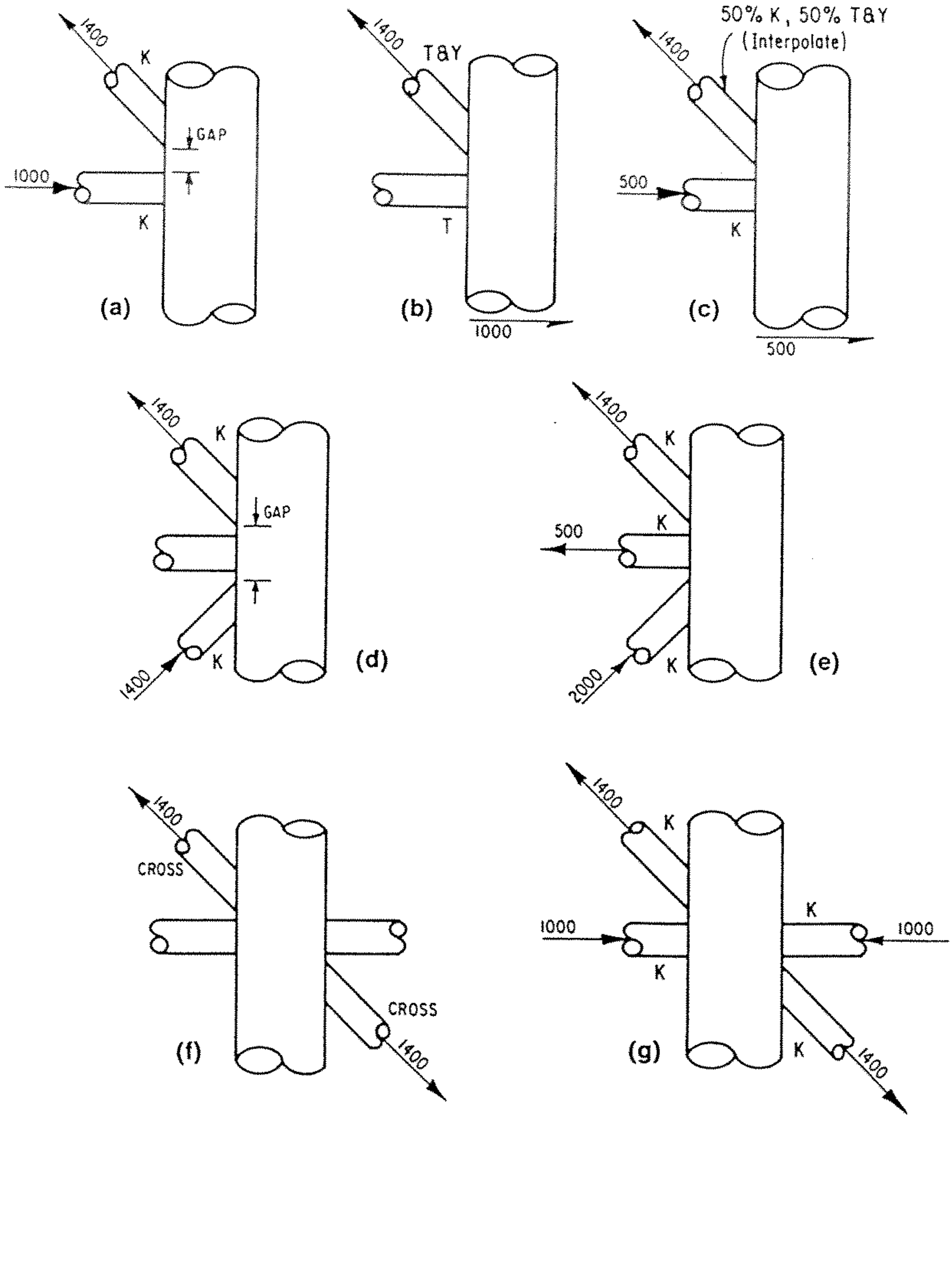
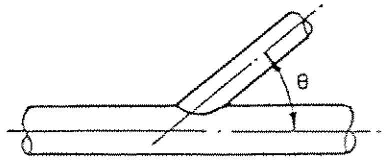
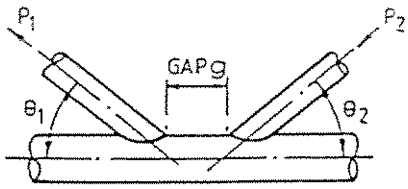
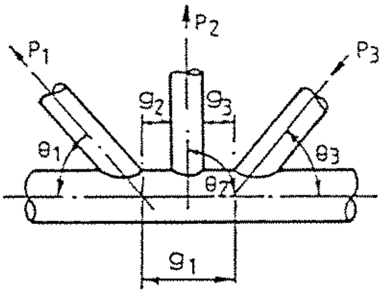
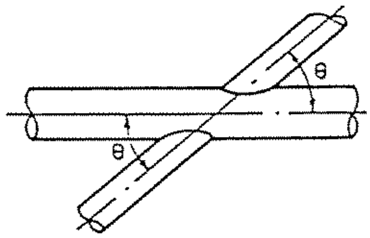
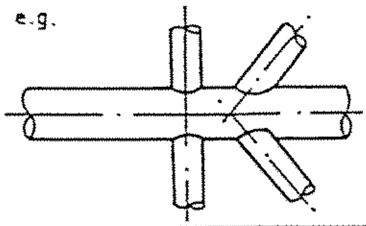


Figure 3.2.1 Typical examples of joint classification (API RP2A, 1993)

JOINT TYPE	CONDITIONS IN ALL CASES: $30° \leq \theta \leq 90°$	DESIGN CLASSIFICATION
		Y
	$1.1 \geq \frac{P_1 \sin\theta_1}{P_2 \sin\theta_2} \geq 0.9$	K
	OUTSIDE ABOVE LIMITS	Y
	$1.1 \geq \frac{P_1 \sin\theta_1}{P_3 \sin\theta_3} \geq 0.9 \quad P_2 \simeq 0$	K WITH GAP = g_1
	$1.1 \geq \frac{P_1 \sin\theta_1 + P_2 \sin\theta_2}{P_3 \sin\theta_3} \geq 0.9$	K WITH APPROPRIATE GAP
	OUTSIDE ABOVE LIMITS	Y
		X
ANY OTHER CONFIGURATION WITH BRACE MEMBERS ON OPPOSITE SIDE OF CHORD e.g. 	THIS INCLUDES ANY JOINT CARRYING LOAD ACROSS THE CHORD E G LAUNCH RUNNER JOINTS	SEE A21.2.4c)

NOTES
1) The loads P_1, P_2 and P_3 are taken to act in the directions shown.
2) For all cases above check each brace separately.
3) This figure should be read in conjunction with A21.2.4c) for further guidance.

Figure 3.2.2 Typical examples of joint classification (HSE, 1990)

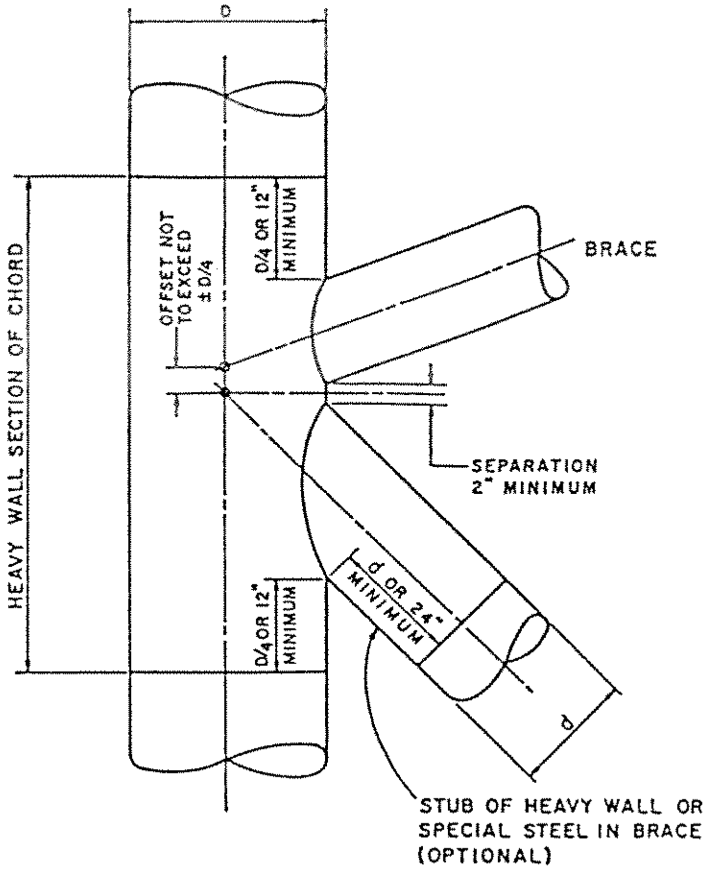


Figure 3.2.3 Detail of Simple Joint (API RP2A, 1993)

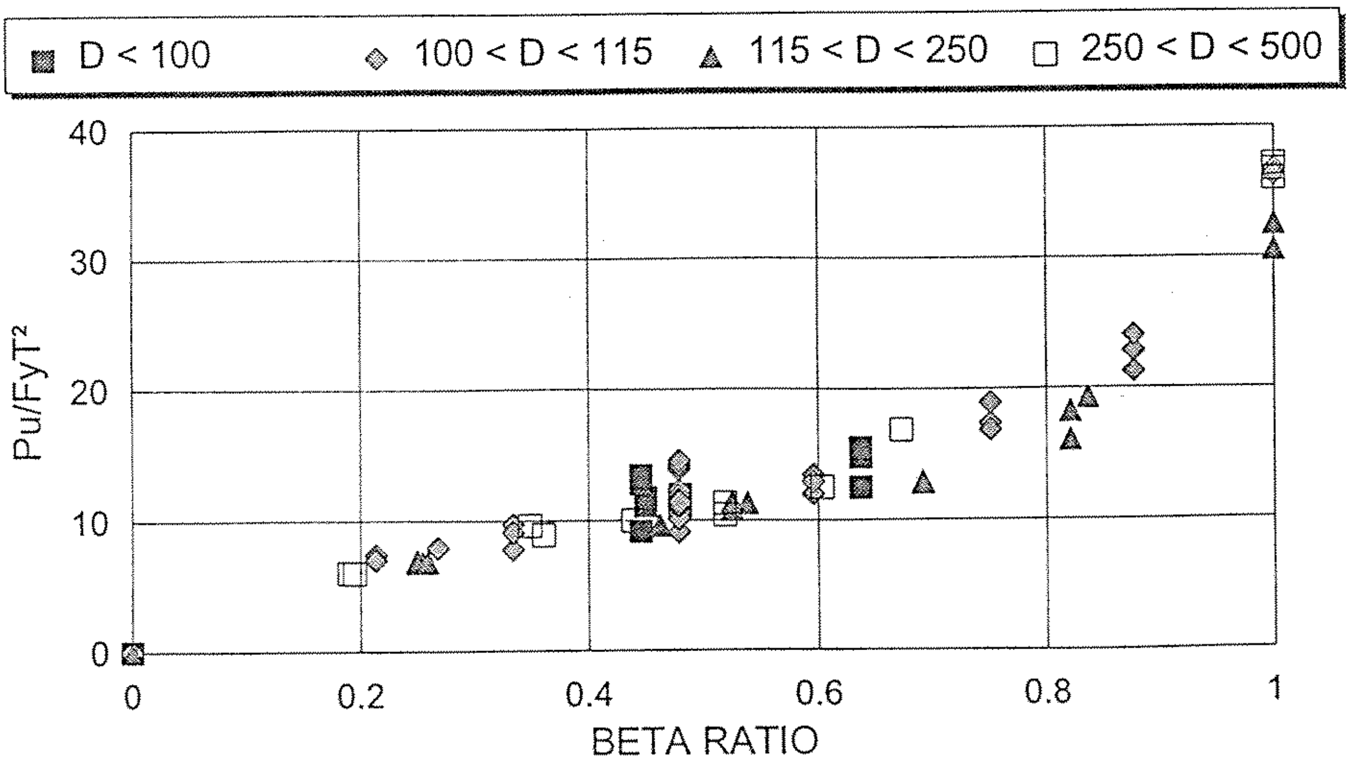


Figure 3.4.1 Effects of chord diameter on nondimensional strength of compression loaded DT joints with $\alpha \geq 8.0$

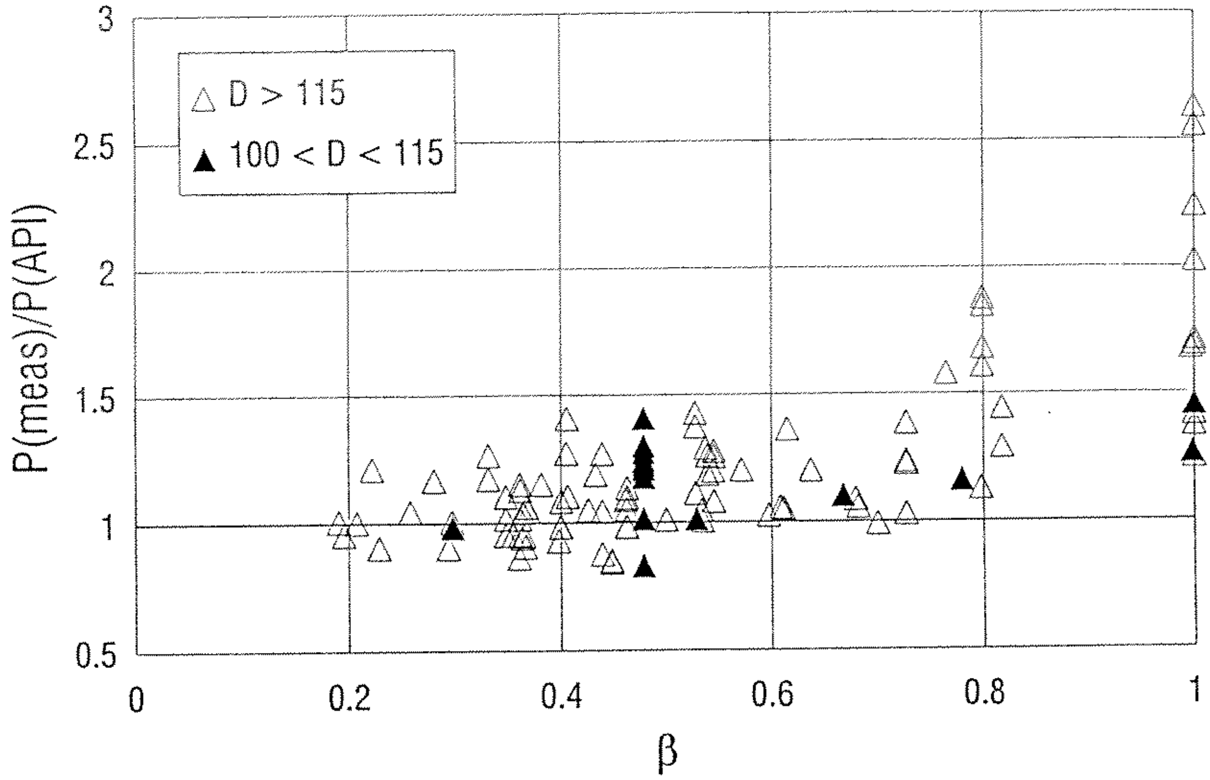


Figure 3.5.1-a Compression loaded T/Y joints: P_{meas}/P_{pred} vs β (API-RP2A)

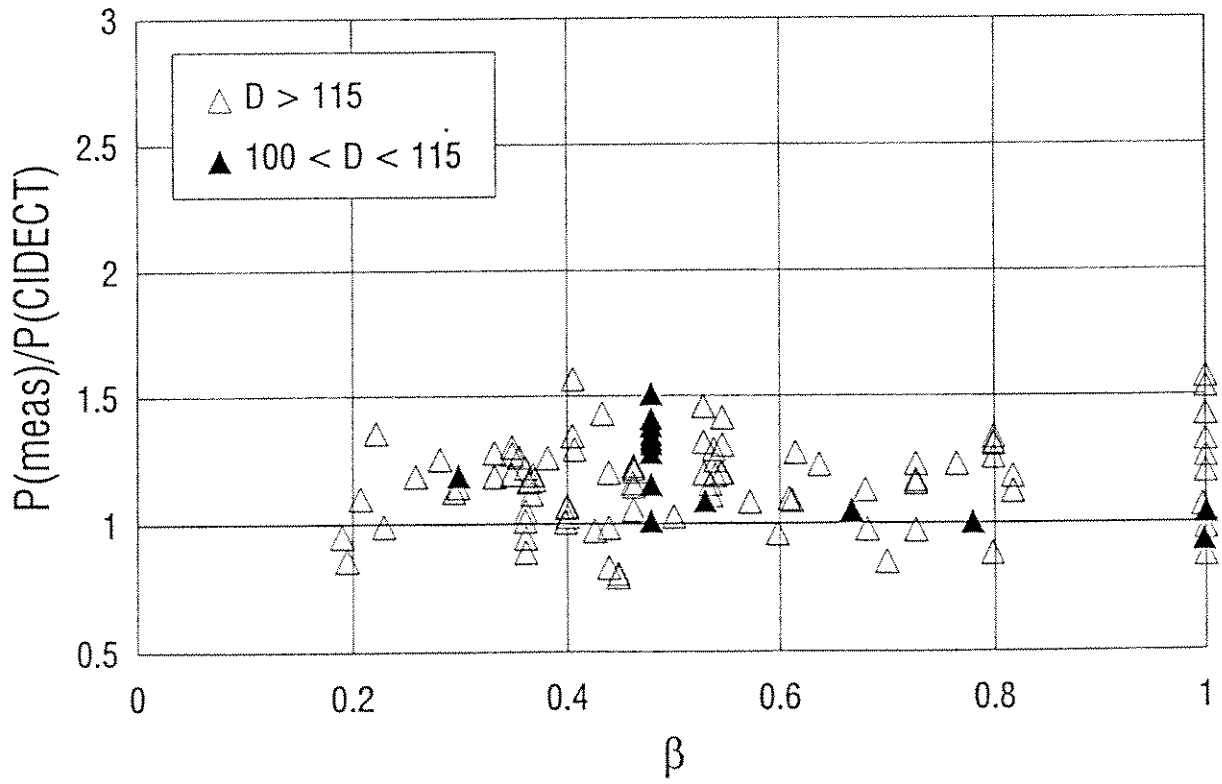


Figure 3.5.1-b Compression loaded T/Y joints: P_{meas}/P_{pred} vs β (CIDECT)

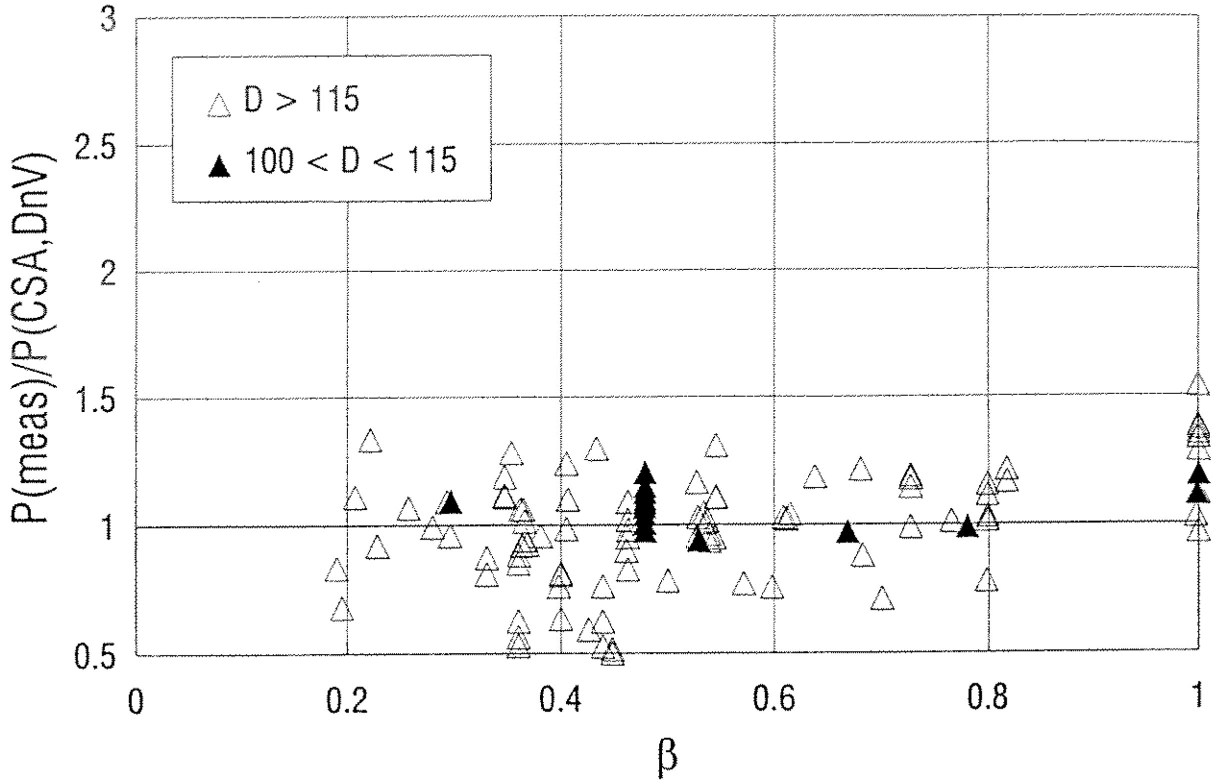


Figure 3.5.1-c Compression loaded T/Y joints: P_{meas}/P_{pred} vs β (CSA, DnV)

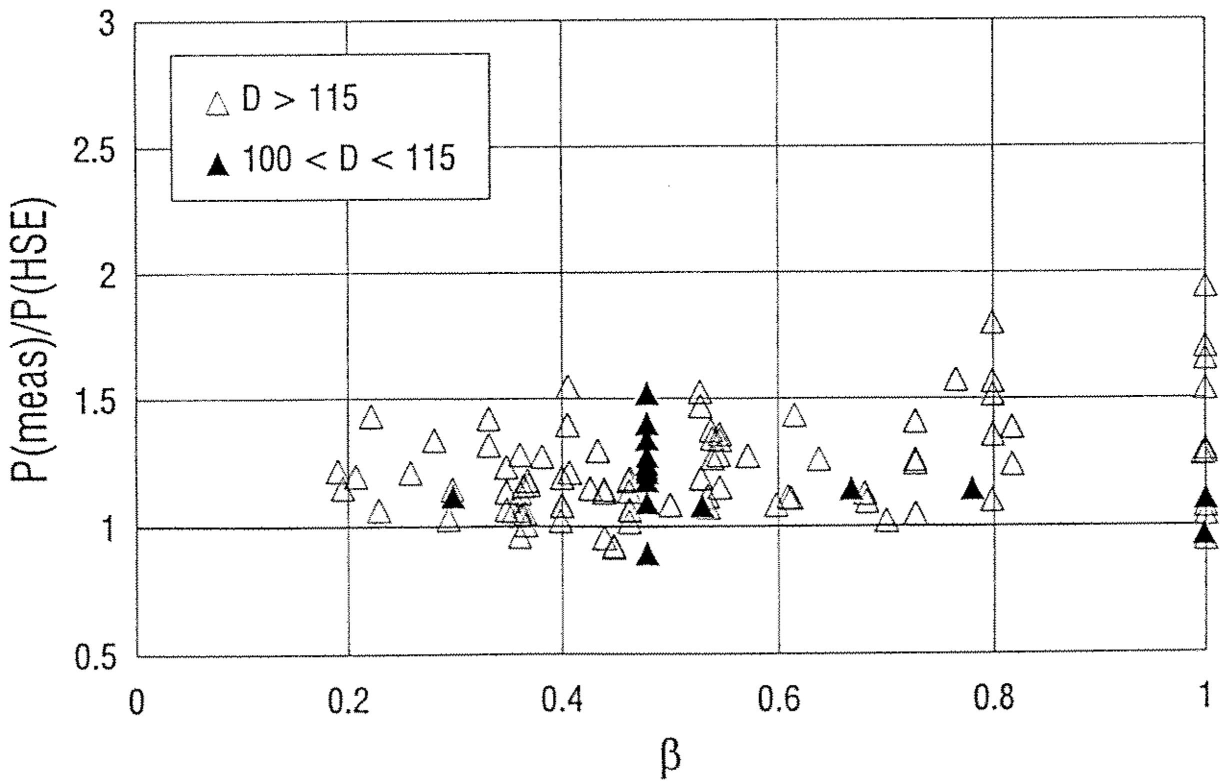


Figure 3.5.1-d Compression loaded T/Y joints: P_{meas}/P_{pred} vs β (HSE)

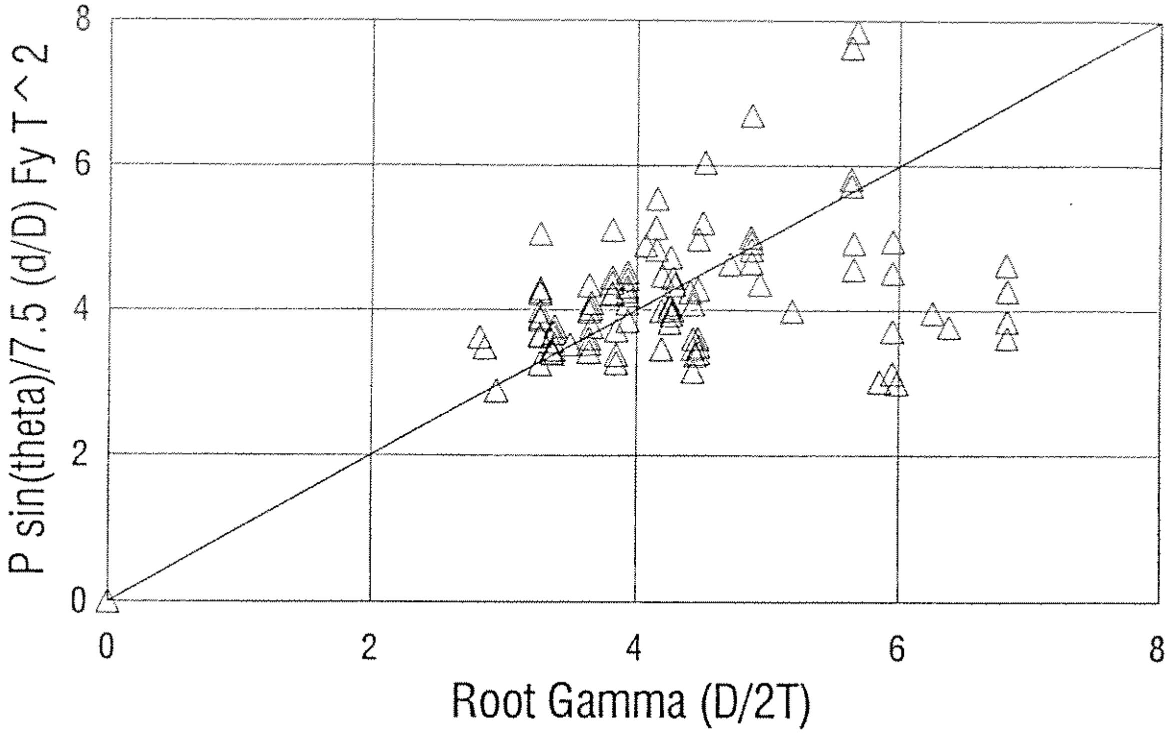


Figure 3.5.2 Compression loaded T/Y joints: Effect of $\sqrt{\gamma}$ (CSA, DnV)

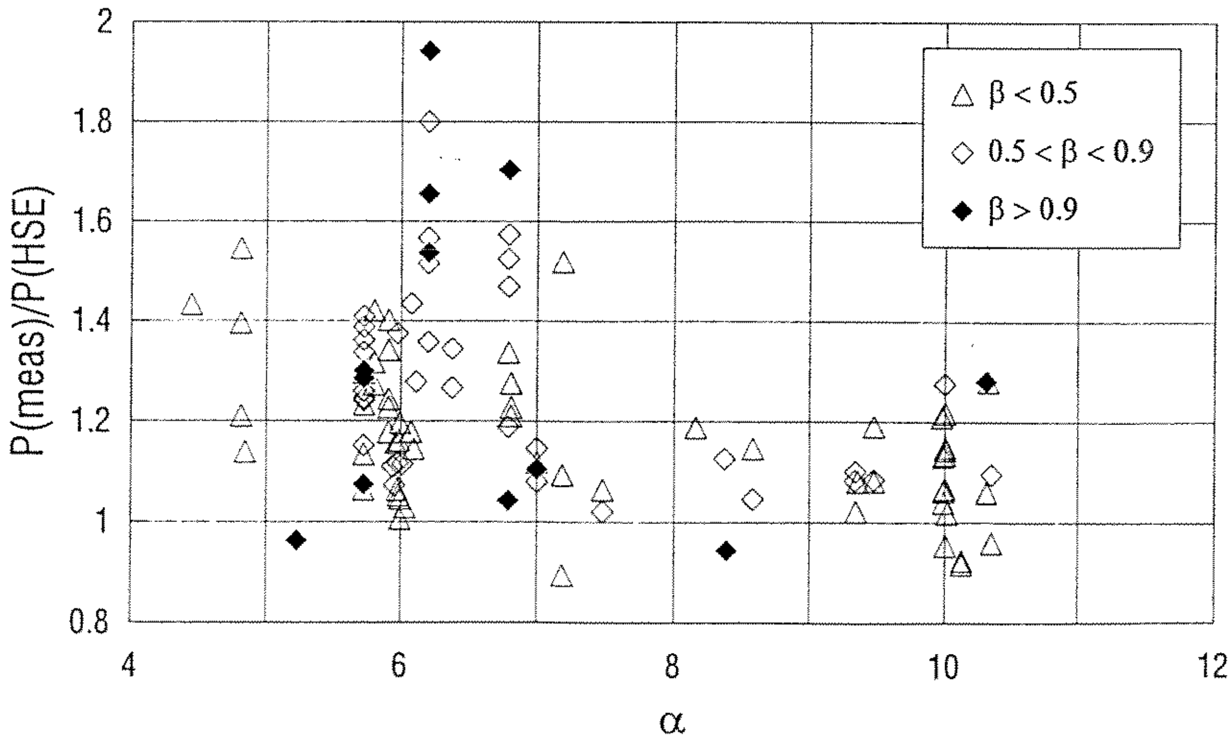


Figure 3.5.3 Compression loaded T/Y joints: P_{meas}/P_{pred} vs α (HSE)

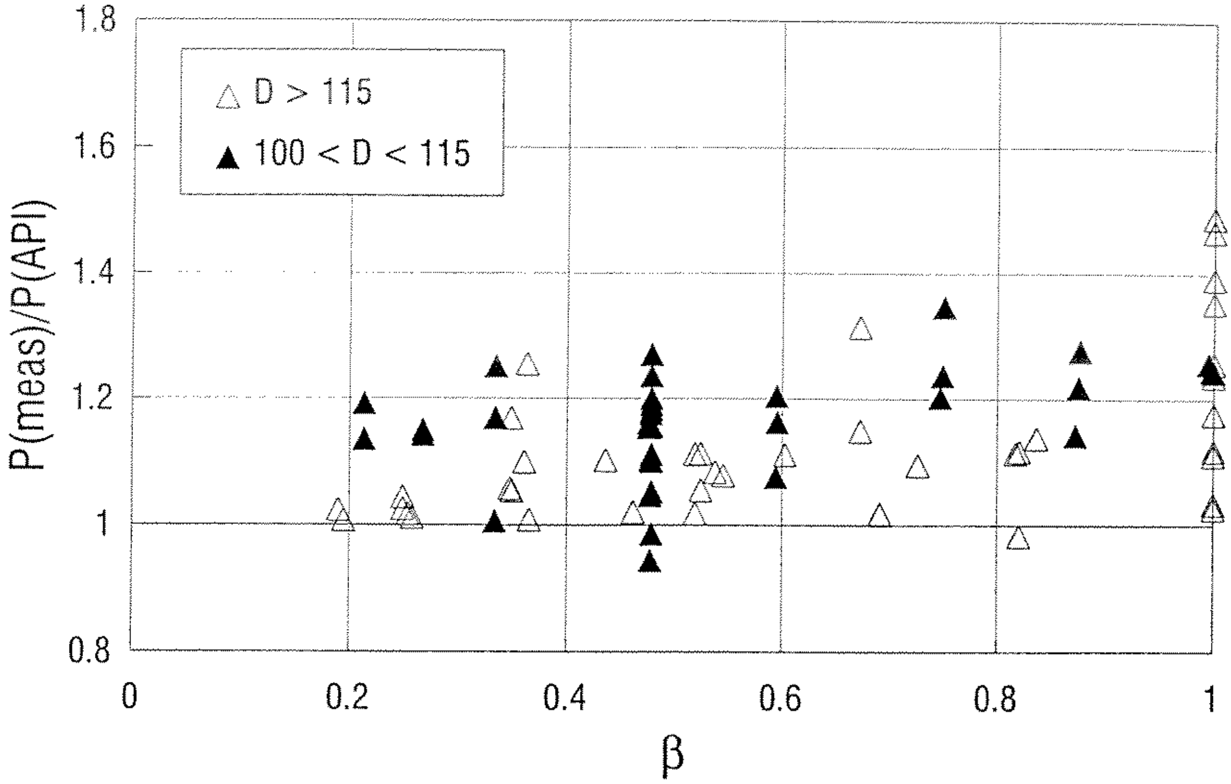


Figure 3.5.4-a Compression loaded DT/X joints: P_{meas}/P_{pred} vs β (API-RP2A)

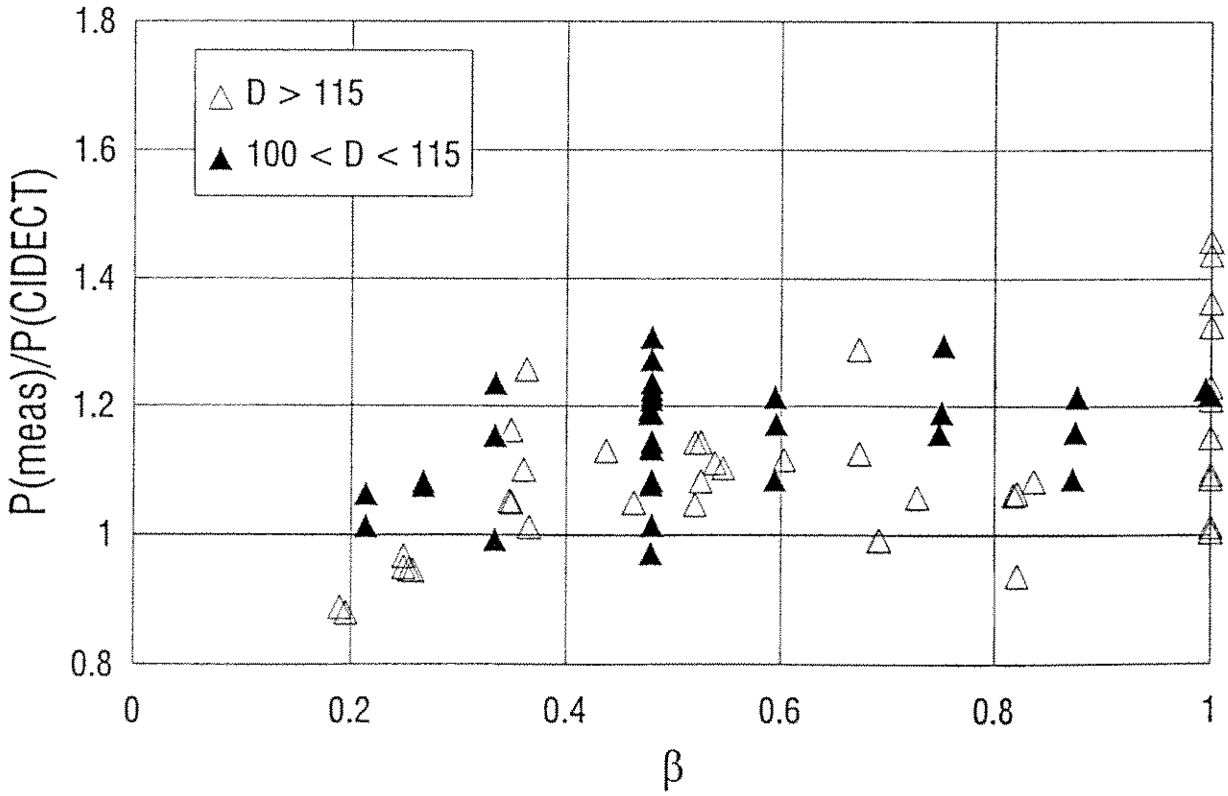


Figure 3.5.4-b Compression loaded DT/X joints: P_{meas}/P_{pred} vs β (CIDECT)

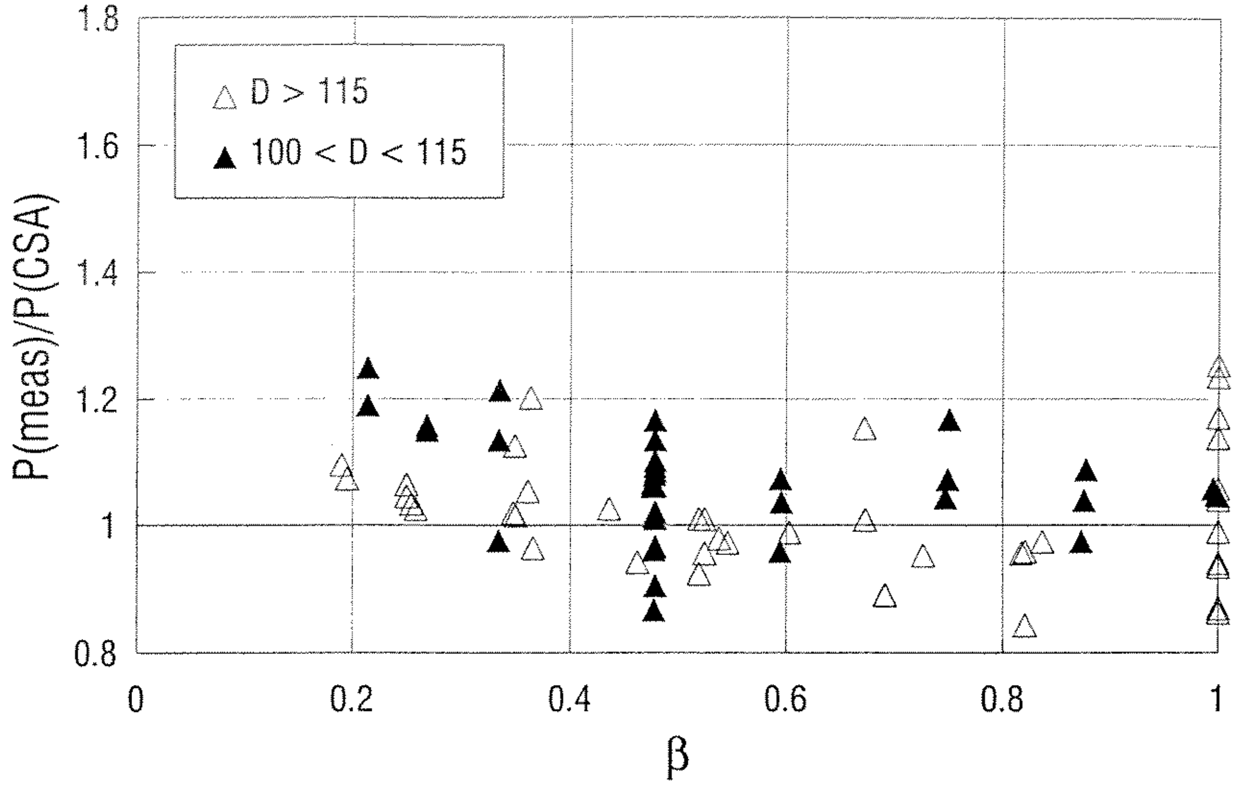


Figure 3.5.4-c Compression loaded DT/X joints: P_{meas}/P_{pred} vs β (CSA)

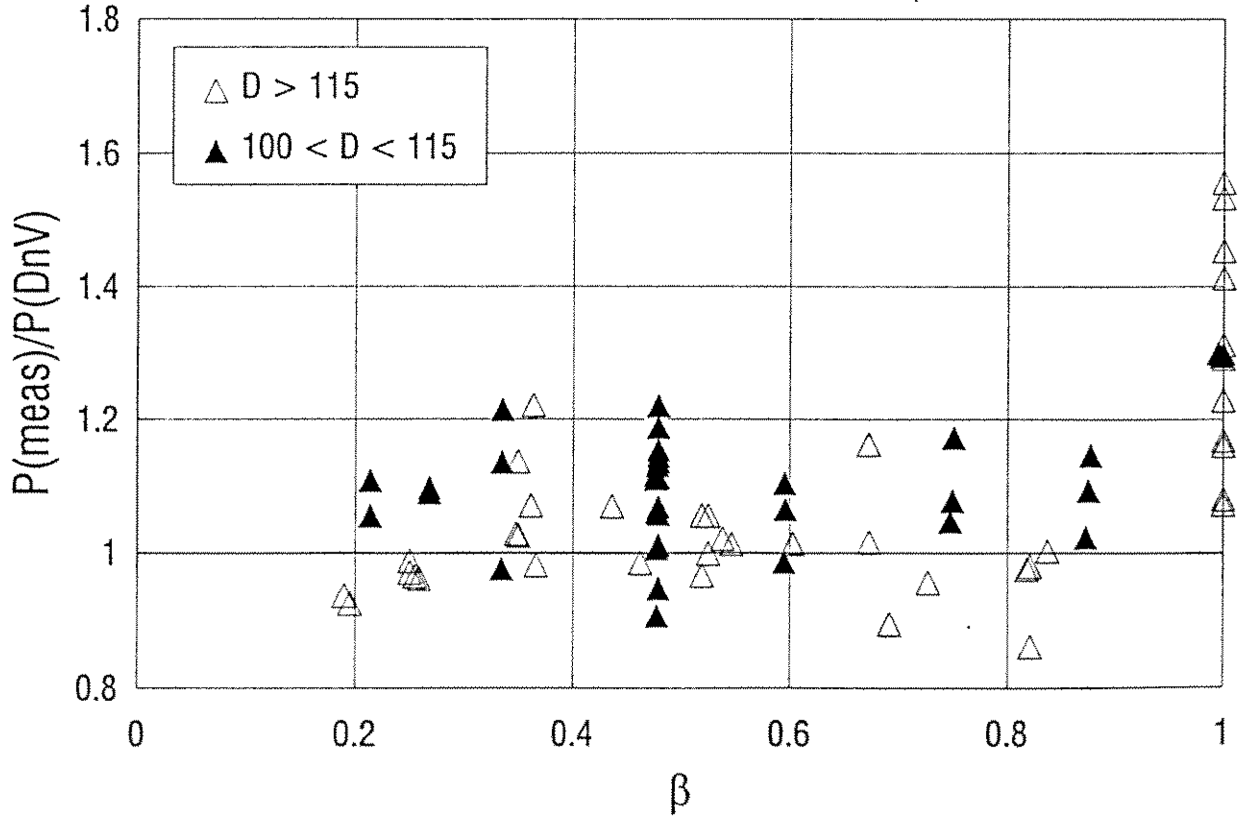


Figure 3.5.4-d Compression loaded DT/X joints: P_{meas}/P_{pred} vs β (DnV)

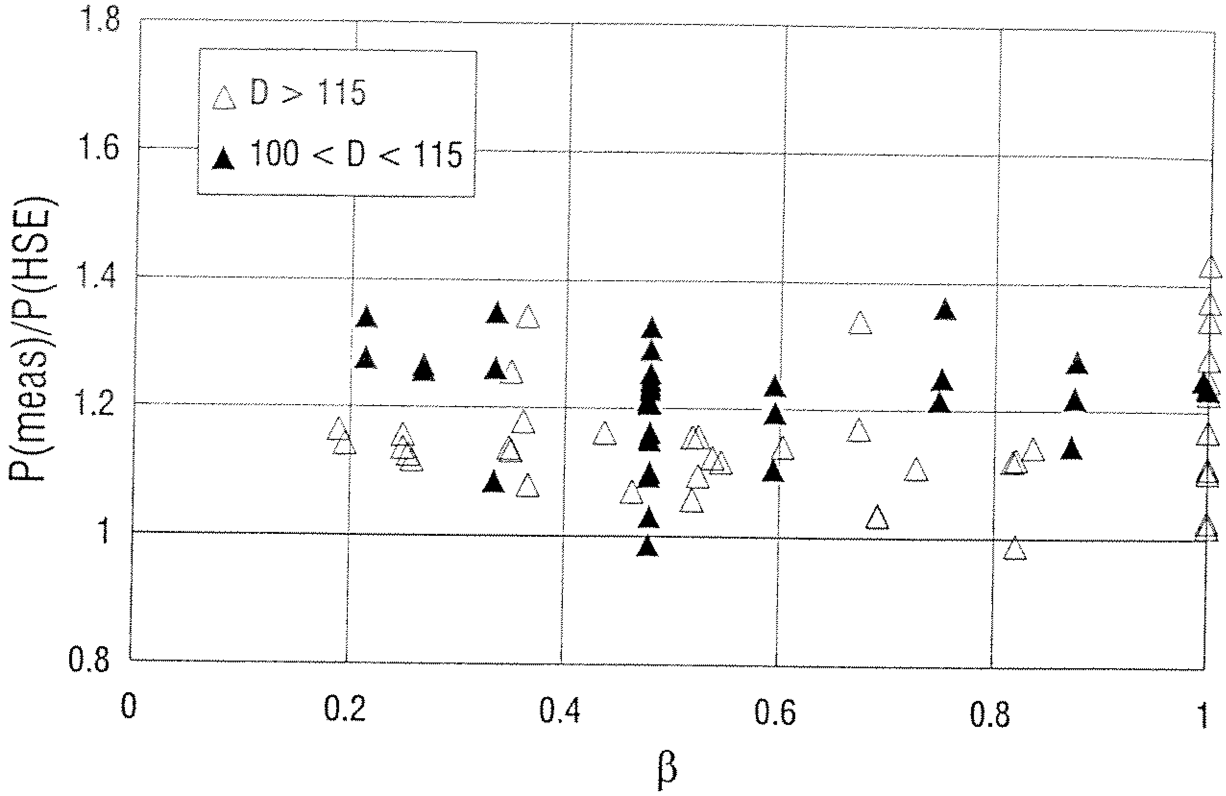


Figure 3.5.4-e Compression loaded DT/X joints: P_{meas}/P_{pred} vs β (HSE)

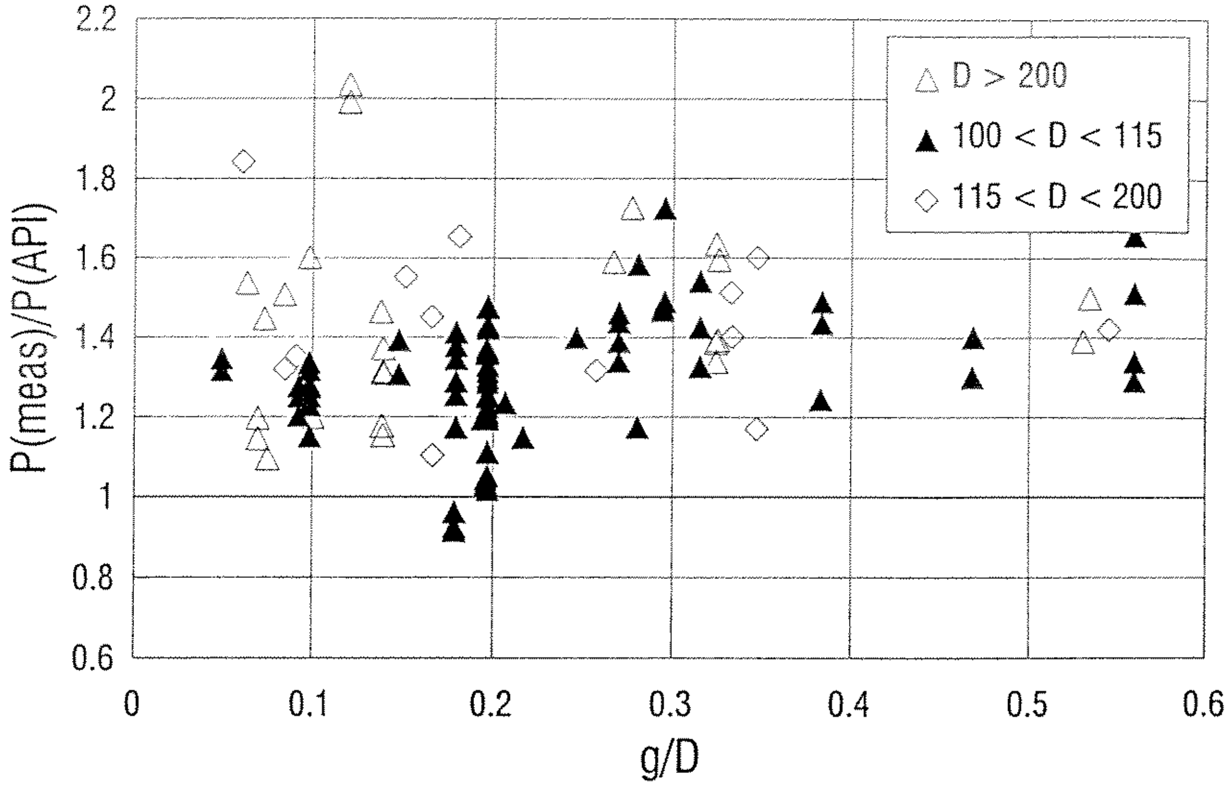


Figure 3.5.5-a Bal. axially loaded YT/K joints: P_{meas}/P_{pred} vs ζ (API-RP2A)

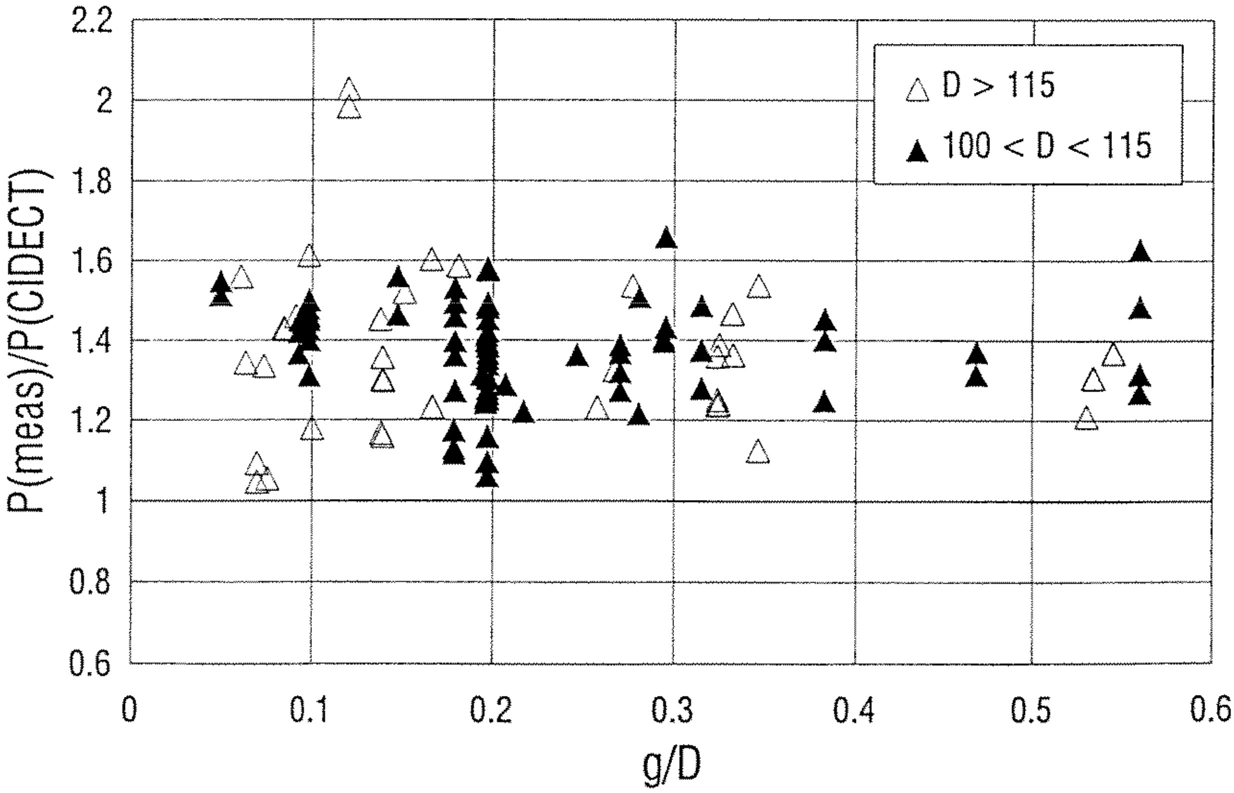


Figure 3.5.5-b Bal. axially loaded YT/K joints: P_{meas}/P_{pred} vs ζ (CIDECT)

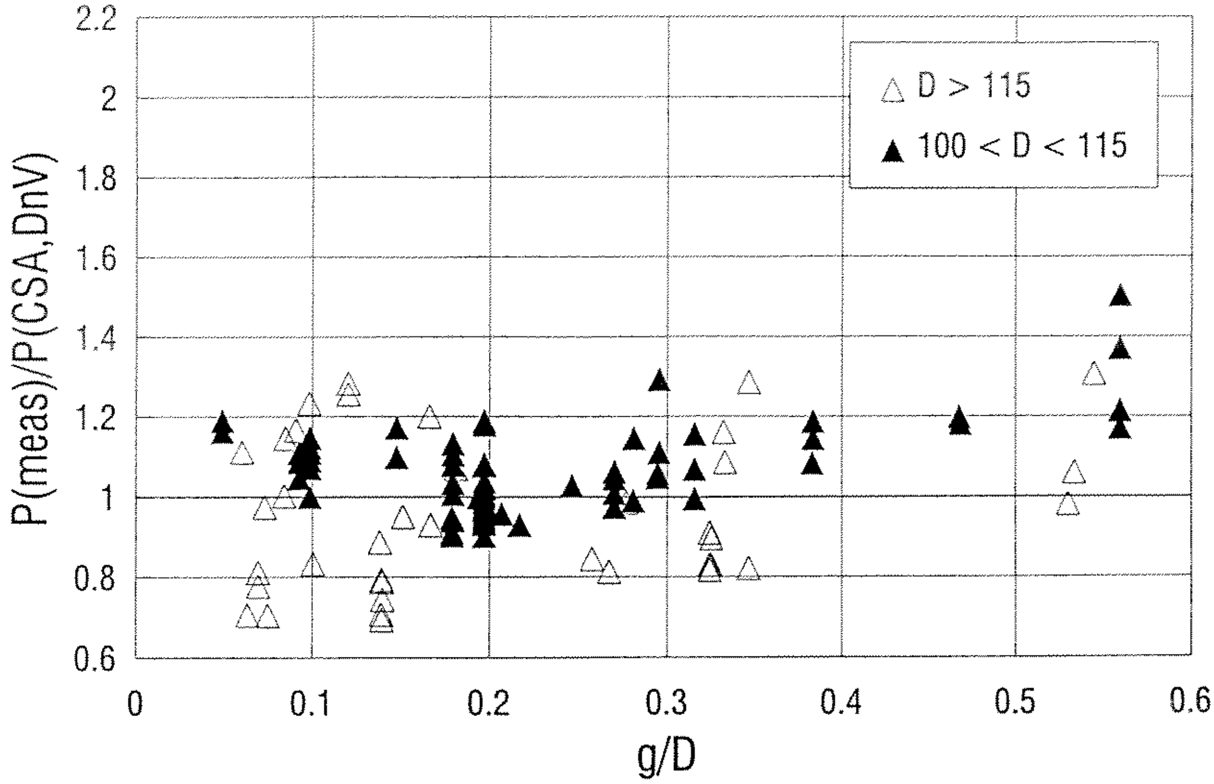


Figure 3.5.5-c Bal. axially loaded YT/K joints: P_{meas}/P_{pred} vs ζ (CSA, DnV)

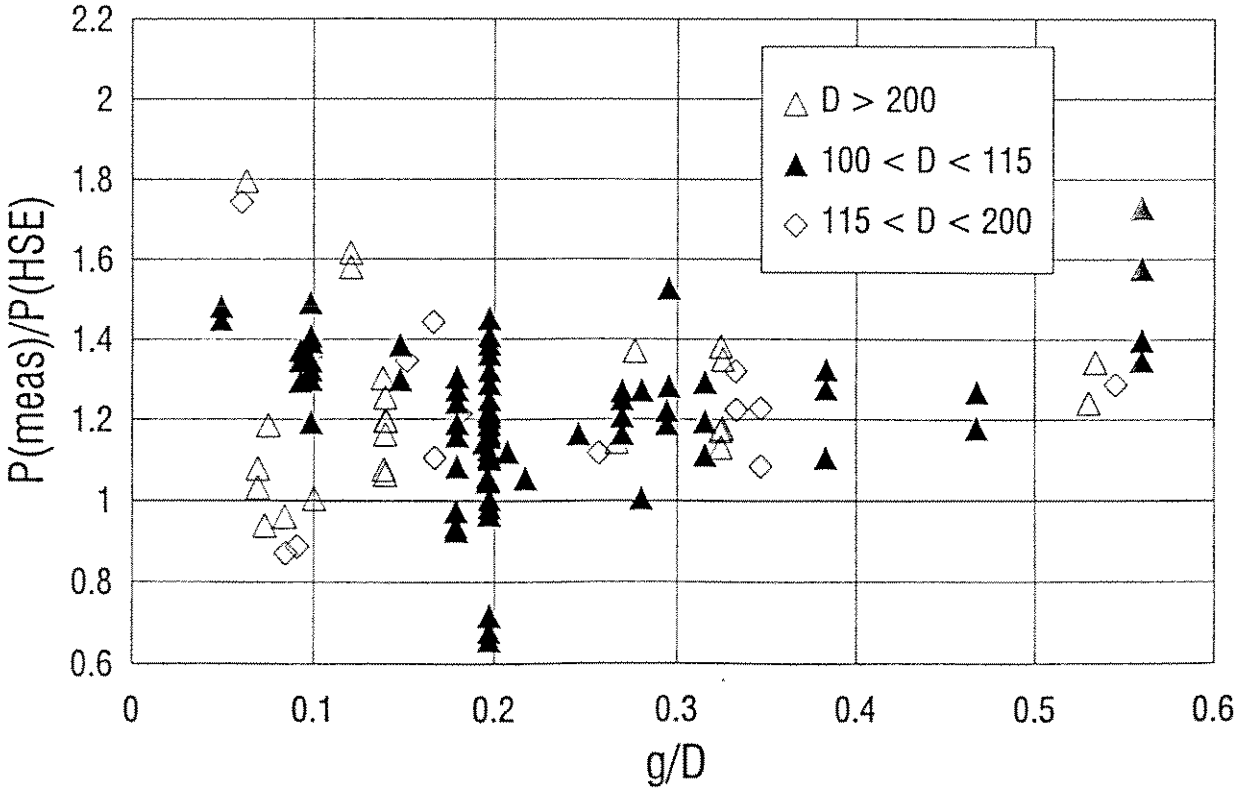


Figure 3.5.5-d Bal. axially loaded YT/K joints: P_{meas}/P_{pred} vs ζ (HSE)

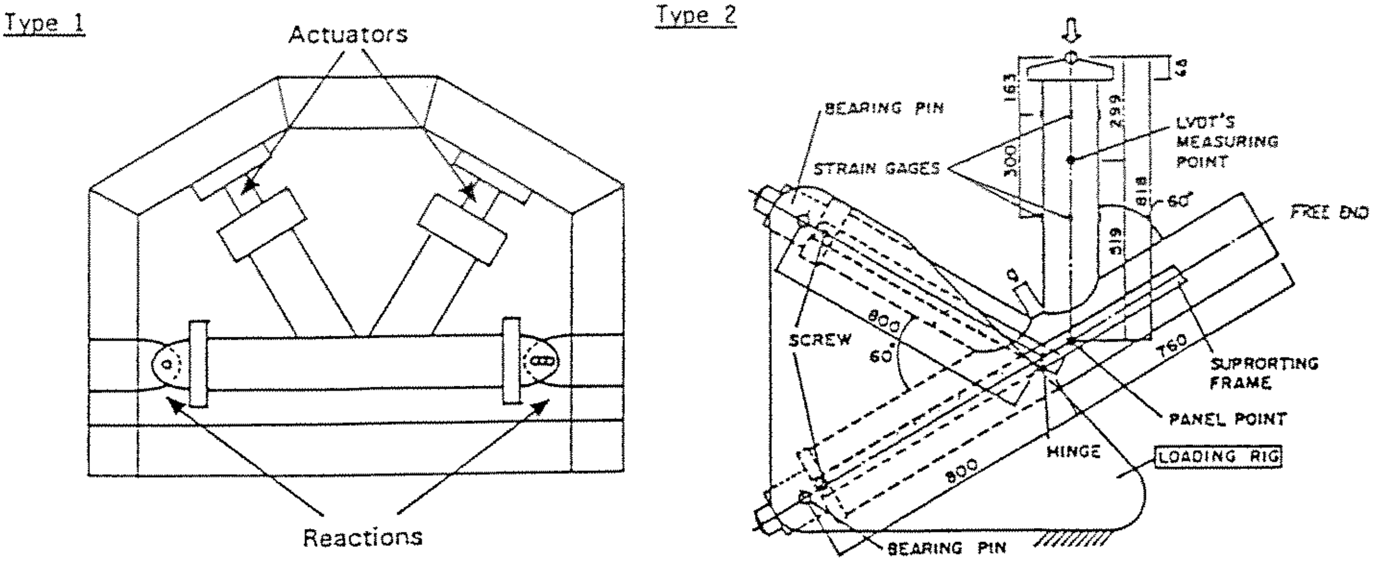


Figure 3.5.6 Typical testing arrangements for K joints

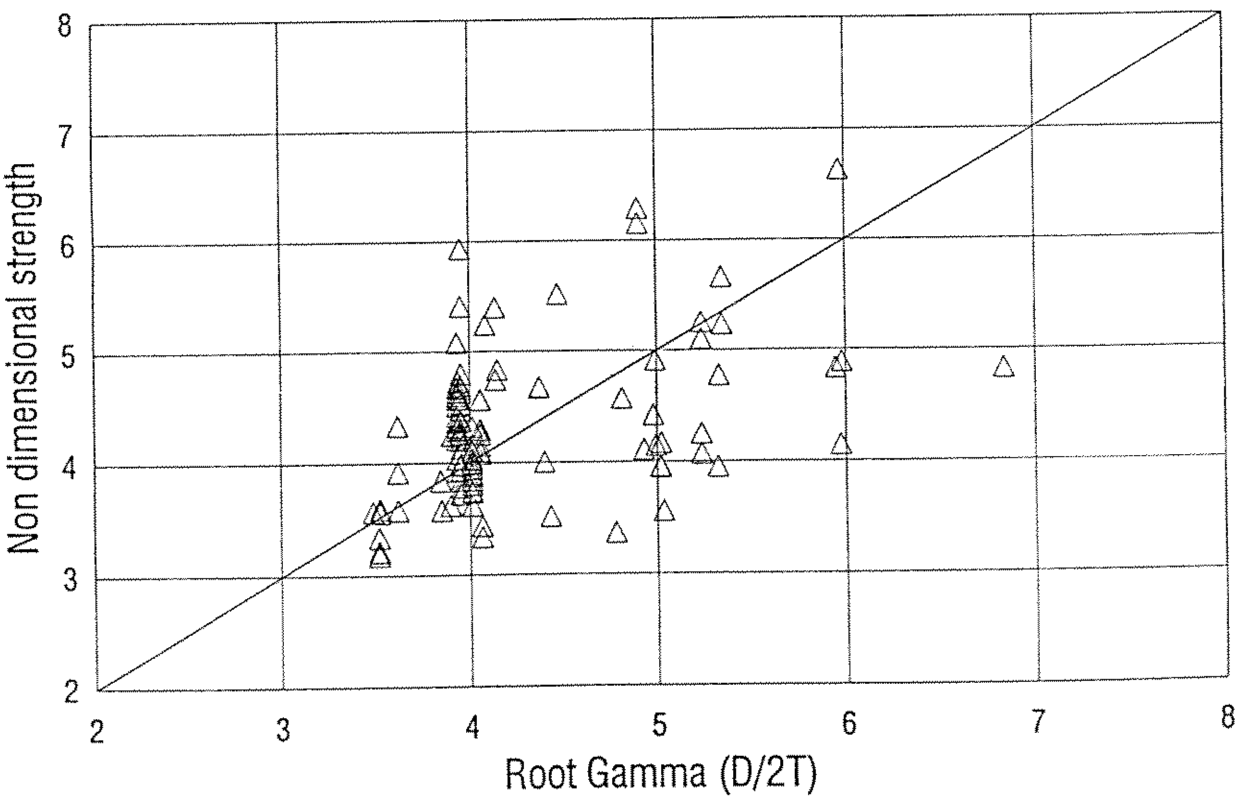


Figure 3.5.7 Bal. axially loaded YT/K joints: Effect of $\sqrt{\gamma}$ (CSA, DnV)

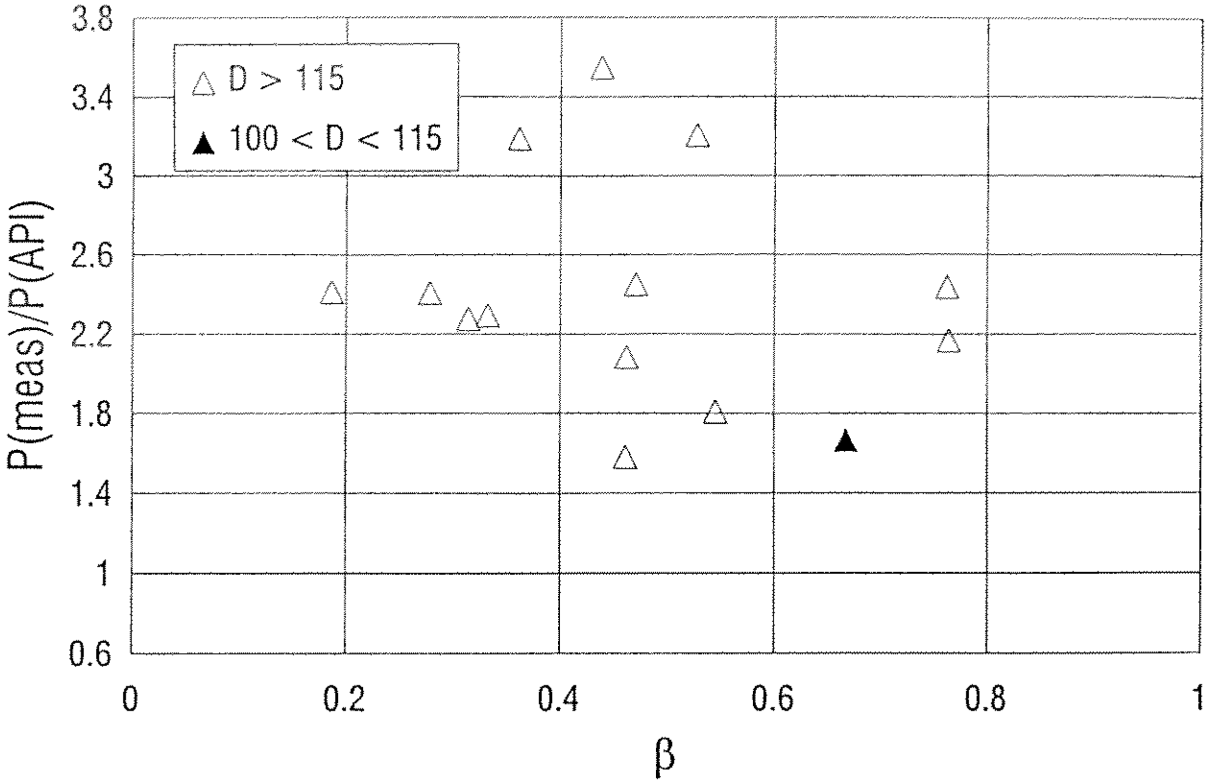


Figure 3.5.8-a   Tension loaded T/Y joints: P_{meas}/P_{pred} vs β (API-RP2A)

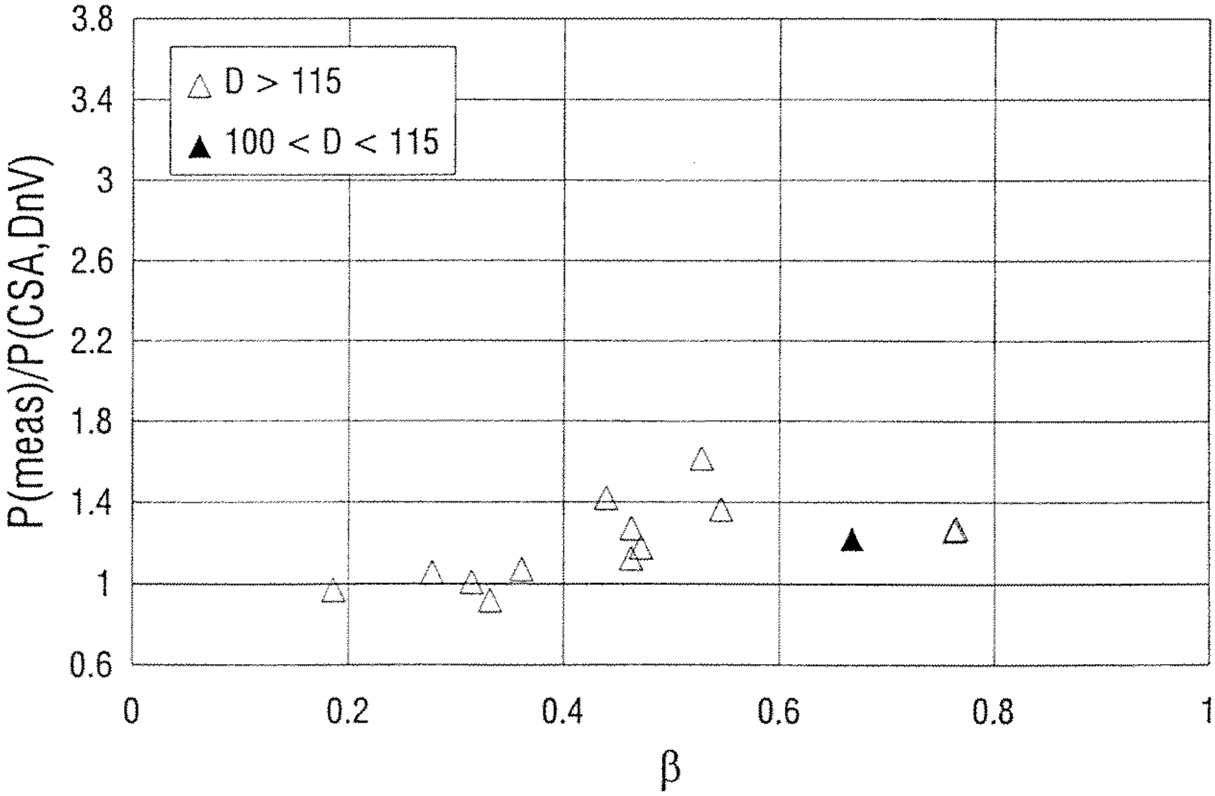


Figure 3.5.8-b   Tension loaded T/Y joints: P_{meas}/P_{pred} vs β (CSA, DnV)

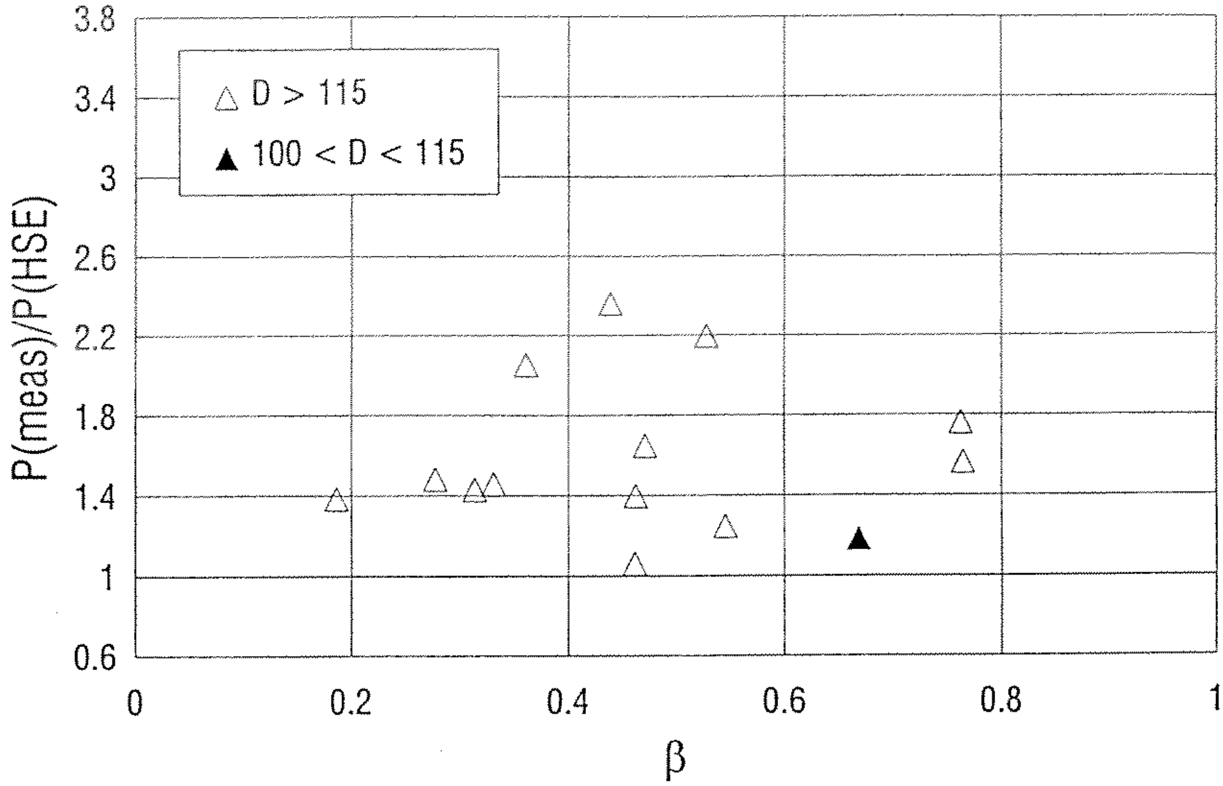


Figure 3.5.8-c Tension loaded T/Y joints: P_{meas}/P_{pred} vs β (HSE)

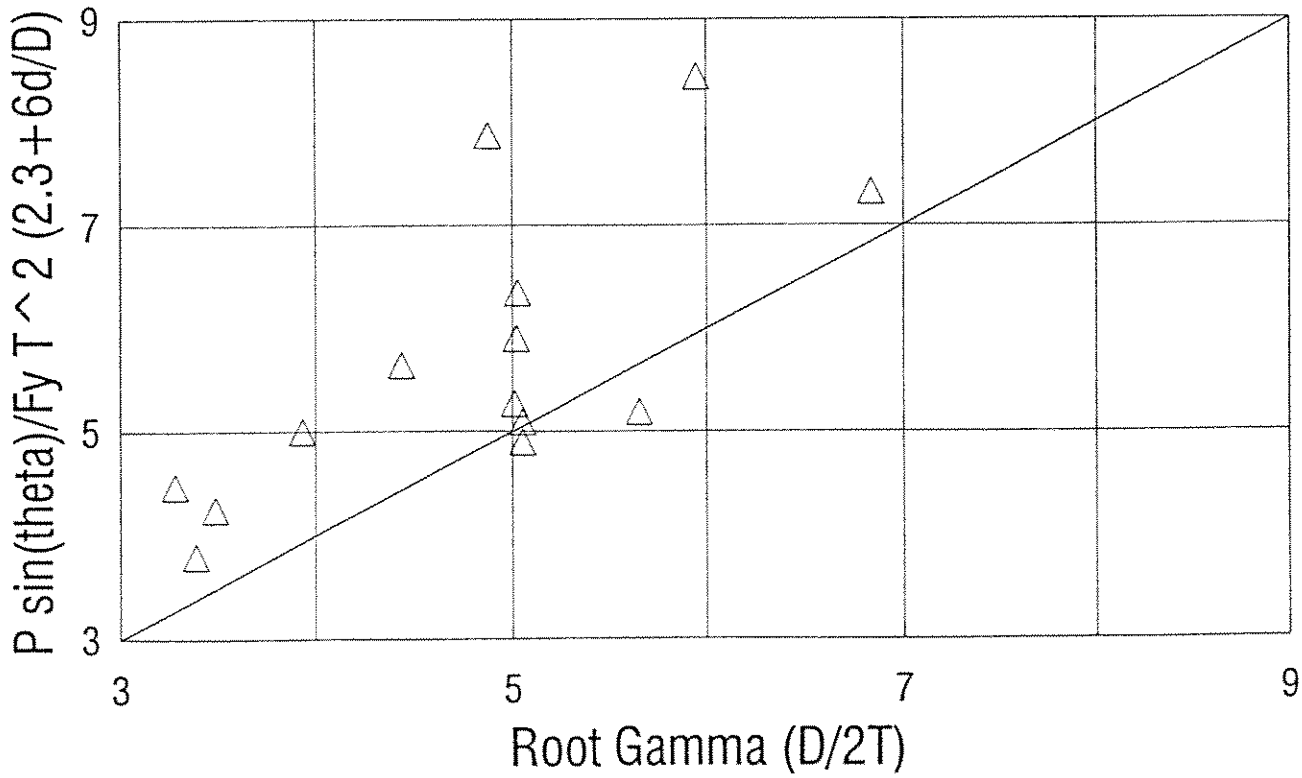


Figure 3.5.9 Tension loaded T/Y joints: Effect of $\sqrt{\gamma}$ (CSA, DnV)

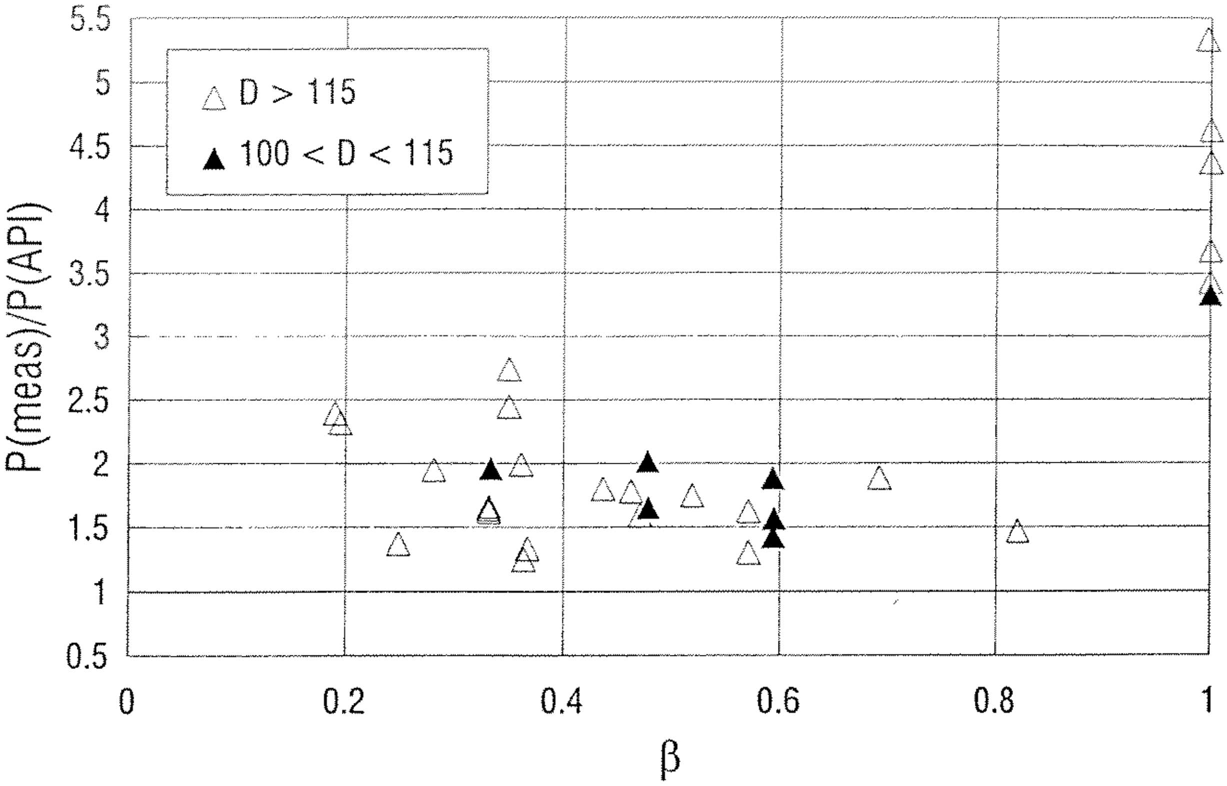


Figure 3.5.10-a Tension loaded DT/X joints: P_{meas}/P_{pred} vs β (API-RP2A)

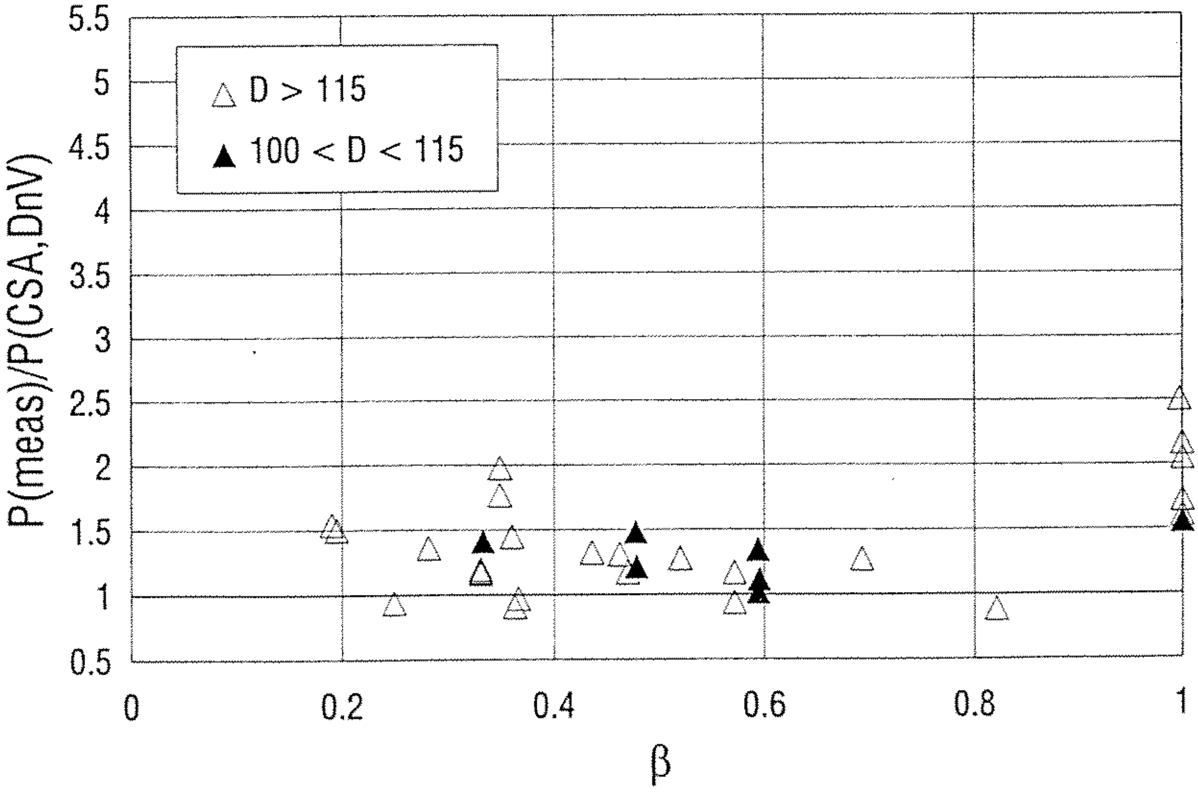


Figure 3.5.10-b Tension loaded DT/X joints: P_{meas}/P_{pred} vs β (CSA, DnV)

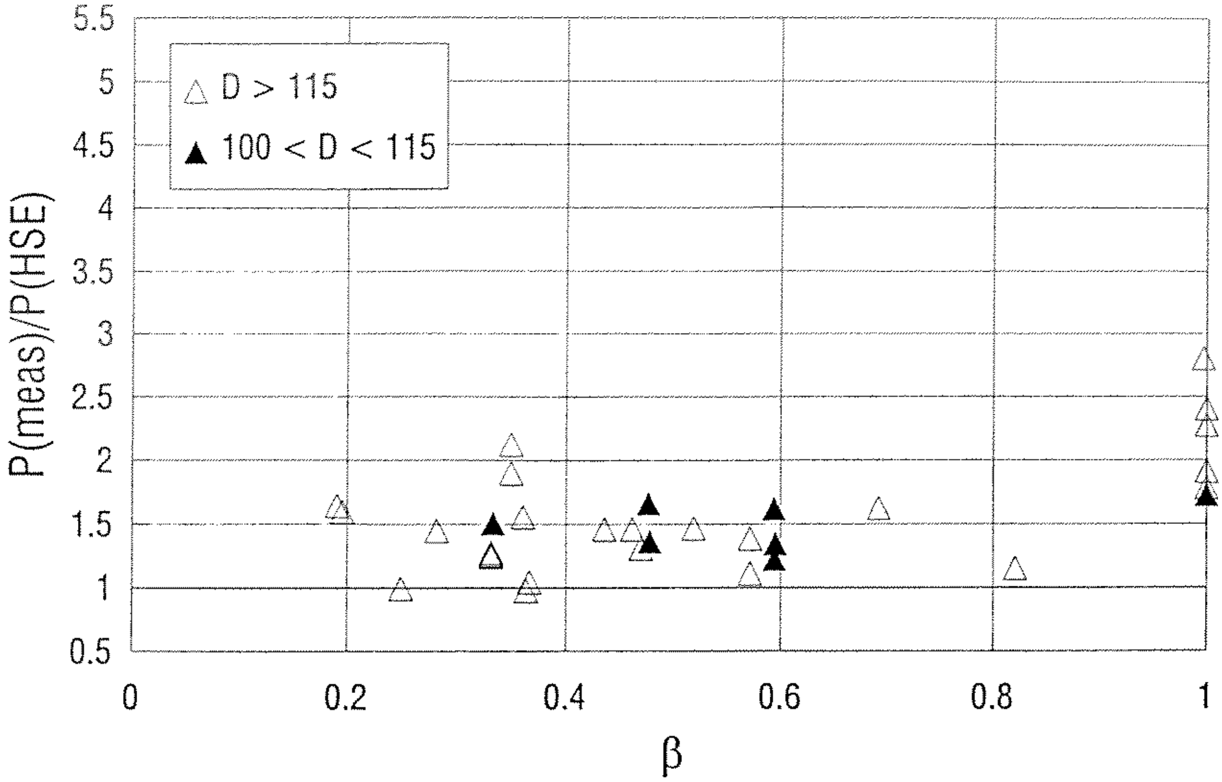


Figure 3.5.10-c Tension loaded DT/X joints: P_{meas}/P_{pred} vs β (HSE)

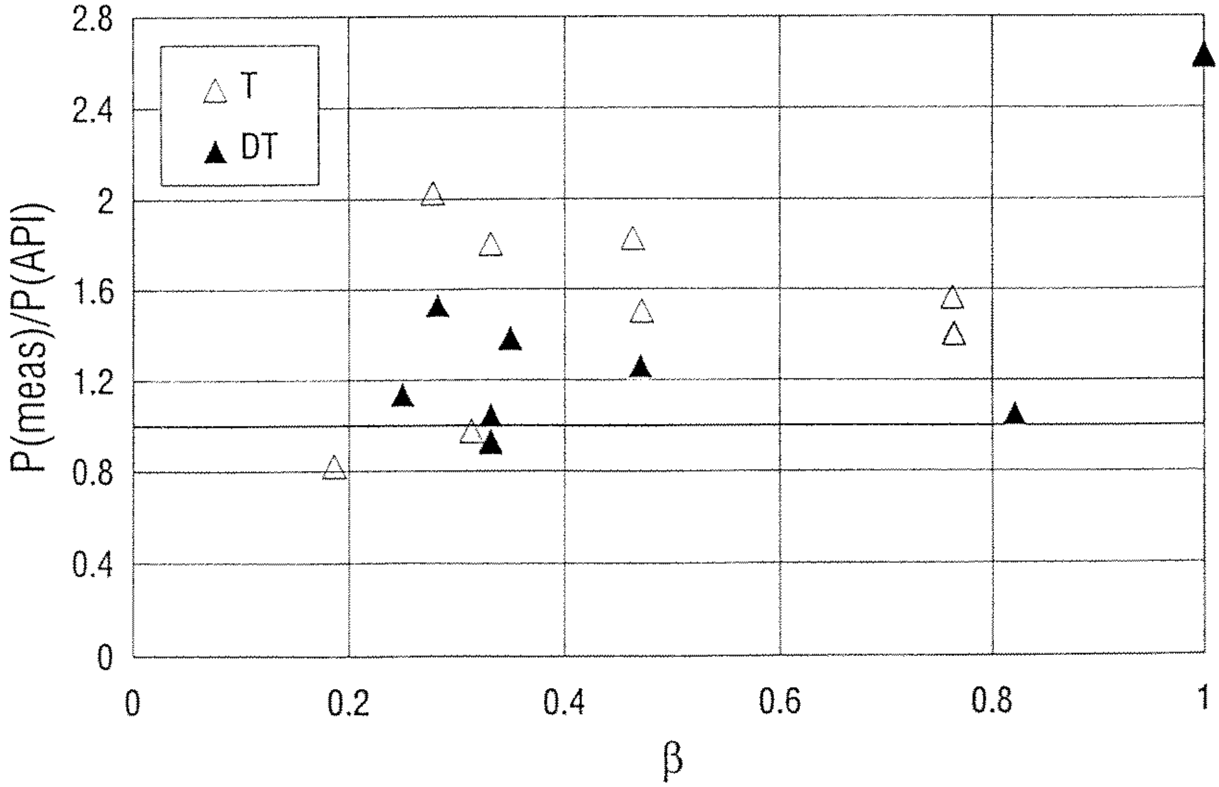


Figure 3.5.11-a Tension loaded T/DT joints: P_{meas}/P_{pred} 1st crack (API-RP2A)

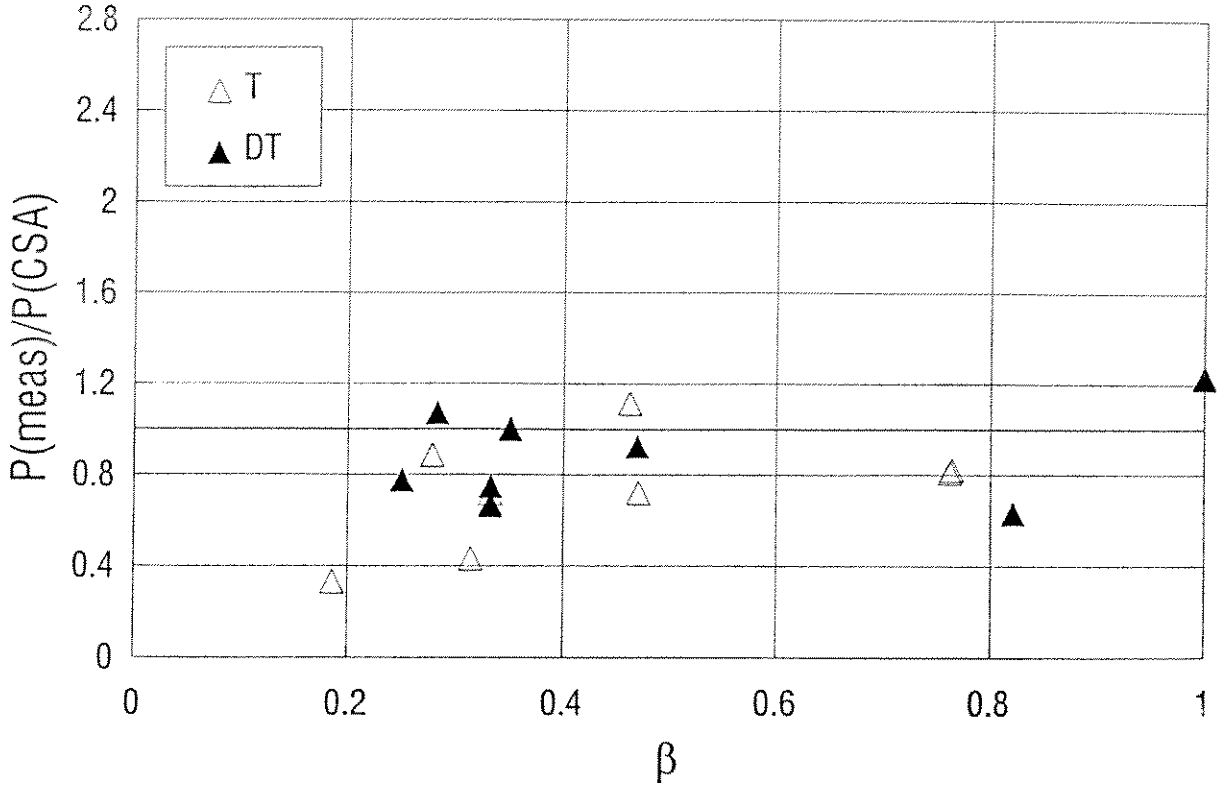


Figure 3.5.11-b Tension loaded T/DT joints: P_{meas}/P_{pred} 1st crack (CSA)

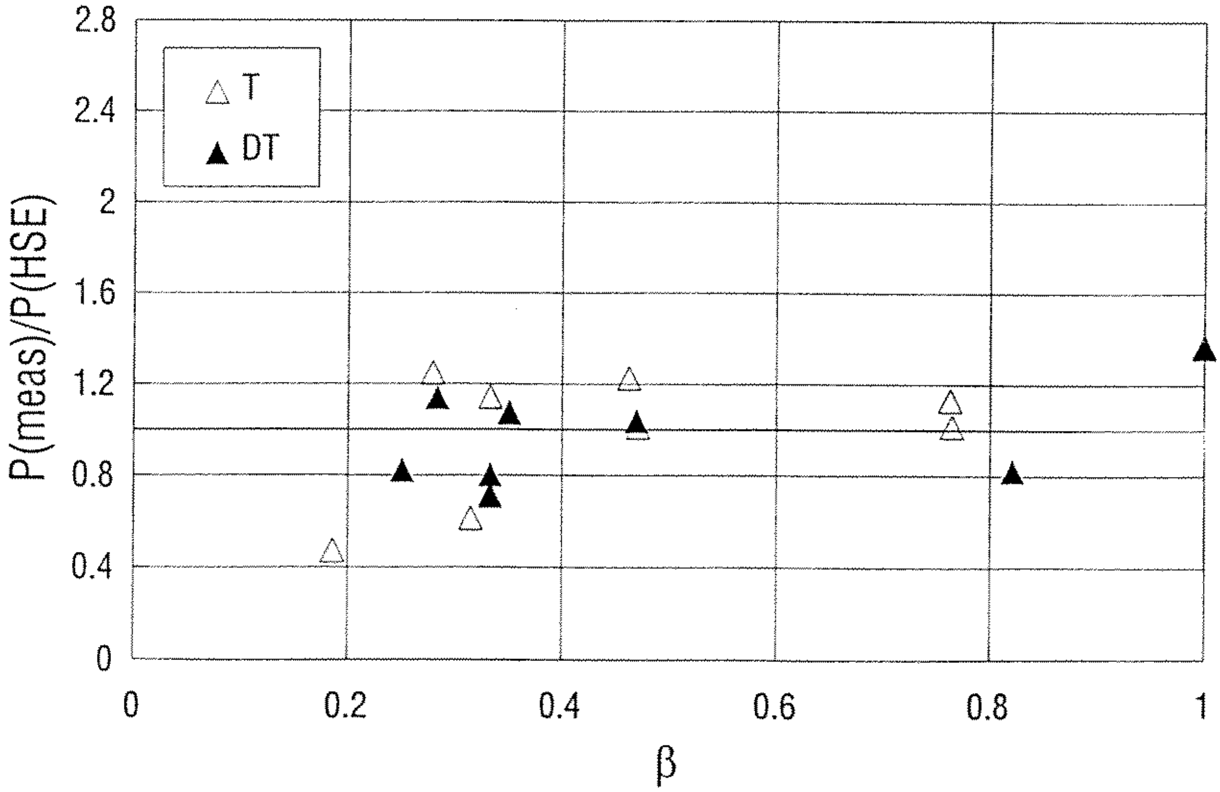


Figure 3.5.11-c Tension loaded T/DT joints: P_{meas}/P_{pred} 1st crack (HSE)

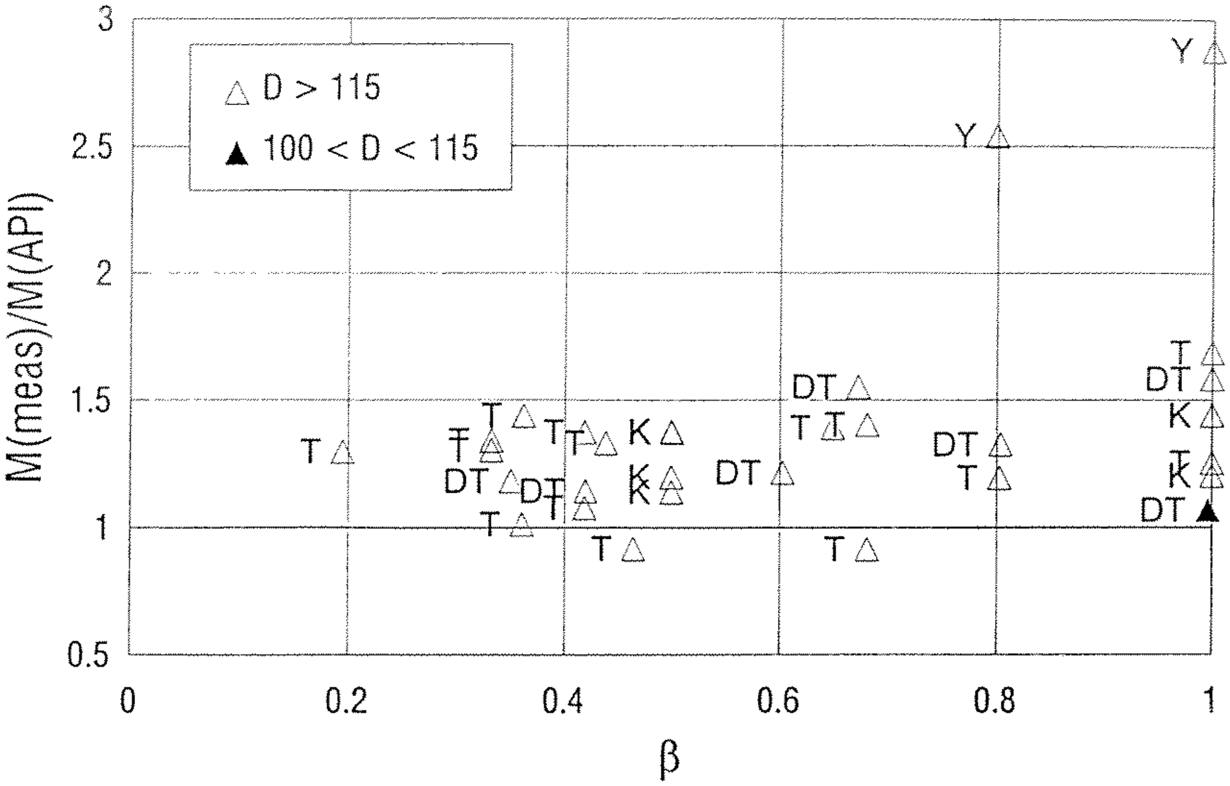


Figure 3.5.12-a IPB loaded simple joints: M_{meas}/M_{pred} vs β (API-RP2A)

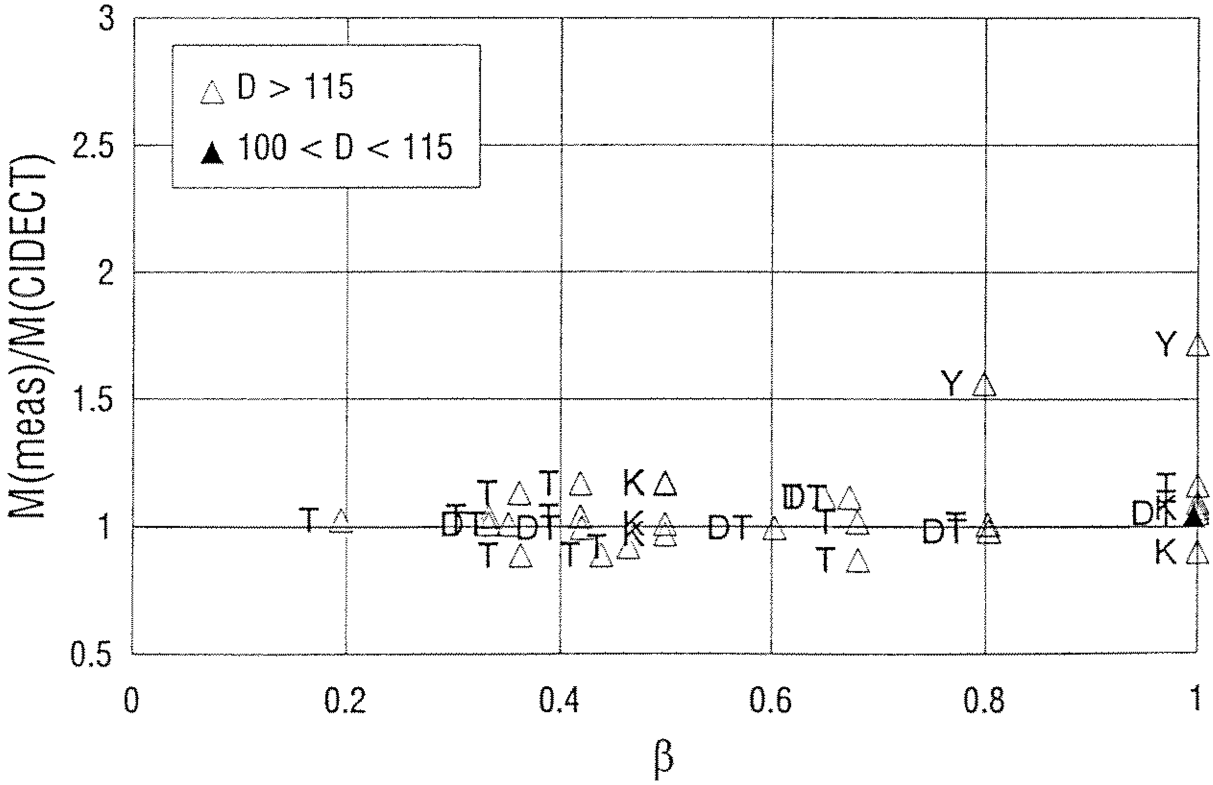


Figure 3.5.12-b IPB loaded simple joints: M_{meas}/M_{pred} vs β (CIDECT)

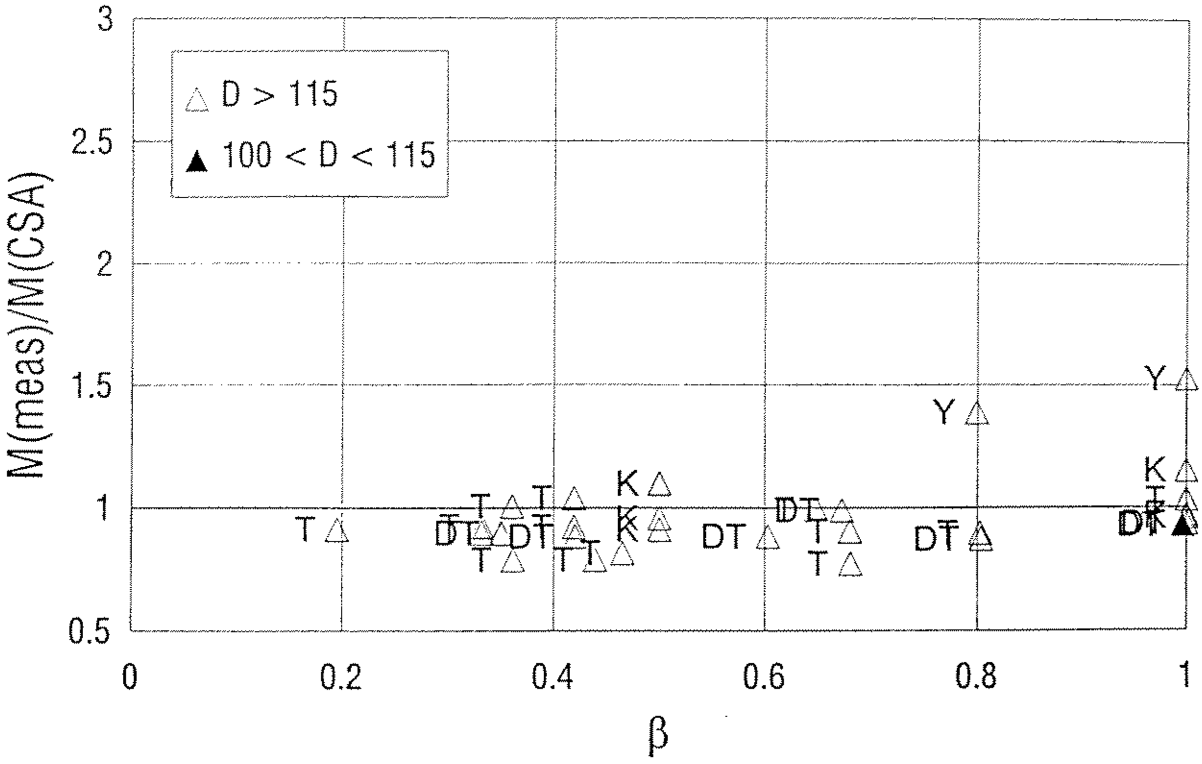


Figure 3.5.12-c IPB loaded simple joints: M_{meas}/M_{pred} vs β (CSA)

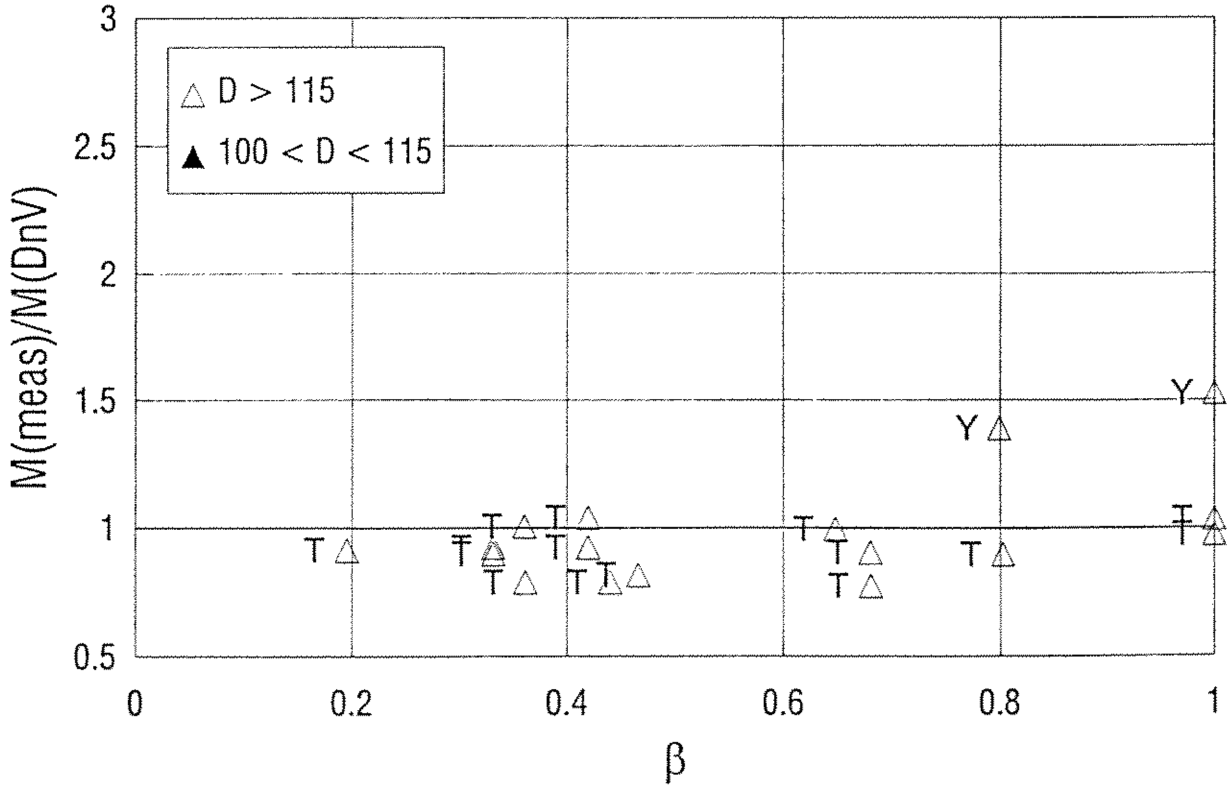


Figure 3.5.12-d IPB loaded simple joints: M_{meas}/M_{pred} vs β (DnV)

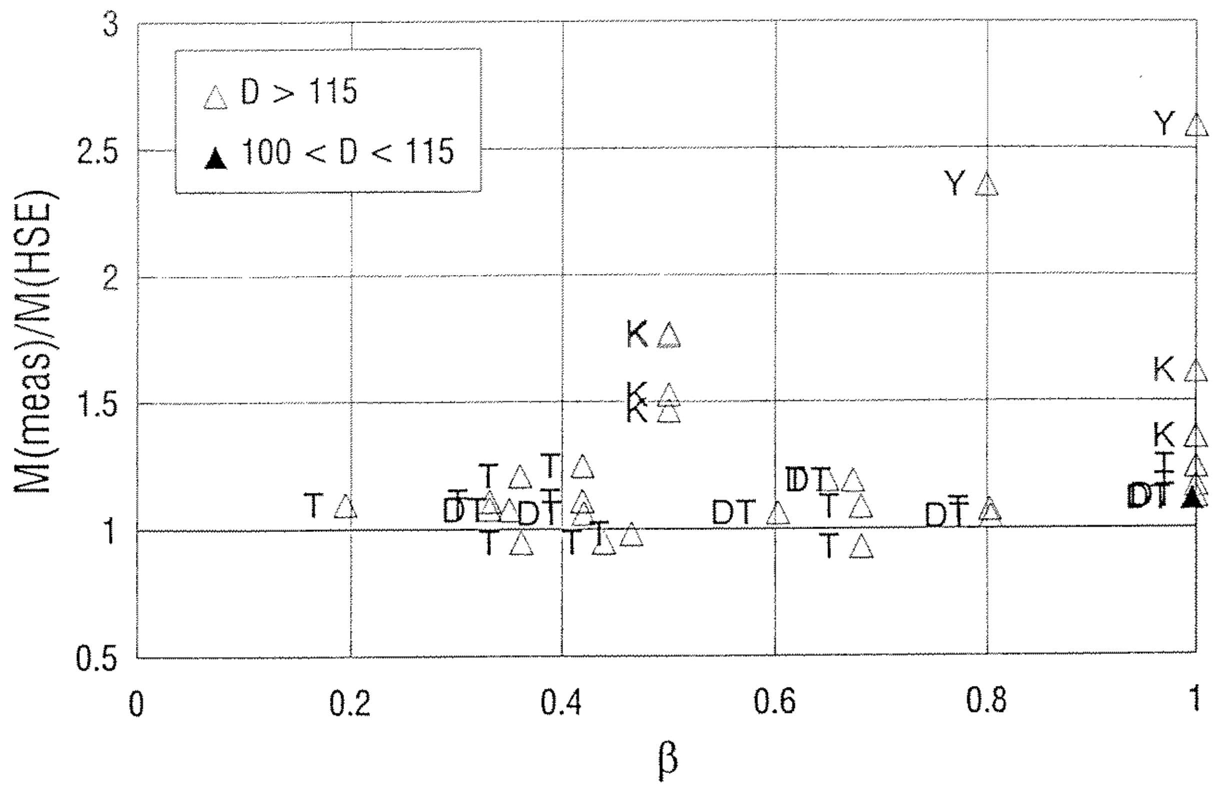


Figure 3.5.12-e IPB loaded simple joints: M_{meas}/M_{pred} vs β (HSE)

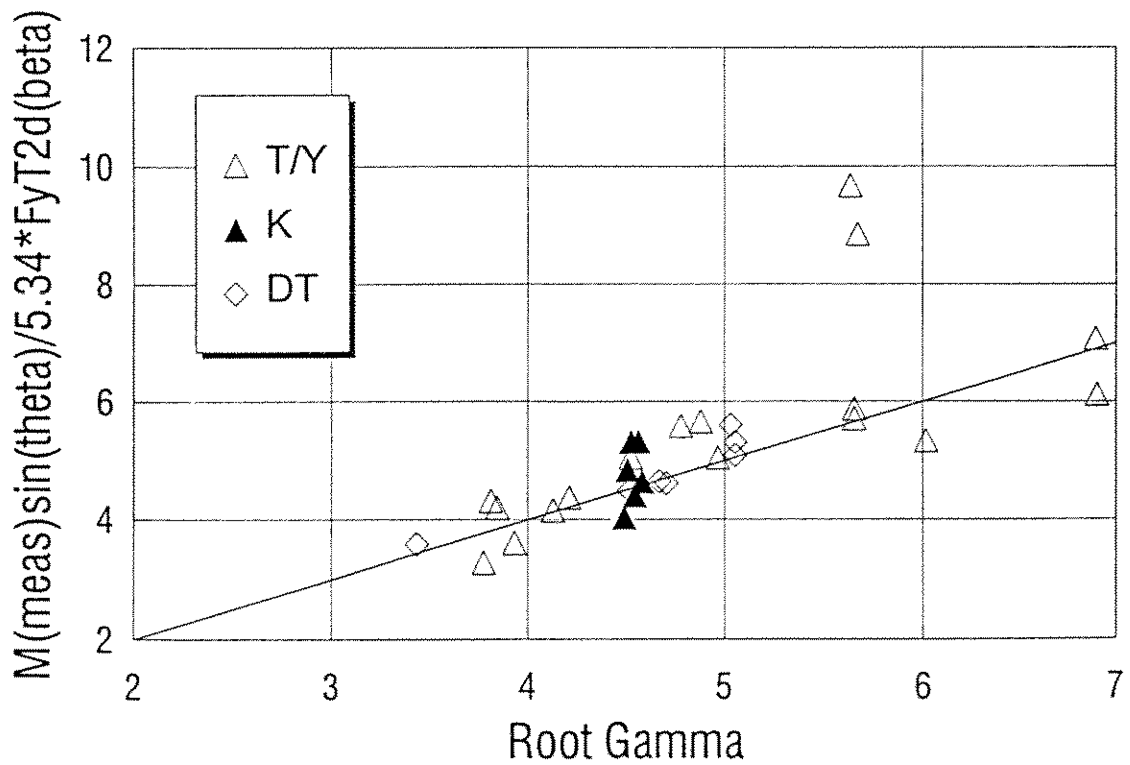


Figure 3.5.13 IPB loaded simple joints: Effect of $\sqrt{\gamma}$ (CIDECT)

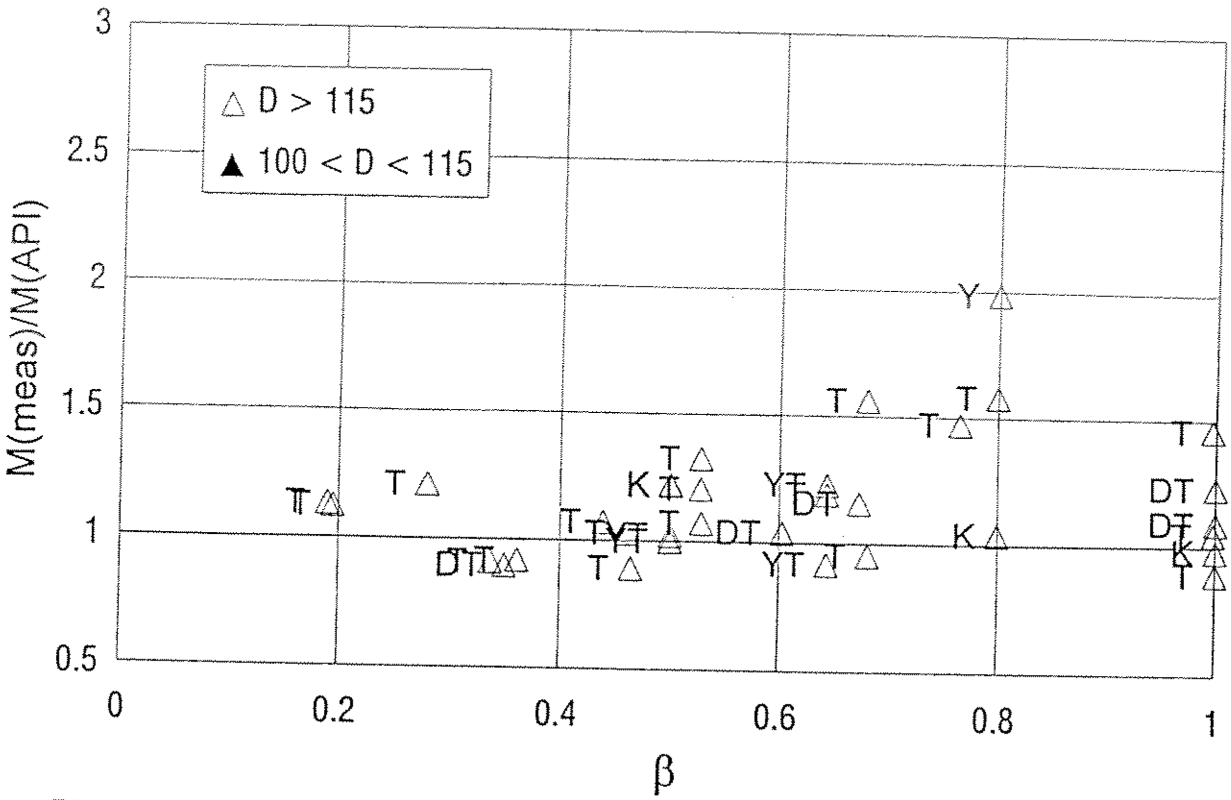


Figure 3.5.14-a OPB loaded simple joints: M_{meas}/M_{pred} vs β (API-RP2A)

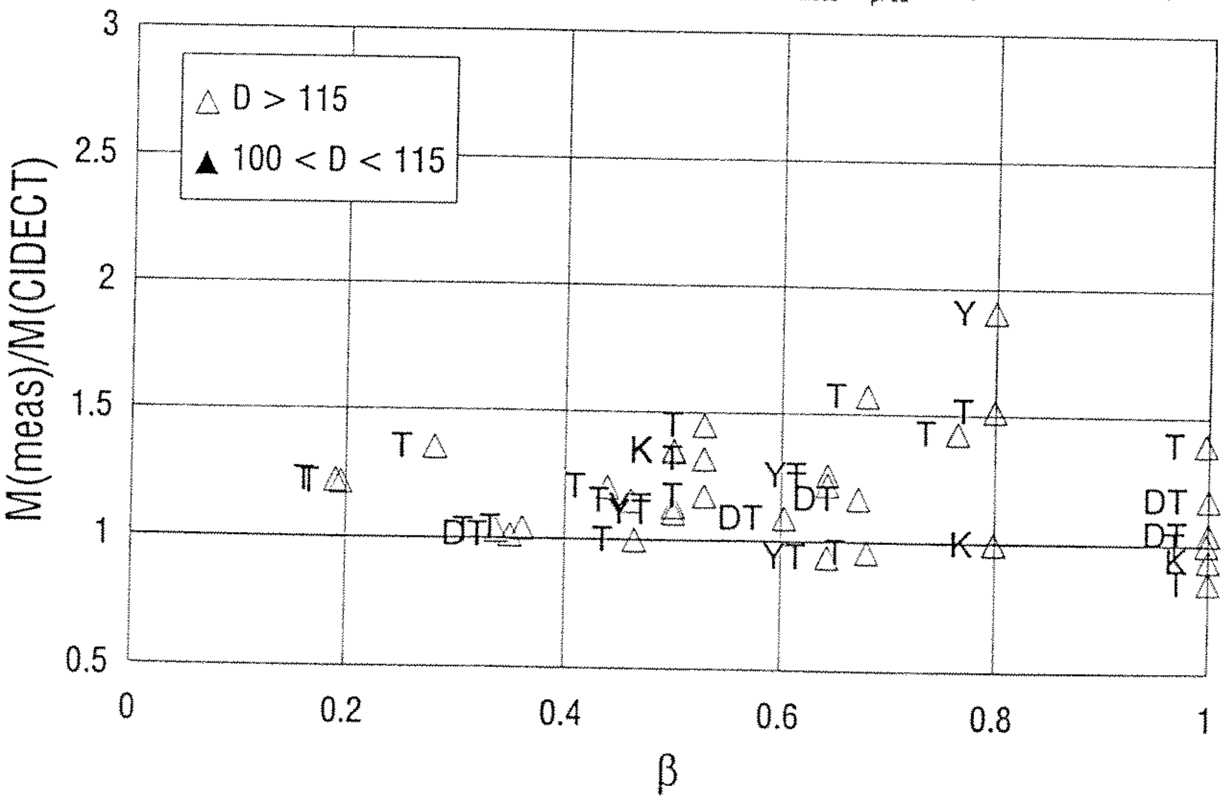


Figure 3.5.14-b OPB loaded simple joints: M_{meas}/M_{pred} vs β (CIDECT)

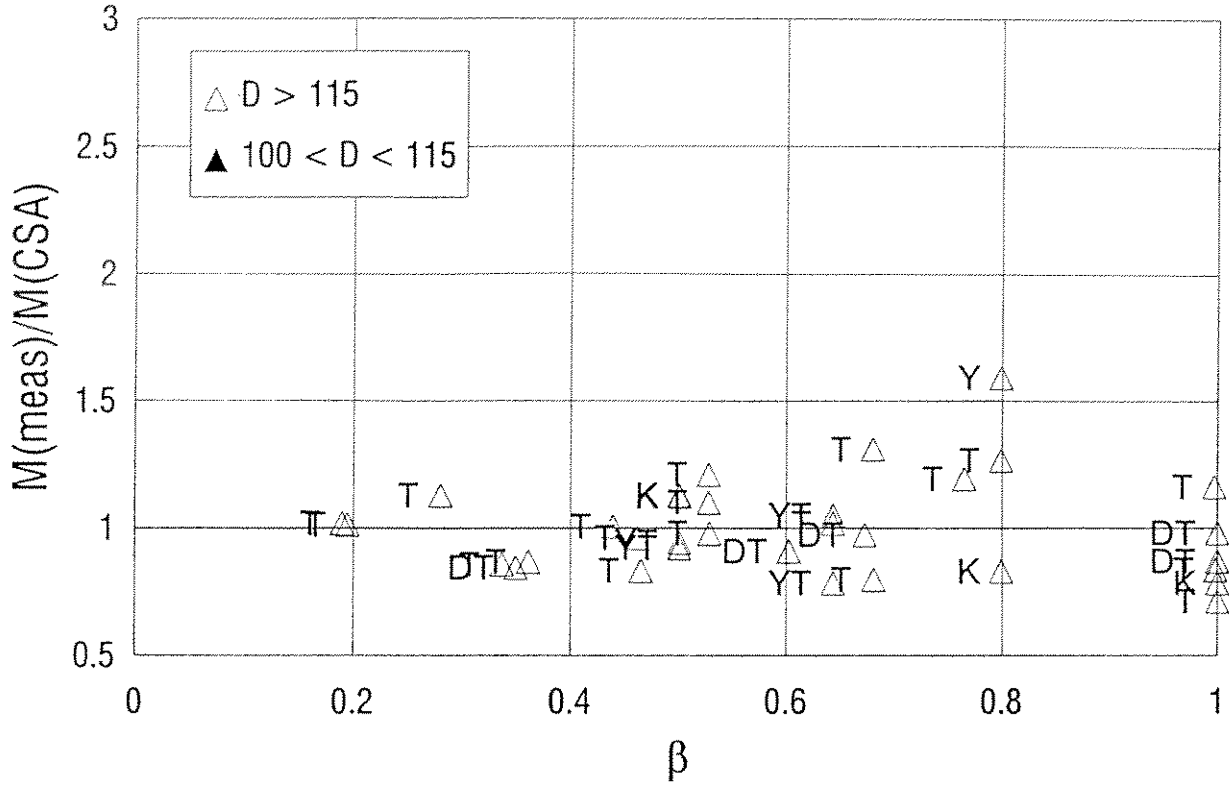


Figure 3.5.14-c OPB loaded simple joints: M_{meas}/M_{pred} vs β (CSA)

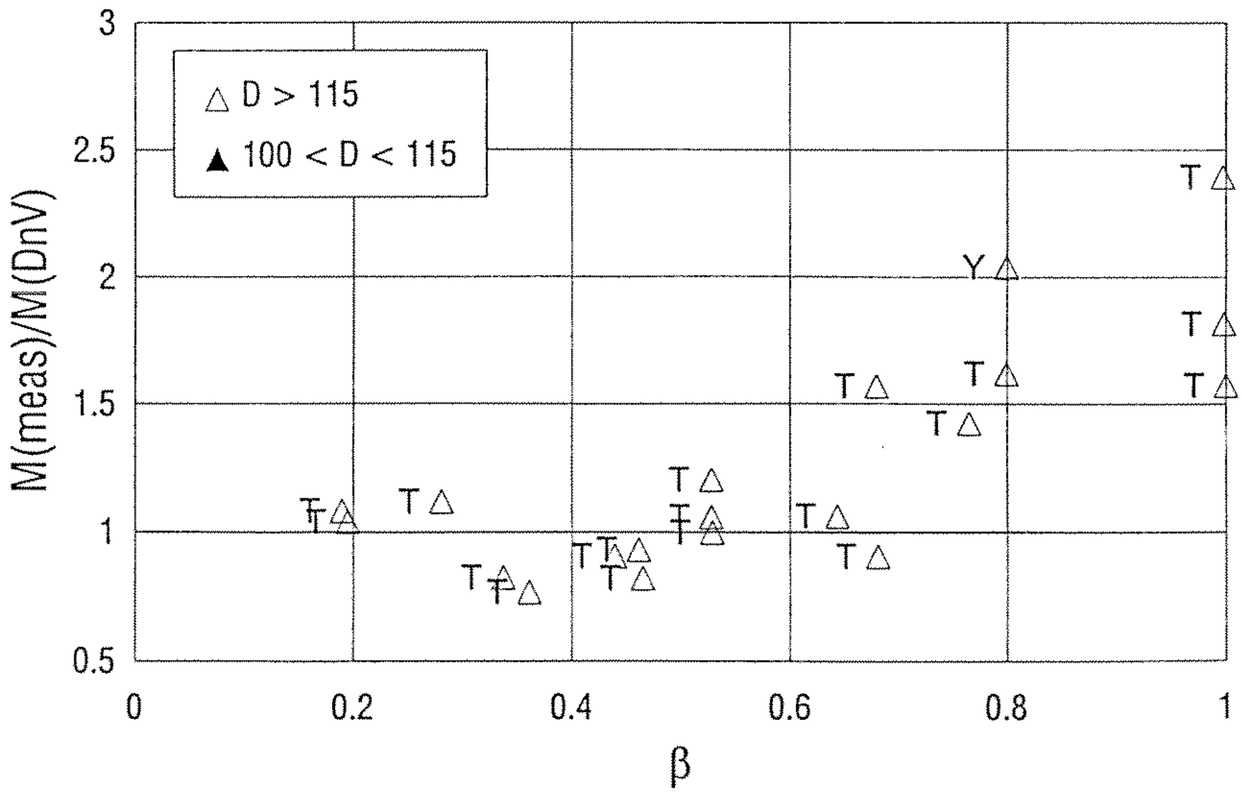


Figure 3.5.14-d OPB loaded simple joints: M_{meas}/M_{pred} vs β (DnV)

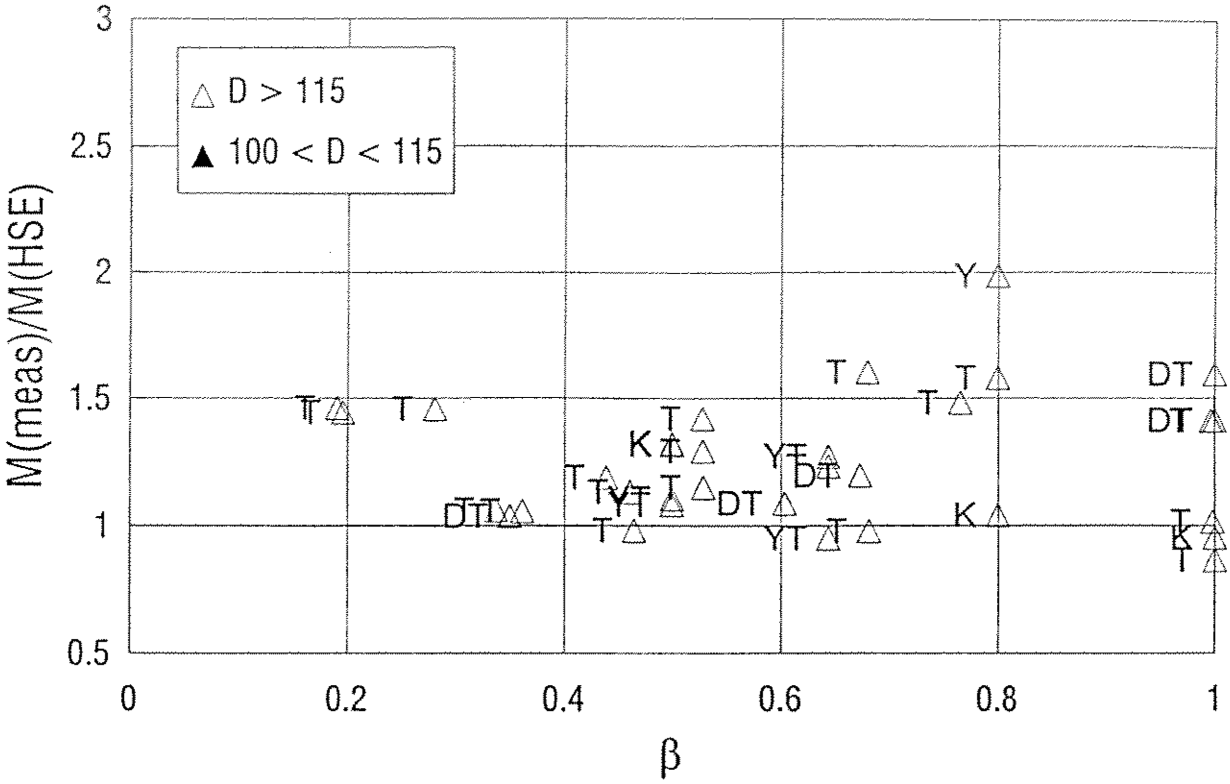


Figure 3.5.14-e OPB loaded simple joints: M_{meas}/M_{pred} vs β (HSE)

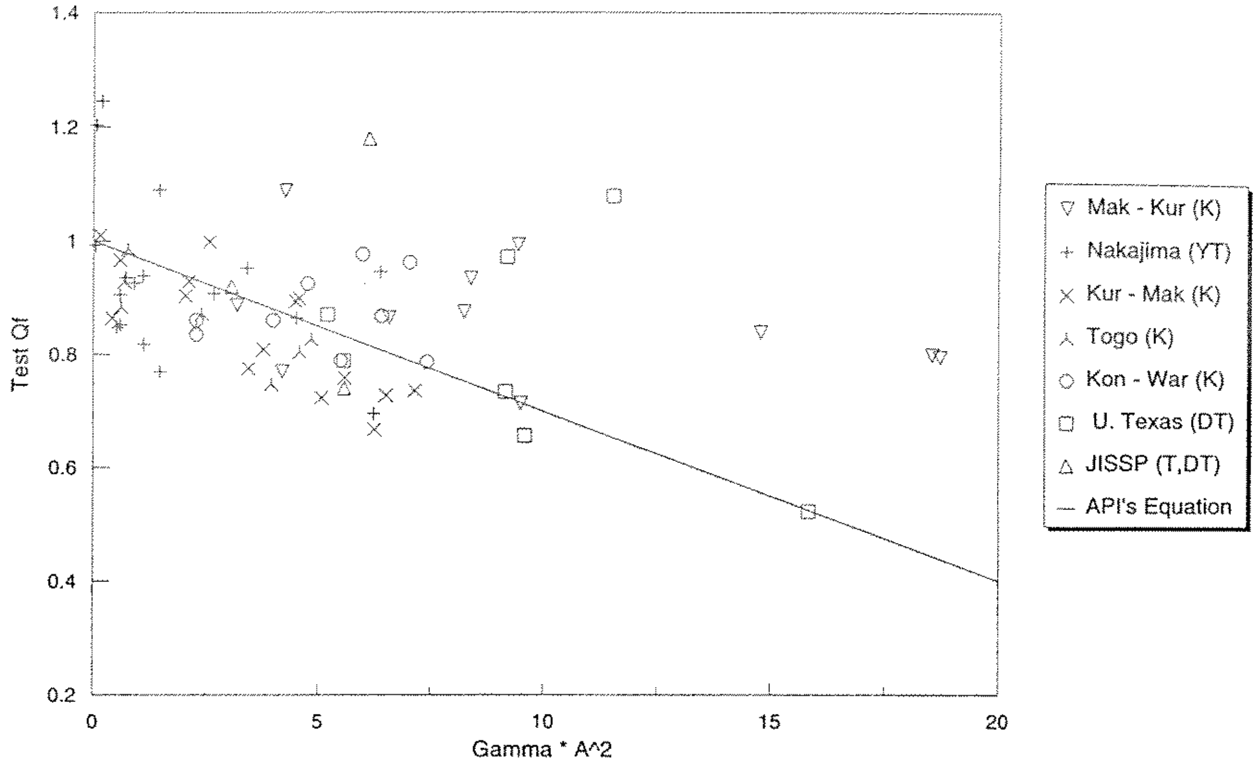


Figure 3.5.15 Chord load effects on axially loaded joints: Q_f vs γA^2

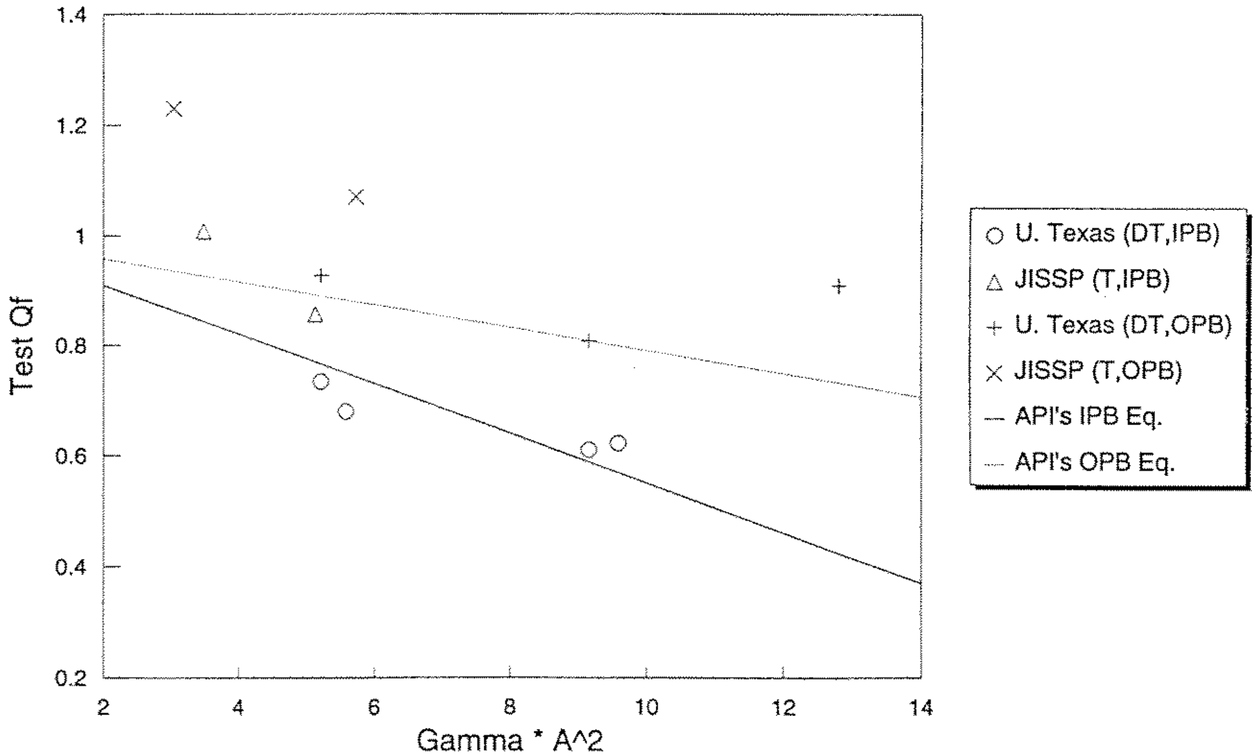


Figure 3.5.16 Chord load effects on T/DT moment loaded joints Q_f vs γA^2

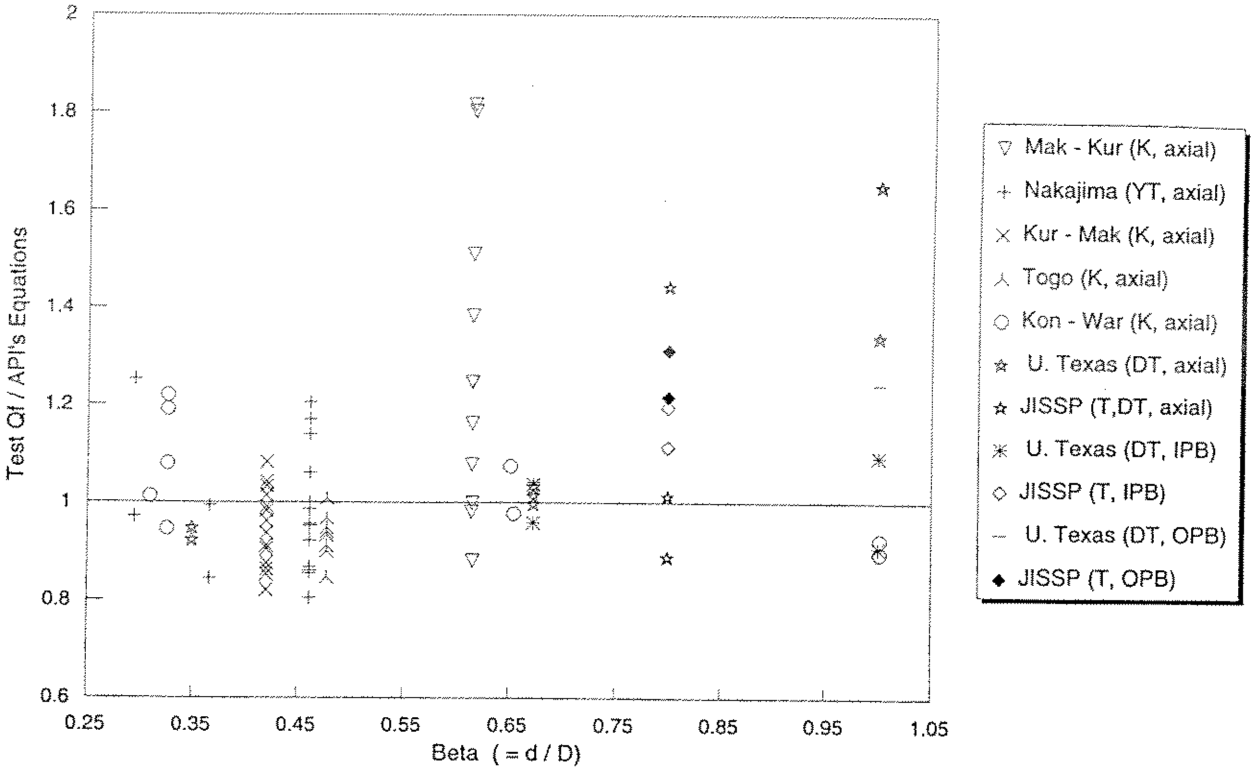


Figure 3.5.17 Effects of chord load and β on axially loaded joints

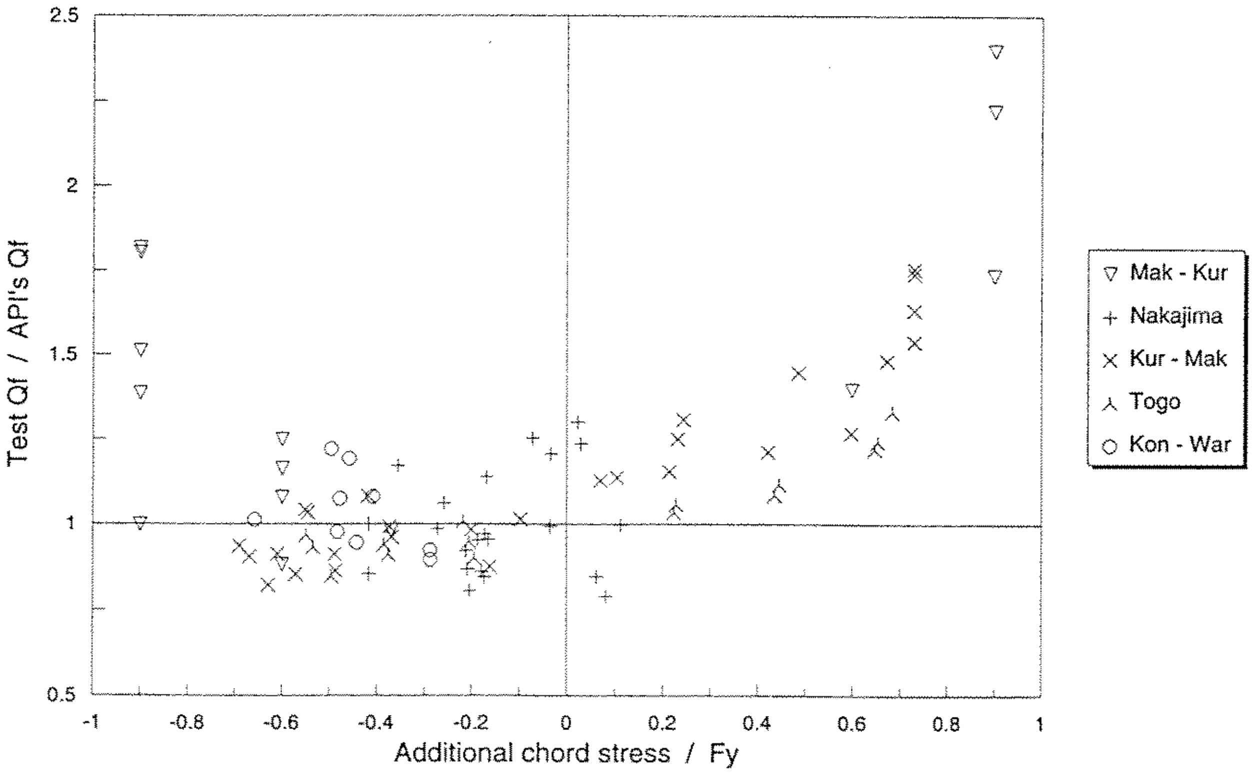


Figure 3.5.18 Effects of compressive chord load (+ve) and tensile chord load (-ve) on balanced axially loaded K joints

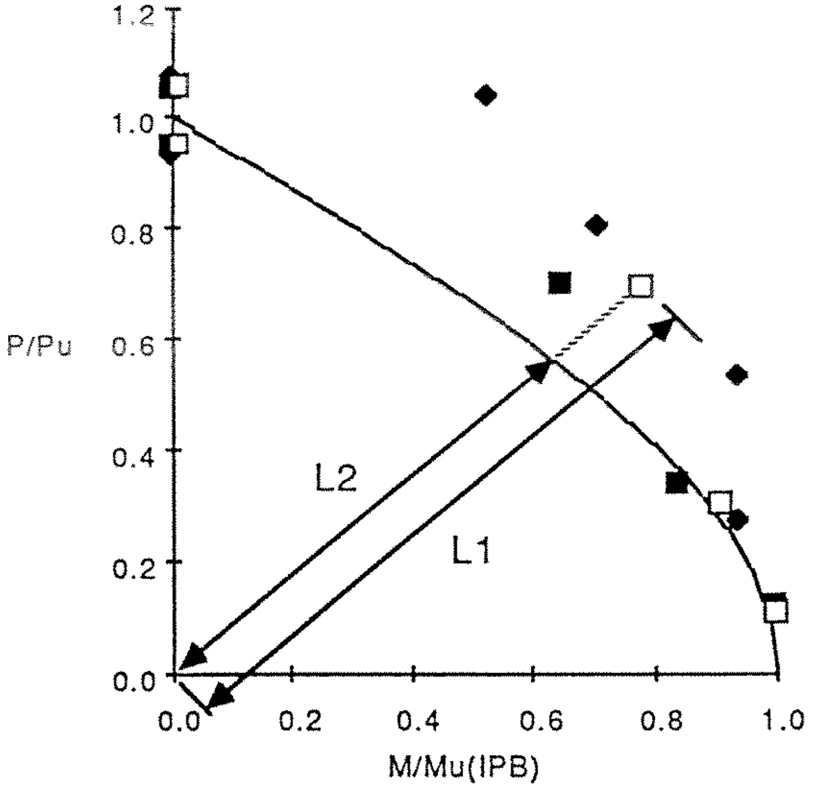


Figure 3.5.19 Definition of the parameter X (= L1 / L2)

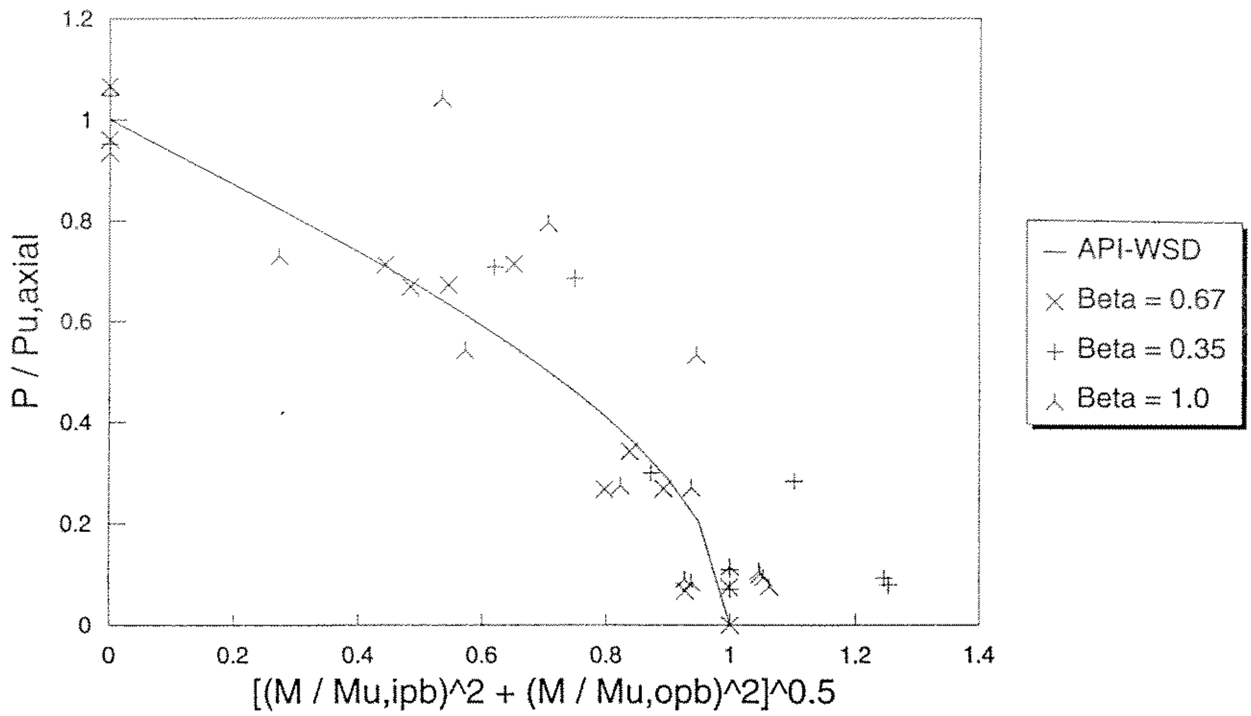


Figure 3.5.20-a Brace load interaction: Univ. of Texas Data, DT joints under combinations of compression, IPB and OPB brace loads (API-WSD arcsin equation)

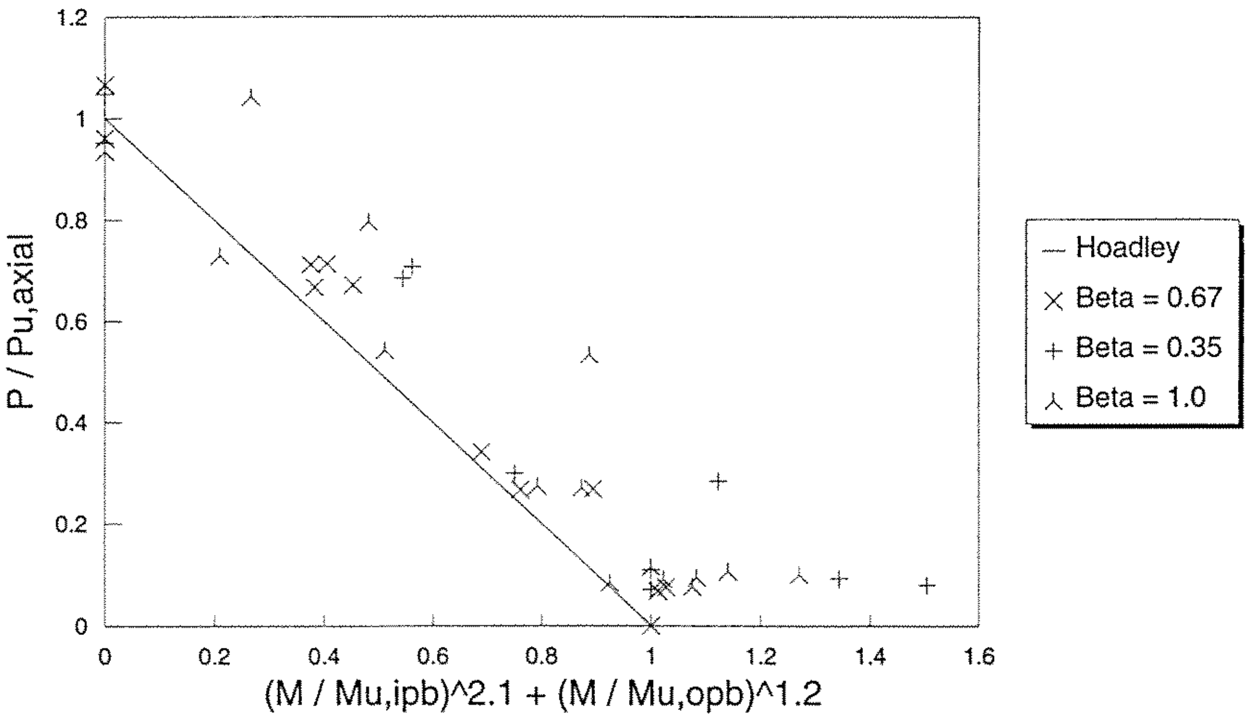


Figure 3.5.20-b Brace load interaction: Univ. of Texas Data, DT joints under combinations of compression, IPB and OPB brace loads (Hoadley's polynomial equation)

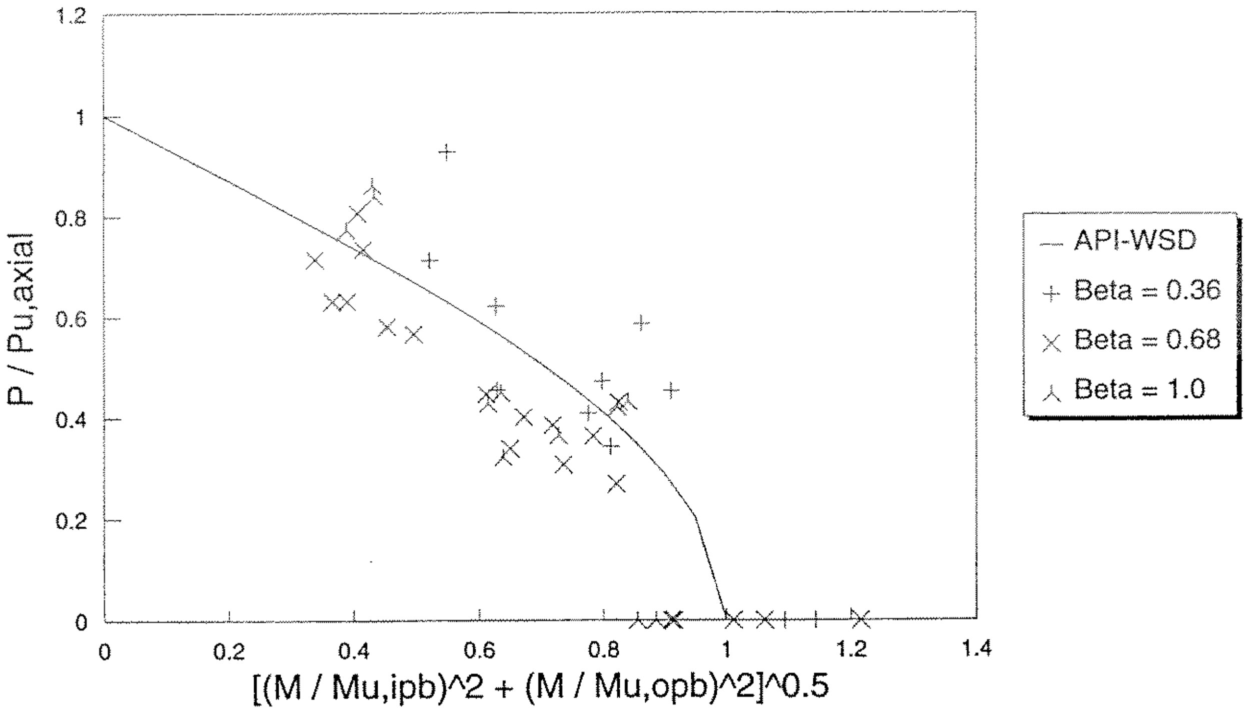


Figure 3.5.21-a Brace load interaction: TNO Data, T joints under combinations of compression, IPB and OPB loads (API-WSD arcsin equation)

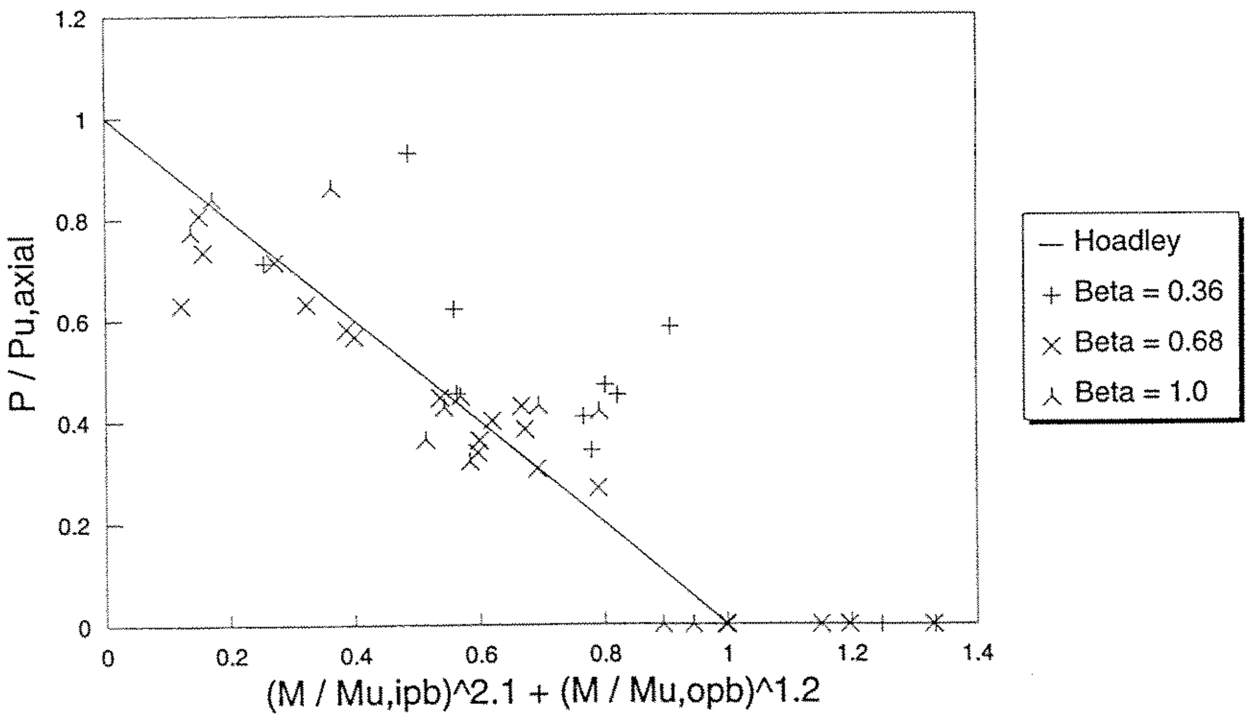


Figure 3.5.21-b Brace load interaction: TNO Data, T joints under combinations of compression, IPB and OPB loads (Hoadley's polynomial equation)

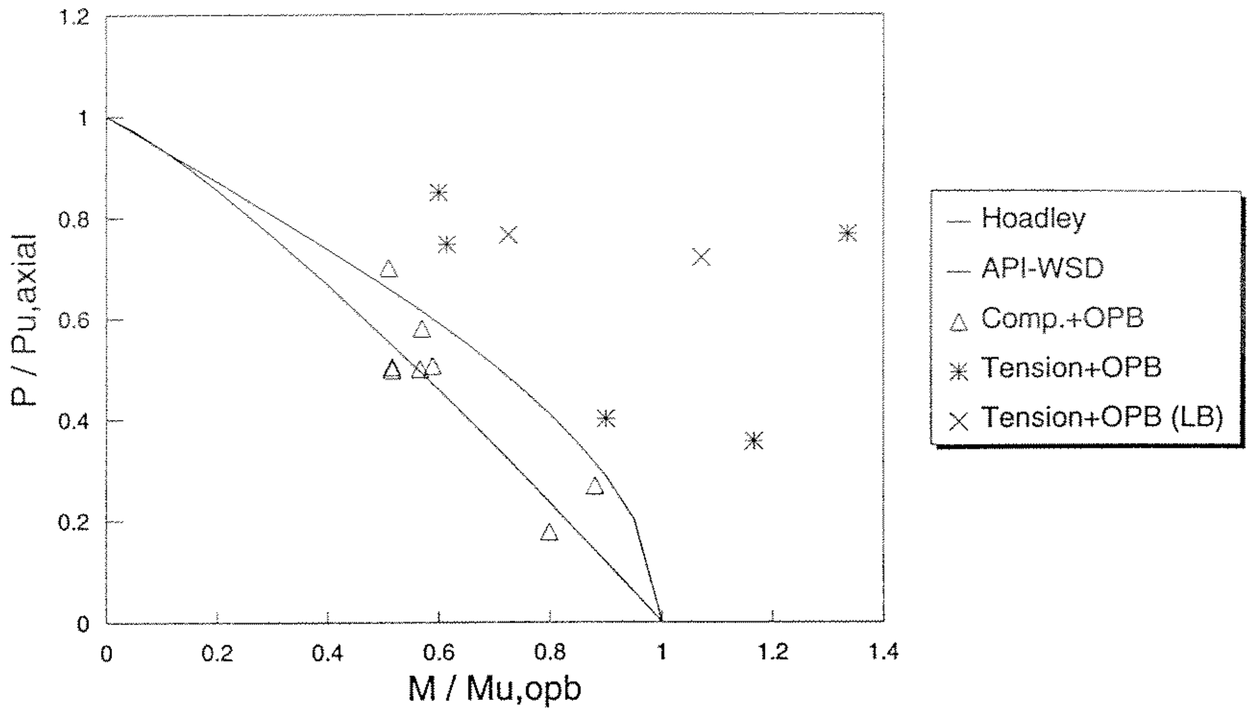


Figure 3.5.22 Brace load interaction: Makino-Kurobane Data, T joints under compression and OPB; and tension and OPB brace loads (API-WSD and Hoadley's equations)

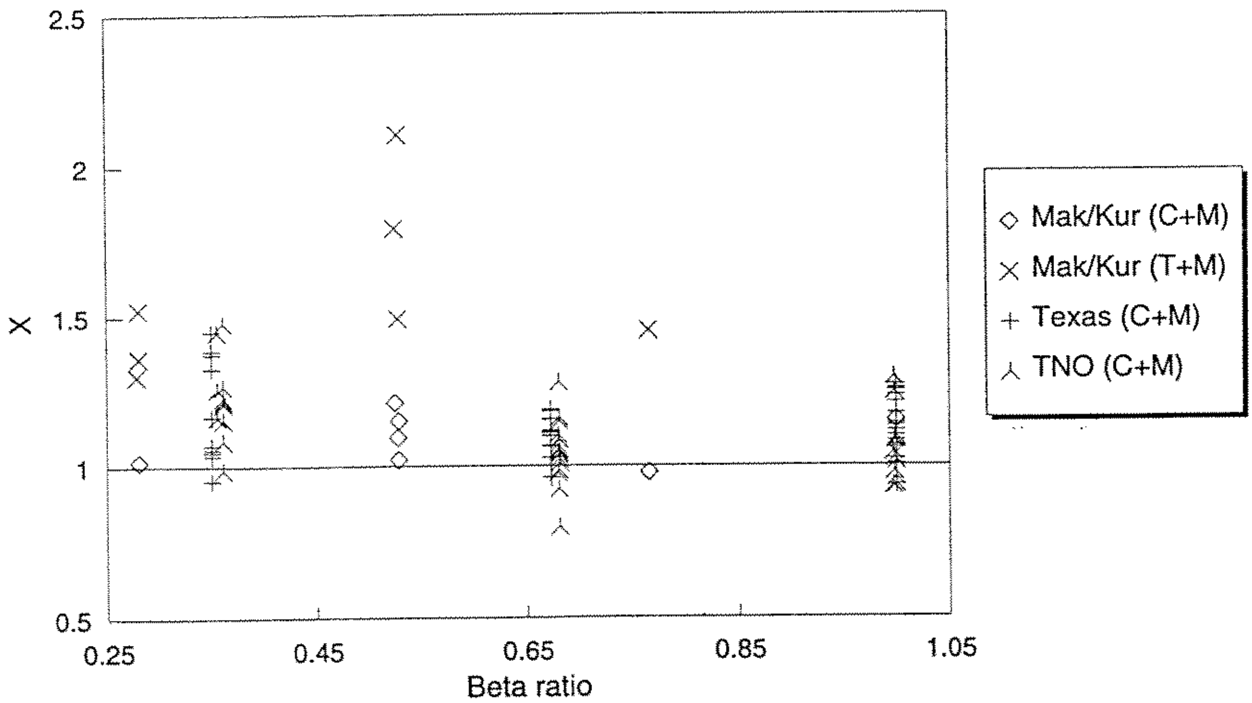


Figure 3.5.23 Brace load interaction: X values vs β (X = Distance to failure point / distance to failure surface)

4. STATIC STRENGTH OF OVERLAPPING UNIPLANAR JOINTS

4.1 General

A uniplanar overlapping joint is defined as a joint with all brace members in a single plane, in which the brace members intersect each other as well as the chord. Thus, the applied load is partially transferred from one brace to the other through their common weld. This is illustrated in Figure 4.1 which shows an overlapping K joint.

Overlapping joints are the result either of congestion at a joint or of design requirement, for instance when increased static strength is needed. In particular, overlapping joints allow thin chord sections to be used efficiently, without joint cans, since the chord is required to carry only a part of the load. However, it is customary to avoid overlapping joints as their use results in increased fabrication effort.

Due to the general lack of data on the static strength of overlapping joints, these are usually designed using simplified semi-analytical models which may be based on approximate limit load analyses such as described by Marshall (1992). The AWS and API code provisions for axially loaded overlapping joints are founded on a simple model proposed by Marshall and Toprac (1974), who report that this is based on 'a crude ultimate strength analysis, in which the punching shear capacity for that portion of the brace reaching the main member and the membrane shear capacity of the common weld between braces are assumed to act simultaneously' (Figure 4.2). Thus, a designer may check the joint for transfer of the load perpendicular to the chord member by considering the resistance afforded by the partial joint between the chord and the portion of the overlapping brace which intersects the chord surface, in addition to the membrane shear resistance of the overlap weld or of the adjacent brace wall if smaller (Section 4.2.1). The loads parallel to the chord are carried by the brace/chord intersection weld and hence the weld and brace wall thicknesses are designed to transmit this load.

4.2 Review of Existing Design Guidance

Several design codes provide formulae or general comments concerning the design of overlapping joints. General design aspects, e.g. relating to format or definition of design strength and safety factors, or to effects of combined loading, are described in connection with simple joints in Section 3.2. This section is restricted to reviewing the clauses dealing specifically with overlapping joints.

4.2.1 API-RP2A (WSD and LRFD, 1993)

The guidance provided in API-WSD is based on either the punching shear or the nominal load formats, whereas the corresponding guidance in API-LRFD is based on the nominal load format only. Since both formats are intended to be equivalent, and the main difference between API-WSD and API-LRFD is in terms of presentation, only the API-WSD guidance based on the nominal load format is reviewed here.

Overlapping joints are defined as those joints '*in which brace moments are insignificant and part of the axial load is transferred directly from one brace to another through their common weld*'. The allowable axial load component, in the overlapping brace, perpendicular to the chord is required not to exceed

$$P_a \sin\theta_{OL} \frac{l_1}{l} + 2 V_{wa} t_w l_2 \quad \text{(WSD: nominal load format)}$$

where

P_a = allowable axial load as defined in connection with simple joints.

l_1 = circumference for that portion of the brace which contacts the chord (actual length)

l = circumference of brace contact with chord, neglecting presence of overlap

V_{wa} = AISC allowable shear stress for weld between braces

t_w = the lesser of the weld throat thickness or the thickness t of the thinner brace.

l_2 = the projected chord length (one side) of the overlapping weld, measured perpendicular to the chord

The basis of this strength model is outlined in Section 4.1 and some of the terms used are illustrated in Figure 4.3 (4.3.2-1 in API-RP2A).

In addition, the following general guidelines are given:

- *The overlap should preferably be proportioned for at least 50% of the perpendicular component of the acting load.* The basis of this recommendation, common to most codes, is explained by Marshall (1992) as follows: Since the overlap is a much stiffer load path than the radially flexible chord shell, it will try to carry much of the load at elastic load levels. If this element is weak it may lack the ductility required to avoid failure before the rest of the connection catches up.

- *Where the braces carry substantially different loads and/or one brace is thicker than the other, the heavier brace should preferably be the through brace with its full circumference welded to the chord.*

- *In no case should the brace wall thickness exceed the chord wall thickness.*

- *Moments caused by eccentricity of the brace working lines and exceeding that in 4.3.1(c) (ie. $|e| > D/4$) may be important and should be assessed by the designer.*

It should be noted that no specific guidance on quantifying P_a (i.e. whether it represents the axial strength of a simple Y or a simple K joint), or formulae for estimating the lengths l, l_1, or l_2 are provided. In addition, no guidance on the design of the through brace is given.

4.2.2 AWS (1994)

Guidance provided in this code for the design of overlapping joints is broadly identical to that given in API-RP2A with exception of the following:

- The allowable axial load component perpendicular to the chord, $P_\perp$, is given in the punching shear format only. The first term in $P_\perp$ (equivalent to $P_a \sin\theta l_1/l$ in the API-RP2A nominal load expression) is $V_p T l_1$, where V_p is specified as the *'allowable punching shear for the main member as K-connection (α = 1.0)'*. The expression of α for a K joint classification is (1.0 + 0.7 g/d) which is equal to 1.0 only if g = 0.0. In other words, it is implied that V_p is quantified assuming a K joint classification with g = 0.0.

- It is not specified explicitly whether the guidance applies to the overlapping brace or to the through brace.

In addition the following checks are required:

- *The allowable combined load component parallel to the chord axis shall not exceed $V_w t_w \Sigma l_1$, where V_w is the allowable shear stress for the weld between braces; t_w is the lesser of the weld effective throat size or the thickness of the thinner brace; and Σl_1 is the sum of the actual weld lengths for all braces in contact with the chord.*

- *Net transverse load on the combined footprint shall satisfy the clauses relating to static strength of simple T/Y and gap K joints.*

- *Minimum weld size for fillet welds shall provide effective throat of 1.0t for F_y < 40 ksi and 1.2t for F_y > 40ksi, where F_y is the yield strength of base metal.*

4.2.3 CIDECT (1991)

The CIDECT code is unique in that it adopts a single formulation for YT/K joints which accounts for both gap and overlapping joints. The strength of these is estimated by inserting the gap in the strength assessment equation, as a positive value for gap joints, and as a negative value for overlapping joints (Section 3). The equation is based on a large test database which was assembled and analysed by Kurobane and co-workers (Ochi et al 1984). It is not stated whether the formula applies to the overlapping or to the through brace. However, tests from the overlapping joint database (Section 4.4), and which together with other Japanese data are believed to form the bulk of the Kurobane/Ochi database, were performed with the through brace loaded in compression. Given that failure is generally associated with the compression brace, it may be inferred that the equation derived on the basis of these tests applies to the through brace.

To avoid interaction between brace local buckling and joint strength, the code recommends to limit the joint strength efficiency by the compression brace for high diameter to wall thickness ratio (d/t). This limit is expressed as follows:

$$\frac{N^*}{A_b F_{yb}} \leq 0.22 \left[\frac{E\,t}{F_{yb}\,d}\right]^{0.6}$$

where N^* is the design compression strength (= characteristic strength / 1.1); F_{yb}, A_b, t, and d are properties of the brace representing, respectively, the design yield strength, the cross section area, the thickness, and the diameter; and E is the modulus of elasticity.

The above limit appears to be recommended for all types of joints, but it is noted that with regard to member buckling it will not be frequently critical.

Examination of the reference on which the limit is reported to be based (Kurobane et al 1989) and a more recent publication by Kurobane and Ochi (1994) reveals that an equation was proposed by Kurobane and co-workers to deal with local buckling of compression braces in K joints only, subject to balanced axial loading. The equation, different to the formula given in CIDECT, is as follows:

$$F_{lb} = 0.217\ \alpha^{1/4}\ (F_{yb}+F_{sb})$$

where F_{lb} refers to the local buckling strength and F_{sb} refers to the shell bending strength (quantified using the basic K joint strength equation given in Section 3), both being represented in terms of the average stress on the cross section of the compression brace; and $\alpha = Et/(F_{yb}d)$.

This equation is based on data from cold-finished tubes (ie. $F_y/F_t >= 0.8$).

The strength interaction between F_{lb} and F_{sb}, evident in the above equation, is explained by Kurobane as follows: 'The compression brace sustains a secondary bending moment with greater compression on the toe side than on the heel side owing to uneven support given to the brace by the chord and tension brace. When the load approaches the brace local buckling load, the bending moment at the brace end decreases because the moment is redistributed owing to local buckling or yielding, and then the compression brace carries a further increase of compression load. When the shell bending failure mode begins to appear, however, the redistribution of bending moment is prevented'.

however, the redistribution of bending moment is prevented'.

4.2.4 CSA (1992)

Guidance in the Canadian Code takes the form of an empirical formula which, with the exception of the gap factor, is identical to the formula adopted for simple gap K joints (Section 3). The basis of the formula is not described and It is not stated whether it is applicable to the overlapping brace or to the through brace.

The gap factor for overlapping joints, designated here as Q_g, is as follows:

$$\frac{1+2.1\,|g|/D}{1+0.8\,|g|/D} \quad \text{for } |g| \leq 0.4D$$

if $|g| > 0.4D$, then for the purposes of computing Q_g, g is to be taken equal to -0.4D.

In addition, the following general guidelines are given:

- In K-joints with overlapping braces, the wall thickness of a brace shall in no case exceed the chord wall thickness. The through brace shall have its full circumference welded to the chord. The wall thickness of the through brace shall not be less than the wall thickness of the overlapping brace.
- If the resistance of the weld joining the overlapping braces in a K-joint is less than 50% of the brace axial load component (normal to the chord axis), the analysis of the joint shall identify the loads carried in the several load paths, and shall also consider the deformations associated with these loads.
- Resistances of overlap joints in which bending moments exist at the ends of bracing members shall be calculated by lower bound analysis or other rational methods of analysis, or shall be determined by experimental tests.

4.2.5 DnV (1993)

Guidance provided in this code for the design of overlapping joints (with no gussets, stiffeners or diaphragms) is broadly identical to that given in API-RP2A with exception of the following:

- Unlike API-RP2A, the first term in the expression representing the design (factored or allowable) axial load component perpendicular to the chord, does not include $\sin\theta$. It is not clear if this omission is deliberate or whether it is intended that $\sin\theta$ is considered in deriving the term P_D (corresponds to P_a in API-WSD).
- It is not specified explicitly whether the guidance applies

to the overlapping brace or to the through brace.

- v_{wa}, the design (factored or allowable) shear stress for the weld between braces, is replaced by $\sigma_{Fd}/\sqrt{3}$, where σ_{Fd} is the design yield stress of the chord.

4.2.6 HSE (1990)

No strength formulae specific for overlapping joints are given in the code. Rather, the following is stated: '*Insufficient data is available to develop any guidance. The behaviour of overlapping joints and an assessment of the available test data may be found in OTH 89 308 and CIRIA UEG UR33 1985. Procedures for the determination of characteristic strength should be agreed with the Certifying Authority. Each overlapping joint should be treated as a separate case and the characteristic capacity of each intersection for each load type should be determined. This capacity can be determined on the basis of available test data where appropriate or through application of rigorous engineering mechanics. The application of engineering mechanics requires the determination of intersection lengths L_1, L_2 and L_3 as defined in Figure A21.7* (Figure 4.4). *In lieu of precise measurements, the intersection length formulae given in Figure A21.7 can be used.*

Overlapping joints depend on the combined action of all braces. Accordingly consideration should be given to checks of the combined moment from all braces on the combined footprint.

For heavily overlapping braces (ie. $L1/L2 \leq 0.5$) the intersection between overlapping brace and the through brace should also be checked separately with the through brace taken to be a chord member under a Y classification.

HSE's Background Document OTH 89 308

Section 8 in the document, contains an assessment of the overlapping joint test data compiled up until the mid 1980s. In this assessment, the through brace capacity and the overlapping brace capacity are treated separately. The former refers to the capacity obtained under compression in the through brace and tension in the overlapping brace, while the latter corresponds to the opposite loading arrangement.

A screened database consisting of a total of 16 YT joint tests was compiled. These are reported to represent the balanced axial loading case with compression applied to the through brace. A statistical analysis of the data enabled a characteristic strength equation to be developed providing a smooth transition between the capacity of gap and overlapping YT joints. However, a recent study performed as part of the Tubular Joints Group activities (BOMEL 1992) revealed some anomalies in the database used in the aforementioned assessment. These include errors in the reported values of yield stress and degree of overlap, relating to tests by Bouwkamp which had not been quoted from the source document. The awareness of these anomalies, which did not affect the general validity of the approach advocated in OTH 89 308, was reported in Offshore Research Focus (No. 94, 1993).

With regard to balanced axial loading with compression applied to the overlapping brace, it is reported that no data were available to investigate this loading case. However, the approach adopted in API-RP2A based on the model proposed by Marshall and Toprac, is described and approximate formulae to quantify the lengths L_1, L_2 and L_3 are reported in detail (corresponding respectively to l_1, l and $2*l_2$ of the API-RP2A formula). Figure 4.4, reproduced from the HSE Guidance Notes, includes illustrations and formulae of the three lengths. It should be noted that L_3 is illustrated as an arc length while its formula suggests that it represents the length of the vertical projection of the common weld. In addition, the L_3 expression does not reduce to zero as the overlap becomes very small which is an anomaly.

4.2.7 NPD (1990)

Guidance provided in this code for the design of overlapping joints (with no gussets, stiffeners or diaphragms) is broadly identical to that given in API-RP2A with exception of the following:

- It is stated that the guidance is valid only for K joints, where compression in a brace is essentially balanced by tension in brace(s) in the same plane on the same side of the joint. However, it is not specified explicitly whether the guidance applies to the overlapping brace or to the through brace.

- The design axial load corresponding to P_a in API-WSD is defined as N_k/γ_m, where N_k is the 'characteristic axial load capacity of brace', and γ_m, the partial material safety factor, is equal to 1.15.

- v_{wa}, the design shear stress for the weld between braces, is replaced by $(f_y/\sqrt{3})/\gamma_m)$, where f_y is defined simply as the yield stress, and γ_m, the partial material safety factor, is equal to 1.15.

4.3 Review of Other Published Information

4.3.1 Dexter et al (1994)

The authors report the findings of a non linear FE study of the static strength of overlapping K joints. The FE models were calibrated using Japanese experimental data (Kurobane et al 1986) with the following geometrical properties: β = 0.76, γ = 13.7, τ = 0.7, ζ = 0.14, -0.12 and -0.42. These joints had failed due to shell bending of the chord and/or brace local buckling.

The above matrix was increased by modifying parameters relating

- For intermediate degrees of overlap, applying loads to both braces and restraining both chord ends produces failure loads which are slightly lower than those achieved under the alternative arrangement, where one brace is loaded (the other is subject to the reaction) and only one chord end is supported (Figure 4.5-a). These results were obtained from models which did not include the hidden weld.

- For intermediate degrees of overlap with the through brace loaded in compression, an increase in capacity of approximately 5% was observed when the hidden weld was present (Figure 4.5-b).

- Joint models, where the overlapping brace was subject to compression and the through brace was subject to tension, failed at slightly higher loads than those achieved with the reverse loading except for the fully overlapped case (g = -190mm). The data are shown in Figure 4.5-c.

- The above findings were obtained for the γ = 13.7 geometry. When γ was increased to 30.0, a different relationship between degree of overlap and strength was observed (Figure 4.5-d). It is suggested that this difference is caused by changes in the failure modes in comparison with those predicted for γ = 13.7. However, insufficient data on the failure modes are reported and no comparisons with design guidance are performed.

4.3.2 Healy (1994)

This reference reports the most comprehensive analytical study, on the strength of overlapping joints, published to date. The scope covers the generation of data for the balanced axial and IPB loading cases in addition to an evaluation of the design guidance of API RP2A (20th Ed. 1993) and CIDECT (1991). The following joint configurations were considered:

Configuration	β	γ	τ	θ	F_{yb}/F_{yc}
1	0.95	24	1.0	60°	1.0
2	0.95	15	1.0	60°	1.0
3	0.5	24	1.0	60°	1.0
4	0.5	15	1.0	60°	1.0
5	0.5	24	0.5	60°	1.0
6	0.5	24	1.0	60°	0.72

Table 4.1 Properties of the numerical test matrix (Healy 1994)

For each configuration three gap ratios, expressed as $(g/d)\sin\theta$ and approximately equal to -0.5, -0.2 (overlap) and 0.2 (gap), were analysed.

Three loading modes and four combinations of boundary conditions and loading modes were considered in relation to the IPB and balanced axial cases respectively (Figures 4.6 and 4.7). The IPB modes depending on the direction of application of the in-plane bending moments are referred to as aligned, closing or opening moments. While the axial modes relate to the applied boundary conditions and to whether the overlapping or through brace is subject to compression.

In all analyses, the hidden weld was assumed present, ie. nodes along the hidden intersection between the through brace and the chord were fully connected.

Results of the IPB analyses: The computed IPB capacities were compared to predictions based on the author's own IPB formula (Section 3.3) and the brace yield and plastic moment capacities. The following conclusions were drawn:

- Regardless of load type, the design capacity of gapped K joints with a large gap may be computed by considering the K joint as an equivalent T/Y joint.
- The design capacity of highly overlapped K joints subject to opening moments may be conservatively taken as the lesser of the brace plastic moment and the capacity computed by considering the K joint as two independent T/Y joints.
- The design capacity of highly overlapped K joints subject to closing moments may be conservatively taken as the lesser of the capacity computed by considering the through brace as the chord and the overlapping brace as the brace in an equivalent T/Y joint and the capacity computed by considering the K joint proper as an equivalent T/Y joint.
- Highly overlapped K joints subject to aligned moments may be designed as an equivalent T/Y joint provided that the sum of the brace moments is considered the design load.
- The computed capacities for a number of configuration and loading modes were determined based on the deformation limit criterion (Yura et al 1980). In such cases, it is noted that cracking is a distinct possibility and that it would be useful if the deformation limit were calibrated to prevent cracking.

Results of the balanced axial load analyses: The computed axial capacities were compared to predictions based on the following:

- The API Model (Section 4.2.1) with P_a evaluated for a K joint configuration, and the gap factor Q_g assumed to be applicable for overlapping joints, ie. for negative gaps thus allowing its value to exceed 1.8.
- The CIDECT equation for chord shell bending failure (or chord plastification) in conjunction with the brace local buckling check as reported in the code (ie. brace local buckling stress $F_{lb} = 0.22 \sqrt{\alpha}\, F_{yb}$, where α is defined as $Et/(F_{yb}d)$).

Figures 4.8 illustrate the computed capacities normalised by the API-RP2A T/Y joint compression capacity. The following conclusions were drawn:

- For joint configurations that are controlled by local brace buckling in the overlapped region, a flat top distribution of capacity with increasing overlap exists. In the absence of local brace buckling, a nearly linear increase in capacity with increasing overlap is observed.

- The CIDECT capacity captures the flat top distribution for local brace buckling, but often does so due to the influence of the factor related to γ and gap (Q_g) rather than the local brace local buckling limit. As a result, the CIDECT capacity also predicts a flat top in the absence of local brace buckling. The API capacity captures the linear increase in capacity when local brace buckling does not control, but exhibits no flat top because local brace buckling is not addressed in the guidance.

- The CIDECT local brace buckling limit fails to predict buckling in the overlapped region of two configurations where it occurs analytically. The CIDECT limit does predict buckling correctly in the overlapped region of a third configuration, but the CIDECT chord plastification capacity correctly and conservatively predicts the flat top distribution in the absence of the limit.

- The CIDECT local brace buckling limit fails to account for instances where a sudden post-peak drop off may be expected. A more stringent safety factor may be preferable in the latter case, but situations where it is applicable would have to be identified.

- Given that the hidden weld is present, the capacity of overlapped K joints with the overlapping brace in compression generally exceeds the capacity with the through brace in compression. It appears that when the overlapping brace is in compression, local brace buckling is less severe, and this lesser tendency to buckle is thought to be the difference. However, the CIDECT local brace buckling limit takes no notice of brace hierarchy.

- There is no numerical evidence that local brace buckling occurs in the gapped regions of the analysed configurations. However, local brace buckling in the gapped region is reported for joints with similar d/t ratio by Kurobane et al (1986). The nature of this buckling may not be fully understood and it may be related to local member buckling.

- The difference between "single" and "double" boundary conditions, when an attempt is made to model frame conditions by restraining the lateral movement in the brace (Figure 4.7), is negligible.

It should be noted that the CIDECT local brace buckling limit applied by the Healy is different to the original model recommended by Kurobane et al (1986 and 1994) and described in connection with the CIDECT guidance in Section 4.2. Application of the original Kurobane model may have led to different conclusions. This issue is addressed in Section 4.4 where the experimental database is evaluated using the equations of API-

RP2A, CIDECT and CSA with and without Kurobane's local brace buckling model.

4.3.3 Van den Valk (1991)

The author reports the findings from a series of finite element analyses on β = 1.0 heavily overlapped K joints where the through brace was connected to the chord along its full circumference. The joints were subjected to balanced axial loading under boundary conditions representing the constraints in isolated tests, and within the confines of a frame. The conclusions may be summarised as follows:

- the strength of the joint within the frame was slightly higher (by approximately 2%) than its strength under isolated test conditions, where the braces were constrained to deflect along their axes.

- the strength of the joint when the overlapping brace was subject to compression was 10% higher than when the overlapping brace was the tension member.

- Comparison of the computed K joint strength with the YT joint data in the HSE database (OTH 89 308) shows that the strength increase due to overlap is much less significant for the K joint considered in this study than for the YT data. This discrepancy (noted prior to discovering the anomalies in the YT joint database outlined in Section 4.2.6) was attributed to effects of joint geometry and configuration.

- the author recommends that the approximate engineering mechanics approach (eg. of API-RP2A) continues to be adopted in preference to the strength levels implied by the YT joint database.

4.3.4 Approximate lengths formulae

Approximate length formulae have been derived in order to facilitate the application of the approximate design approach recommended in a number of codes (eg. API-RP2A, AWS, DnV, NPD).

The derivation, described in Appendix A3.5, is based on the following assumptions:

- The braces are of equal diameters.

- The footprints are of elliptical shape which is described by the mathematical expression of an ellipse.

Formulae for the three lengths are as follows:

$$l = \pi \, d_{OL} \, K_a$$

$$l_1 = d_{OL} \, K_a \left(\pi - \arccos \lambda\right)$$

$$l_2 = \frac{|g|}{\mathrm{cotan}\,\theta_{TH} + \mathrm{cotan}\,\theta_{OL})} + \frac{D}{2}\left(1 - \sqrt{1 - \beta^2 (1 - \lambda^2)}\;\right)$$

where

$$K_a = \frac{1 + \dfrac{1}{\sin\theta_{OL}}}{2}$$

$$\lambda = 1 - \frac{2|g|}{\dfrac{d_{OL}}{\sin\theta_{OL}} + \dfrac{d_{TH}}{\sin\theta_{TH}}}$$

Θ_{OL} and Θ_{TH} are the overlapping and through brace angles respectively; d_{OL} and d_{TH} are the overlapping and through brace diameters; and g is the distance between the weld toe of the through brace and projected weld toe of the overlapping brace.

It should be noted that l, l_1, and l_2, defined according to the Nomenclature of API-RP2A and AWS (Figures 4.2 and 4.3), correspond to L_2, L_1 and $L_3/2$ of the HSE Nomenclature (Figure 4.4).

4.4 Database on Overlapping YT/K Joints

All known available experimental data on the static strength of overlapping joints have been considered. The resulting full database including the screened set is given in Appendix A3.4. All the tests were performed under nominally balanced axial loading. No data on other loading modes, eg. IPB or OPB are available. In addition to the failure modes reported in connection with simple joints in Section 1.3, overlapping joints may fail by local buckling of the compression brace near the intersection (Kurobane et al 1986).

In order to maintain consistency between the simple joint and overlapping joint databases the same screening criteria have been adopted for both datasets (Section 3.4) except that the limit on τ has been reduced from 1.2 for simple joints to 1.1 for overlapping joints. This is justified on the basis of the observed enhancement in strength for $\tau > 1.1$, which is not surprising given that a part of the applied load is transferred directly from one brace to the other. Thick braces allow higher loads to be transferred regardless of the chord, and increase the compression brace resistance to local buckling, a failure mode which may be critical especially for overlapping joints.

Difficulties have been encountered with regard to tracing information on a number of parameters which are known to affect the capacity of overlapping joints. These parameters, referred to in some but not all source documents, include:

- Data on failure modes, especially whether or not local brace buckling adjacent to the overlap region occurred or interacted with shell bending failure in the chord. This uncertainty applies particularly to a considerable dataset reported in Japanese by Togo (1967) and is due to the lack of an English translation.

- Whether or not the through brace is welded to the chord along its full circumference, ie, whether or not the hidden weld is present. Limited data on the effects of this parameter are reported in Section 4.3 based on finite element investigations.

- Whether compression loading is applied to the overlapping or to the through brace. Limited data on the effects of this parameter are reported in Section 4.3 based on finite element investigations.

The screened data are taken from the tests of Fumagalli and Pugno (1985), Veritec (1993), de Koning and Wardenier (1981), Kurobane et al (1980), Kurobane et al (1986), Ochi et al (1981), and Togo (1967). Differences in the testing arrangements and in parameters relating to geometrical and material properties are bound to introduce scatter into the data. The following differences may be noted:

- In the Ochi and Kurobane tests the through brace was in compression and welded to the chord around its whole circumference.

- In the de Koning tests the overlapping brace was in compression suggesting a higher capacity (Section 4.3) but the through member was not fully welded to the chord.

- The Fumagalli specimens were tested integrally within a lattice beam whereas in most of the other tests one chord end was free.

- The ratio F_y/F_t for most of the joints reported by Kurobane et al (1986) is very close to 0.9. Although this is unrepresentative of traditional offshore materials the data are considered particularly valuable because failure in most of the tests is reported to be due to local brace buckling.

4.5 Assessment of Design Guidance

Scope

This section considers test results for a total of 54 K joints (including 32 tests reported by Togo 1967) and one YT joint (Appendix A3.4).

Evaluation of design equations

The ratio P_{meas}/P_{pred} has been evaluated for all the screened data and plotted versus $g*\sin\theta/d$ in Figures 4.9 to 4.11. Two estimates of P_{pred} have been calculated, $P_{pred,1}$ and $P_{pred,2}$, depending on whether or not a local brace buckling check is performed. This is recommended by Kurobane et al (1986 and 1994) and described in connection with the guidance of CIDECT in Section 4.2. $P_{pred,1}$ refers to estimates of overlapping joint strength excluding local brace buckling and based on the equation of API-RP2A (assuming K joint classification with $Q_g = 1.8$), and the equations of CIDECT and CSA, and excluding global and partial safety factors (Section 4.2). $P_{pred,2}$ is taken as the lowest of $P_{pred,1}$ and $P_{pred,L}$, where $P_{pred,L}$ is estimated as follows:

$$P_{pred,L} = 0.217\ \alpha^{1/4}\ (A_b*F_{yb}+P_{pred,1})$$

where $\alpha = Et/(F_{yb}d)$ is the brace local buckling parameter and A_b is the cross section area of the brace (see Section 4.2).

Data representing $P_{pred,1}$ are plotted on Figures 4.9-a to 4.9-c; and data where $P_{pred,L}$ is lower than $P_{pred,1}$, ie. where the brace local buckling check governs, are highlighted on Figures 4.9-b to 4.11-b. Based on these results the following may be noted:

- The formulae of the API, CSA and CIDECT provide reasonable representations of the data although they do not embody all the relevant failure modes. The most conservative model is that of CIDECT, followed by the API. The CSA formula underpredicts the capacity for a significant proportion of the data.

- Application of the local buckling model, as described above produces results which differ from one code to another. The CIDECT formula is the least affected with strengths for only six joints predicted to be dependent on local brace buckling. This compares with 17 joints and eleven joints, respectively, in the case of the CSA and API formulae.

The results detailed in Table 4.2, indicate that at least in the case of Kurobane's dataset (Kurobane, 1986) where all the joints are reported to have failed by local brace buckling, predictions based on the API and CSA formulae incorporating Kurobane's model are governed by local brace buckling for most of the data. This is an encouraging finding which supports Kurobane's model. In addition, Figures 4.9 to 4.11 show that application of the model narrows the differences between the predicted and actual failure loads conservatively.

Reference	(1)	(2) API	(2) CSA	(3) CIDECT
Ochi	7	2	2	none
Kurobane	5	4	5	3
Togo	unknown	5	10	3
Total	-	11	17	6

(1) Number of joints reported to have failed by local brace buckling.

(2) Number of joints where local brace buckling is predicted to determine joint strength.

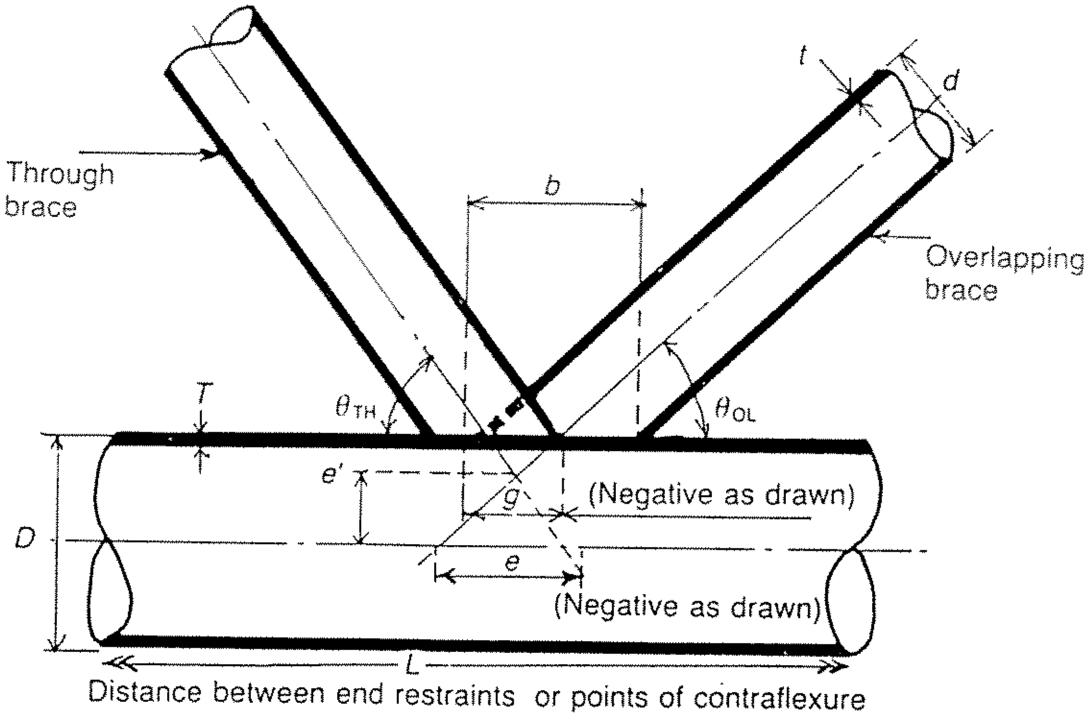
Table 4.2 Effects of application of Kurobane's local brace buckling model

4.6 Recommendations

The substantial uncertainties which surround some parameters in the overlapping joint database and affect interpretation of the data, require further attention before improved design guidance can be recommended. Finite element studies such as those reviewed in Section 4.3 offer great potentials for providing valuable data.

The formulae of the API, CIDECT or CSA may be applied for the design of axially loaded joints. However, limitations relating to effects of local brace buckling should be considered. It is recommended that the model proposed by Kurobane to allow for local brace buckling is applied as described in Section 4.5.

With regard to in-plane moment loaded joints, it is recommended that the guidance proposed by Healy (Section 4.3) are adopted at least until further data are available.



$$\alpha = 2L/D \quad \beta = d/D \quad \gamma = D/2T \quad \zeta = g/D \quad \tau = t/T$$

Figure 4.1 Geometric notation for overlapping joints

$$P \sin\theta = (v_p \cdot T \cdot \ell_1) + 2(v_w \cdot t_w \cdot \ell_2)$$

P Sin θ		($v_p \cdot T \cdot \ell_1$)		2 ($v_w \cdot t_w \cdot \ell_2$)
ALLOW-ABLE		PUNCHING SHEAR ON MAIN MEMBER		MEMBRANE SHEAR @ OVERLAP WELD

WHERE

v_p = ALLOWABLE PUNCHING SHEAR STRESS EQUATION FOR THE MAIN MEMBER

T = MAIN MEMBER WALL THICKNESS

ℓ_1 = CIRCUMFERENTIAL LENGTH FOR THAT PORTION OF THE BRACE WHICH CONTACTS THE MAIN MEMBER

AND

v_w = ALLOWABLE SHEAR STRESS FOR THE COMMON WELD BETWEEN THE BRACES

t_w = THROAT THICKNESS FOR THE COMMON WELD BETWEEN BRACES

ℓ_2 = THE PROJECTED CHORD LENGTH (ONE SIDE) OF THE OVERLAPPING WELD, MEASURED IN THE PLANE OF THE BRACES AND PERPENDICULAR TO THE MAIN MEMBER

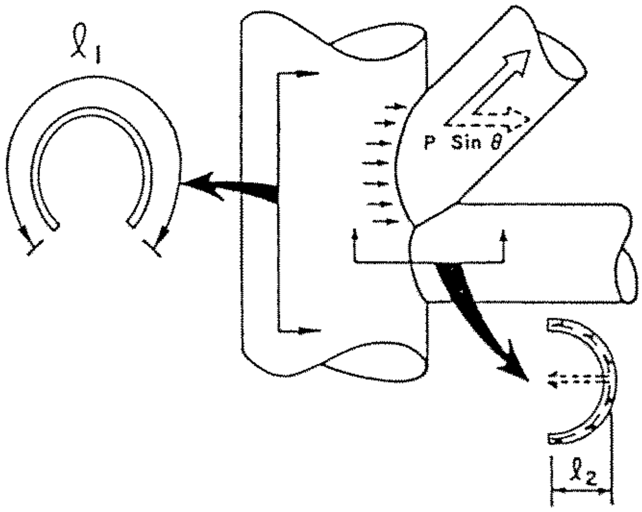


Figure 4.2 Simplified limit analysis
- transverse load check (Marshall 1992)

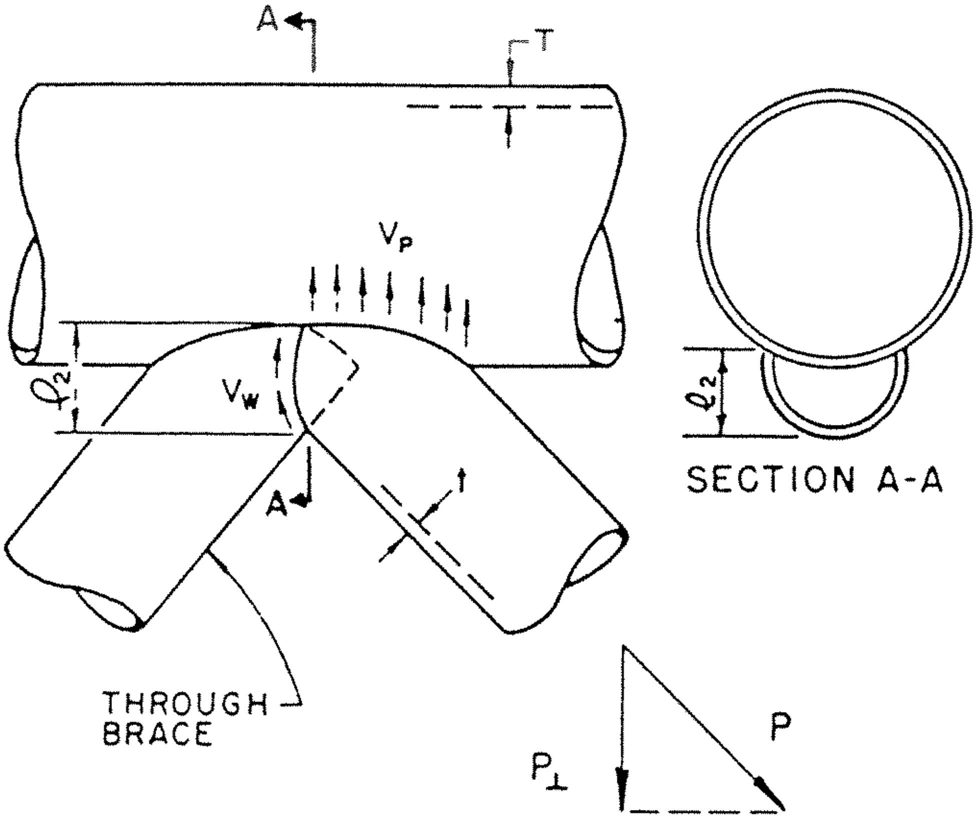
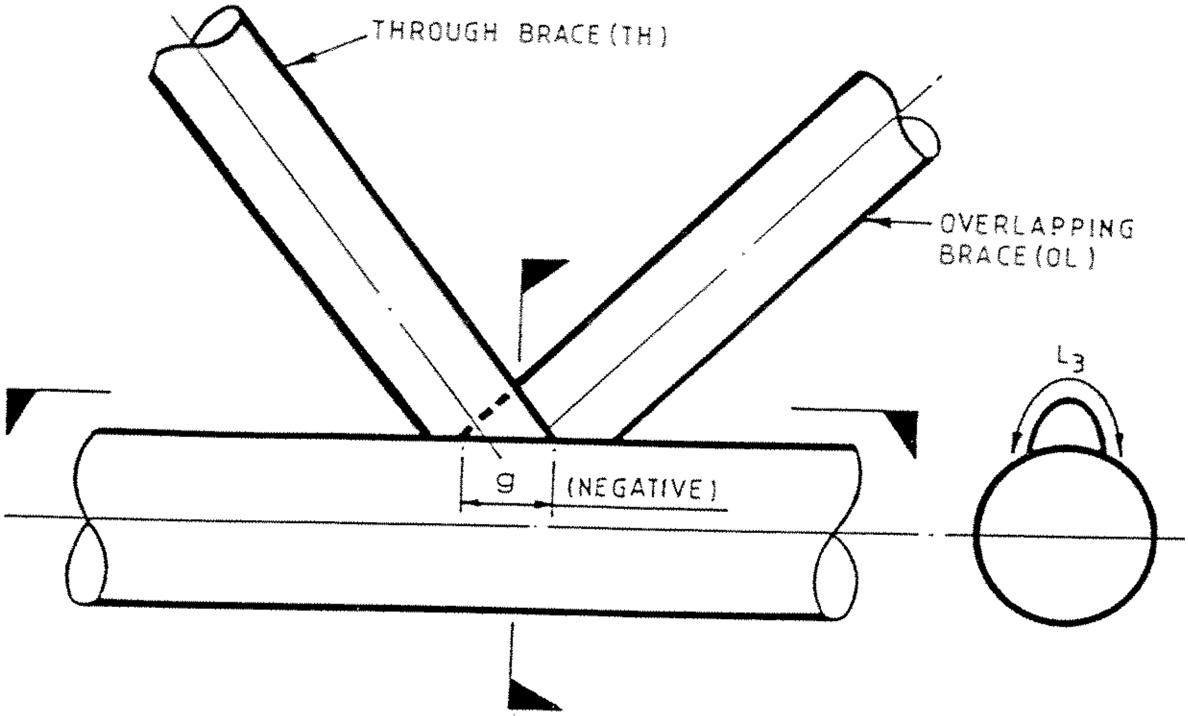
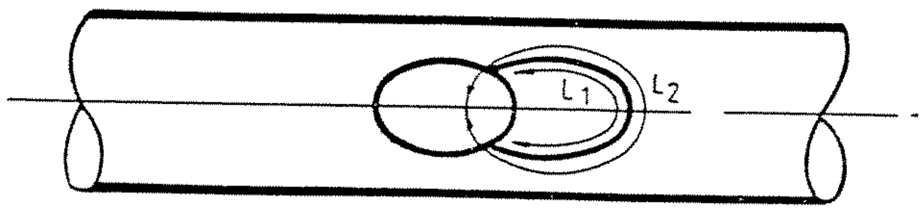


Figure 4.3 Detail of overlapping joint (API RP2A, 1993)





In the absence of precise measurements L_1. L_2 and L_3 may be approximated by the following formulae:-

$$L_1 = d_{OL} K_a \cos^{-1} \left[\frac{2 \ |g| \sin \Theta_{OL}}{d_{OL}} - 1 \right]$$

$$L_2 = \pi \, d_{OL} K_a$$

$$L_3 = \frac{2 \ |g|}{\text{cotan } \Theta_{TH} + \text{cotan } \Theta_{OL}} + D \left(1 - (1 - \beta^2)^{0.5} \right)$$

Where $K_a = \dfrac{1 + 1/\sin \Theta_{OL}}{2}$

Figure 4.4 Definition of intersection lengths for overlapping joints (HSE, 1990)

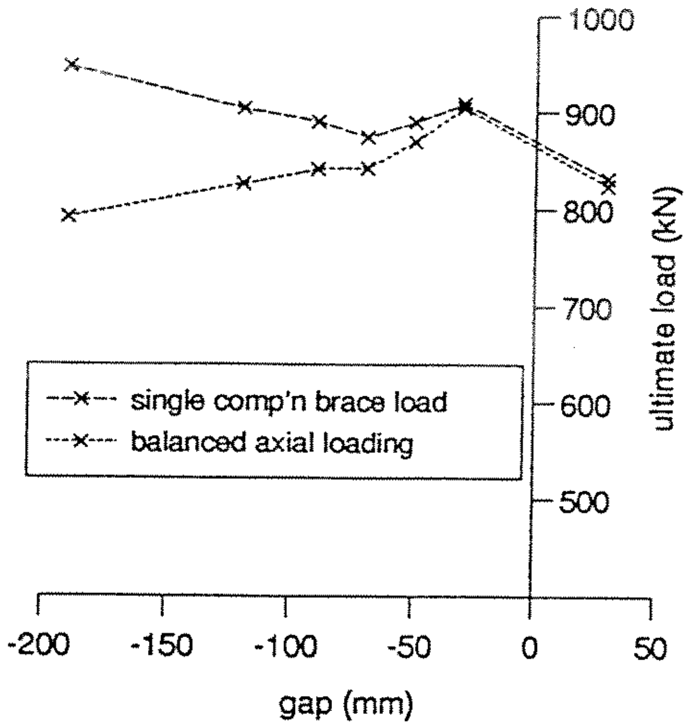


Figure 4.5-a Strength-overlap results for approximate and exactly balanced loading conditions (through brace in compression, hidden intersection sliding)

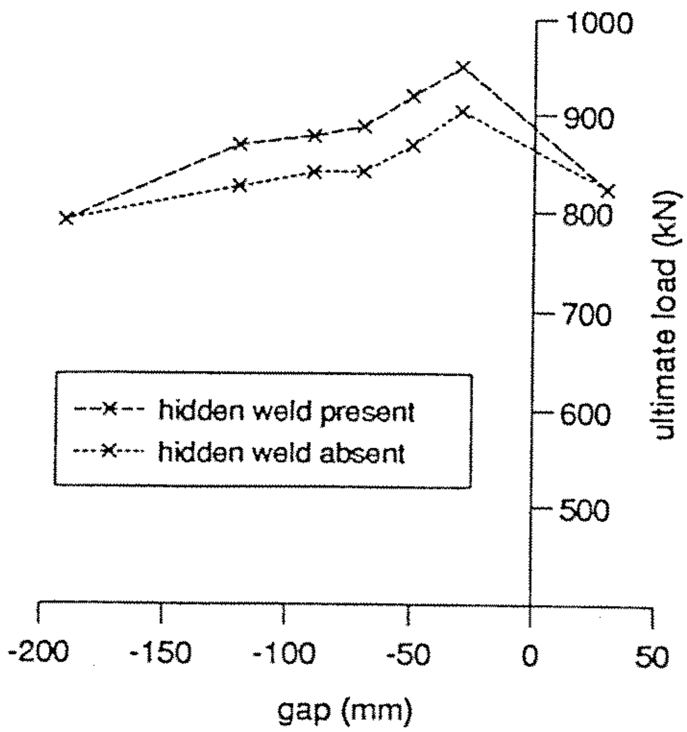


Figure 4.5-b Strength-overlap results for hidden weld presence and absence (through brace in compression balanced axial load)

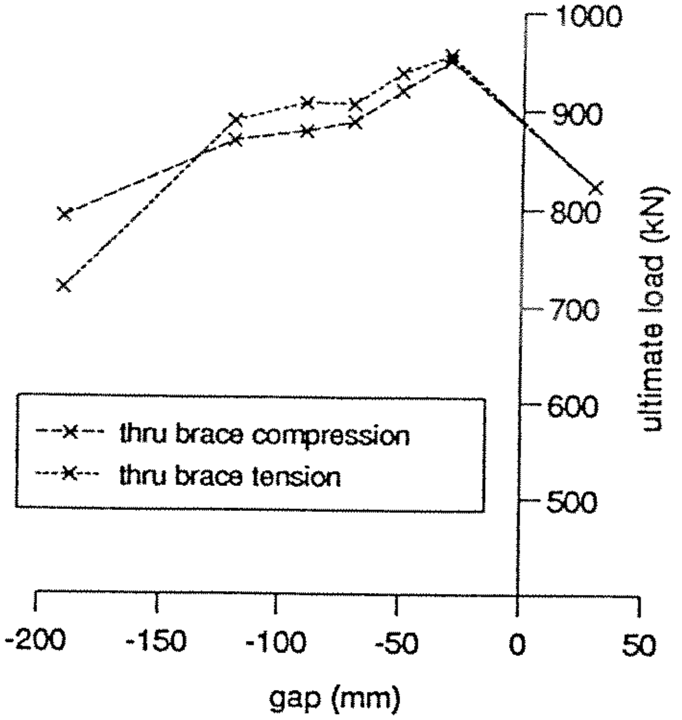


Figure 4.5-c Strength-overlap results for loading hierarchy reversal (hidden intersection connected, chord in compression)

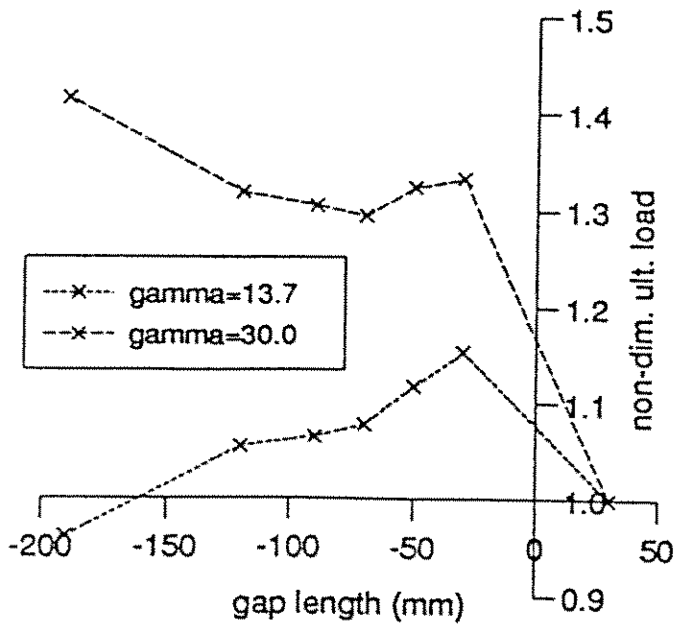


Figure 4.5-d Strength-overlap results for different failure modes (hidden intersection connected, through brace in compression, chord in compression)

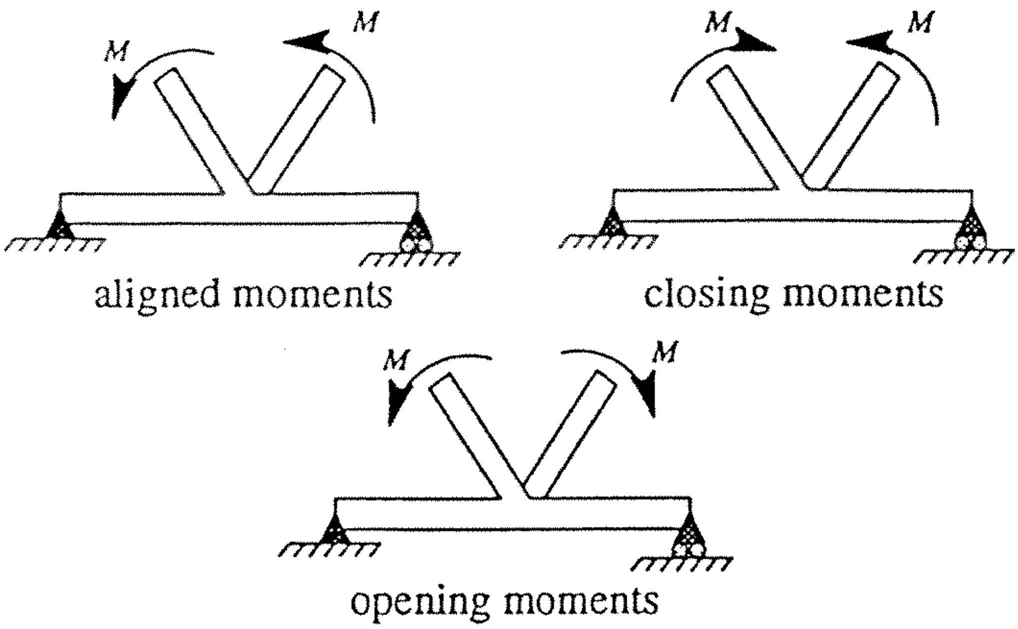


Figure 4.6 Load hierarchies and BCs for IPB analyses (Healy, 1994)

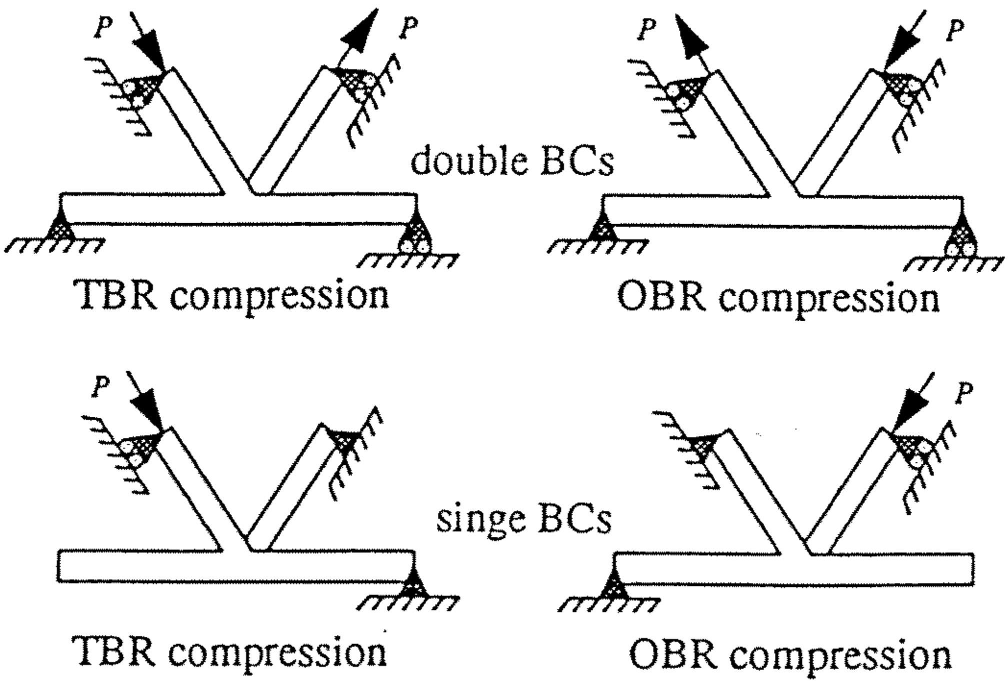
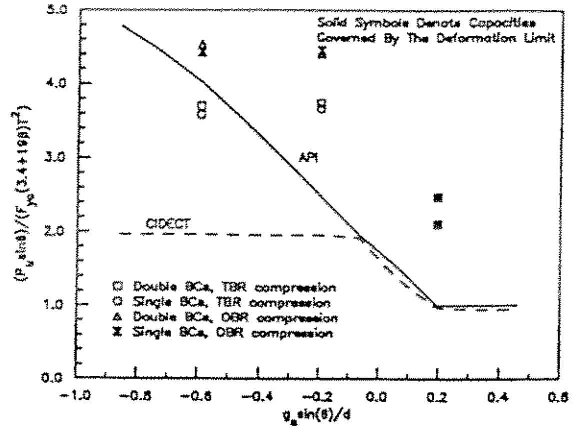
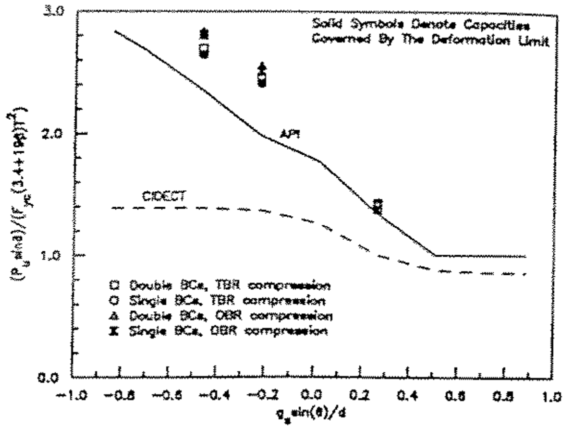


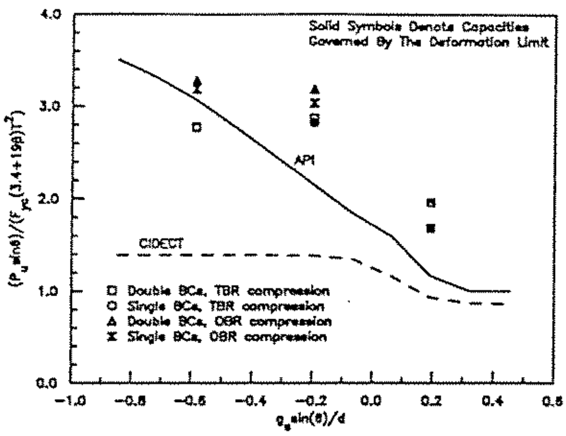
Figure 4.7 Load hierarchies and BCs for ATL analyses (Healy, 1994)



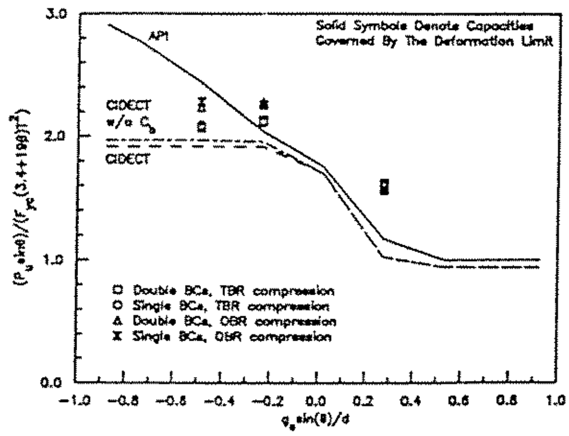
ATL capacity vs. gap, configuration 1



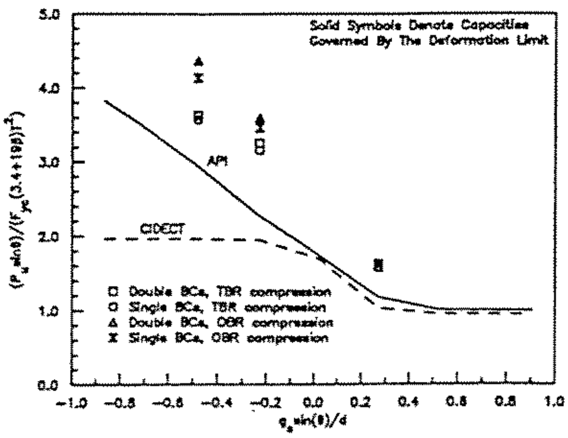
ATL capacity vs. gap, configuration 4



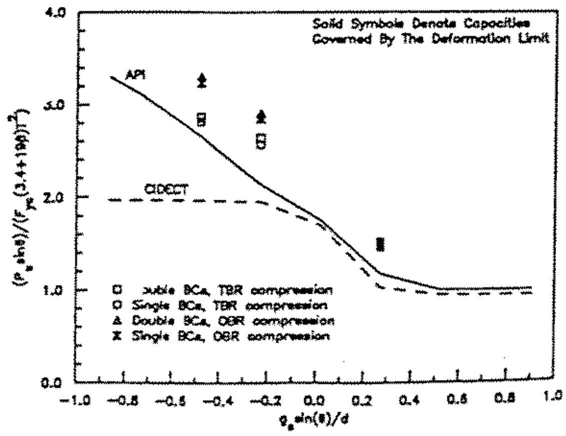
ATL capacity vs. gap, configuration 2



ATL capacity vs. gap, configuration 5



ATL capacity vs. gap, configuration 3



ATL capacity vs. gap, configuration 6

Figure 4.8 Results of the balanced axial load analysis (Healy, 1994)

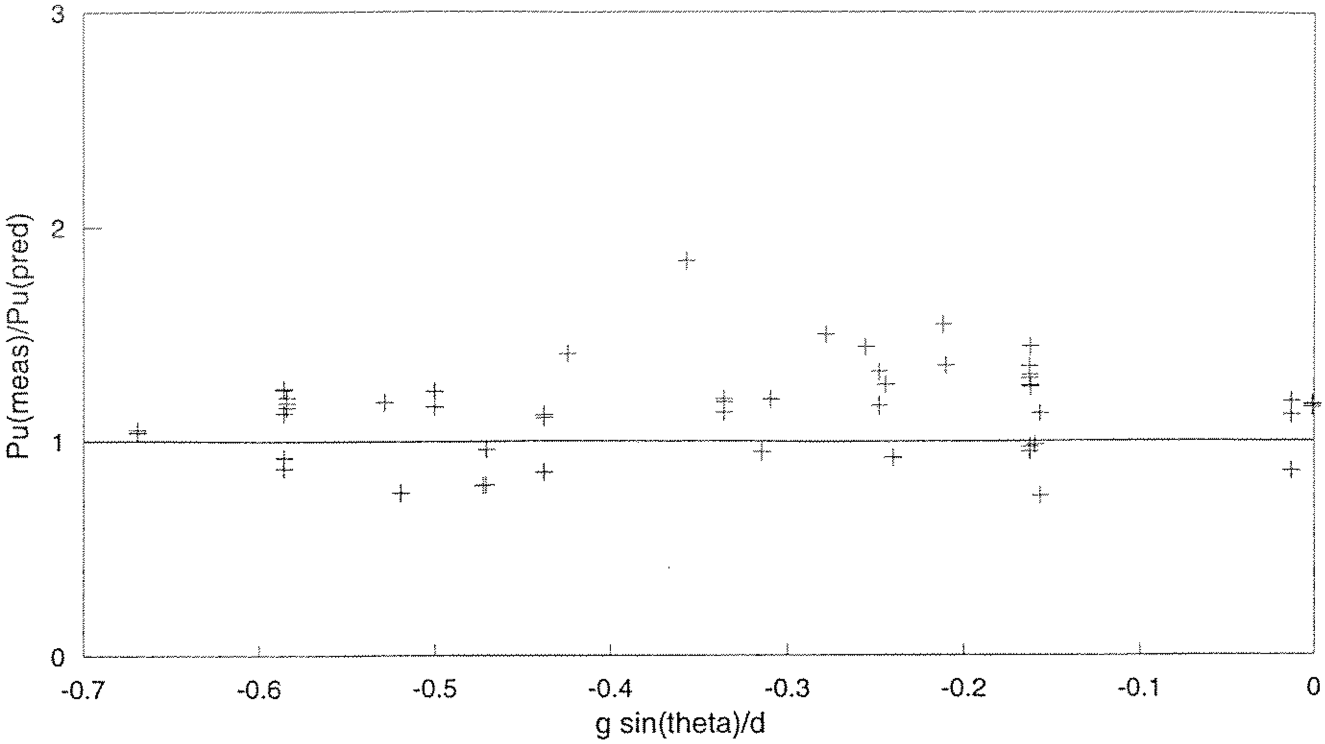


Figure 4.9-a Axially loaded overlapping joints (API RP2A)

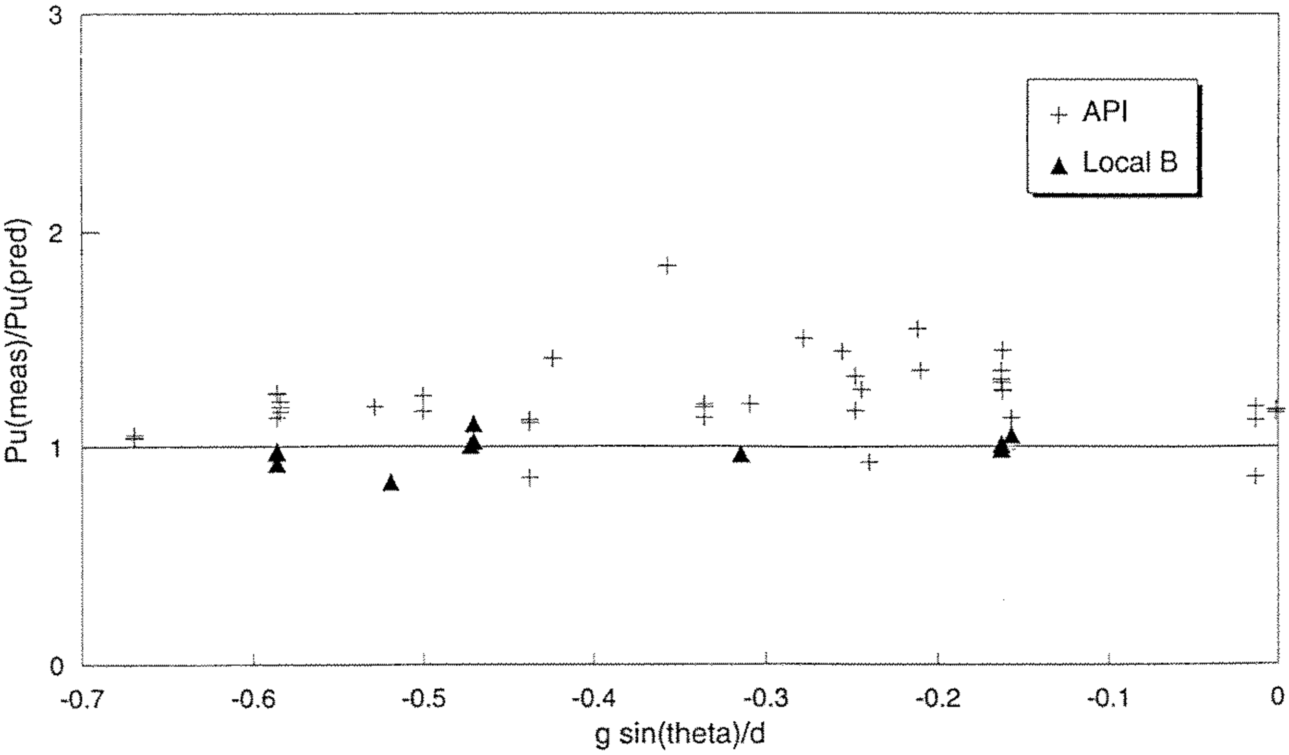


Figure 4.9-b Axially loaded overlapping joints, local brace buckling effects (API RP2A)

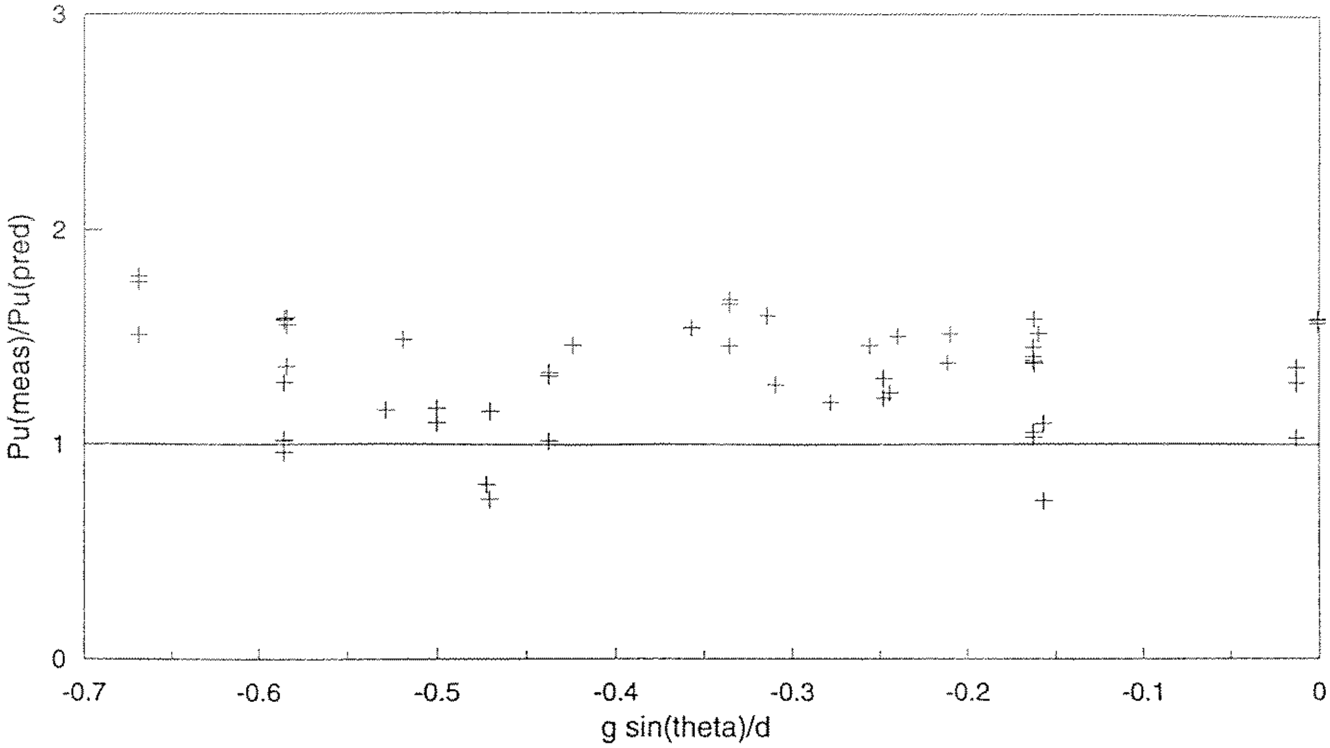


Figure 4.10-a Axially loaded overlapping joints (CIDECT)

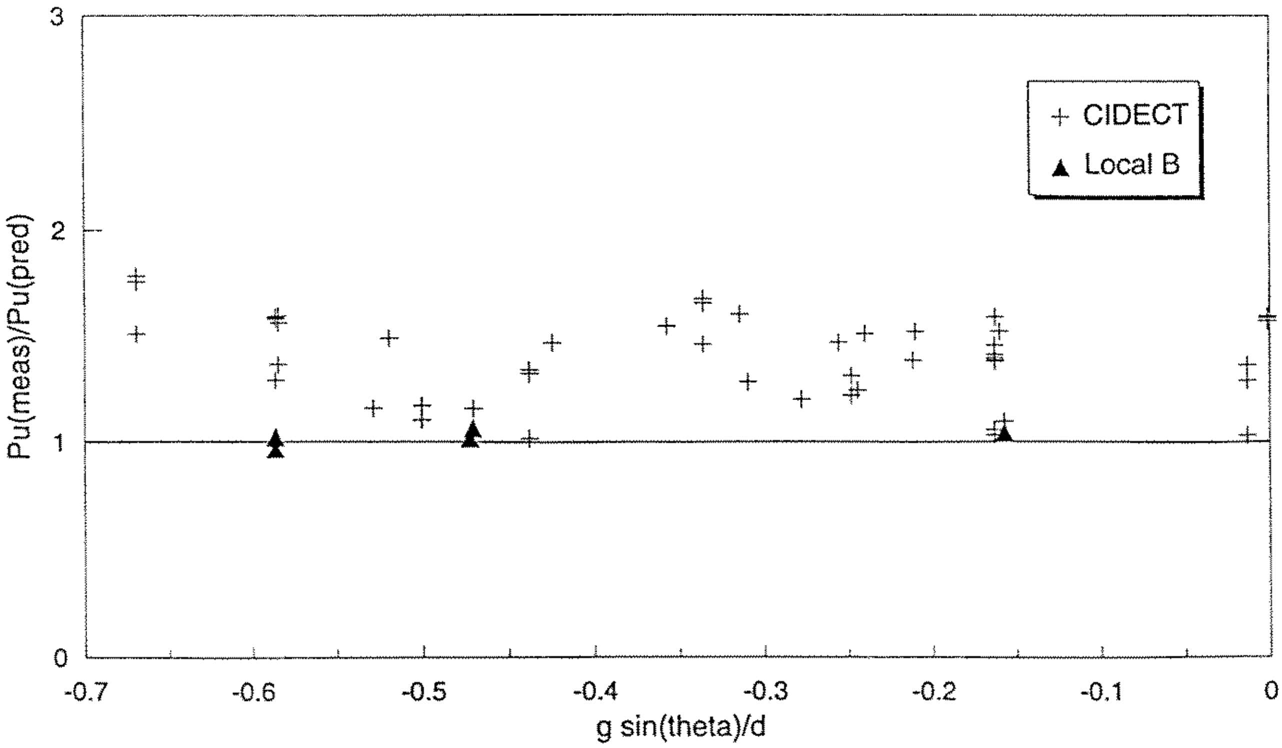


Figure 4.10-b Axially loaded overlapping joints, local brace buckling effects (CIDECT)

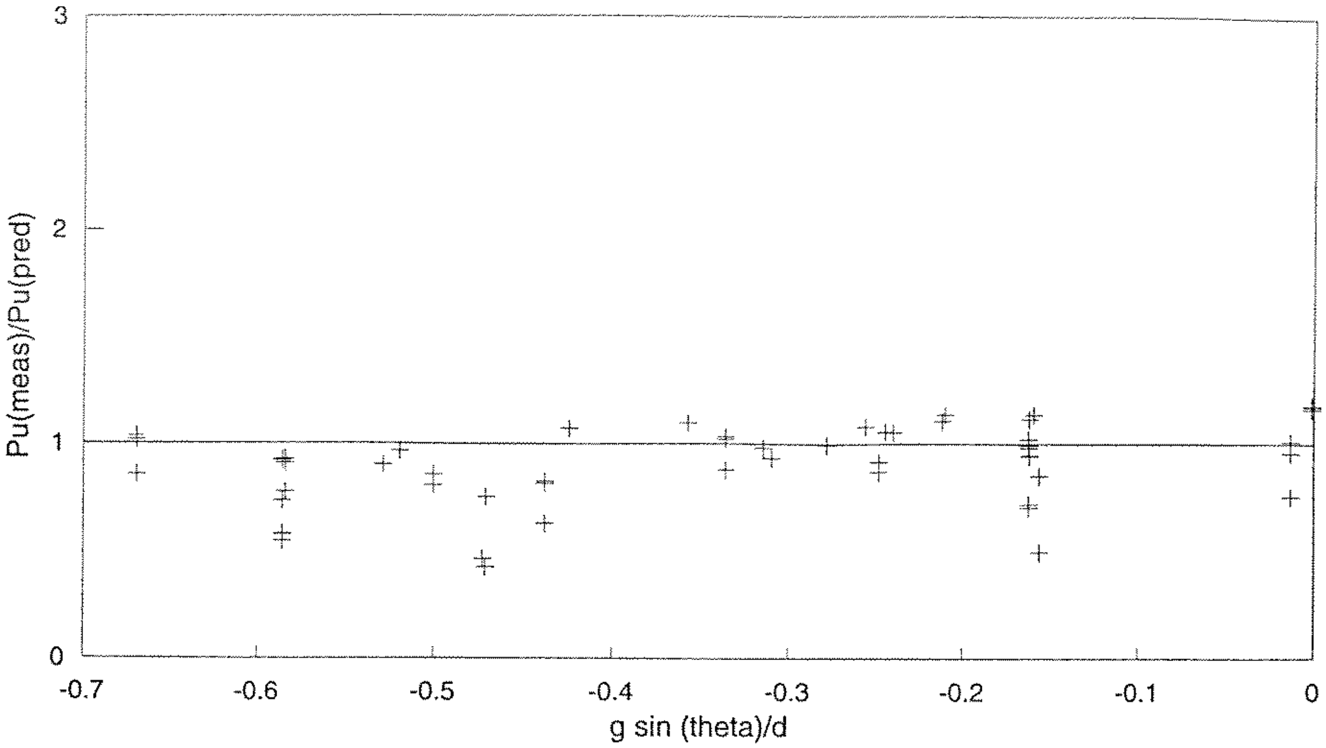


Figure 4.11-a Axially loaded overlapping joints (CSA)

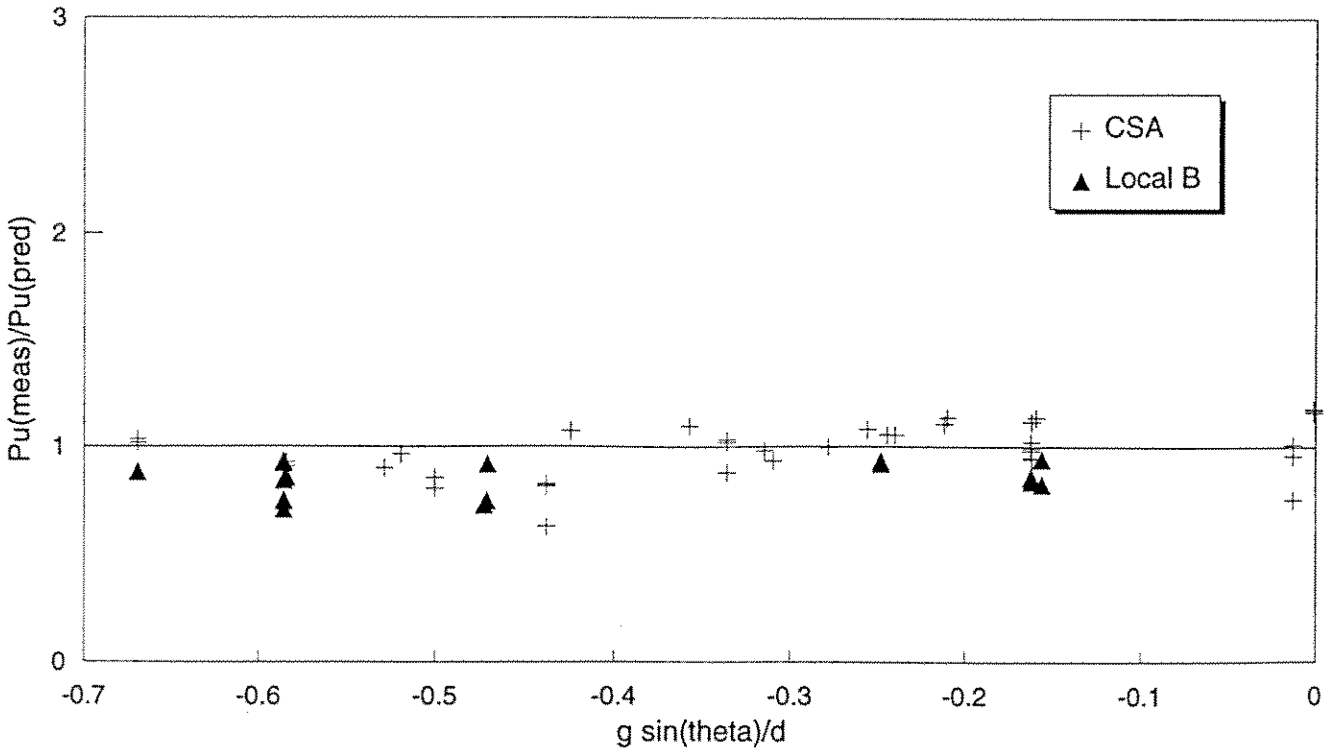


Figure 4.11-b Axially loaded overlapping joints, local brace buckling effects (CSA)

5. STATIC STRENGTH OF MULTIPLANAR JOINTS

5.1 General

Multiplanar joints are defined as joints with brace members in more than one plane. They can have overlapping or non-overlapping braces. An example joint is illustrated in Figure 5.1 which also shows the nondimensional geometrical parameters.

Multiplanar joints are an avoidable feature of steel jacket structures. They are required to provide load paths to the foundation system. Commonly accepted offshore design codes do not provide specific guidance for quantifying the static strength of multiplanar joints. Historically, with regard to both static strength and fatigue, multiplanar joints have been treated as a series of uniplanar connections with no reference to the influence of out-of-plane braces and/or loads in such braces. This approach can yield conservative or unconservative solutions depending on the geometric configuration and attendant loads. This can be readily appreciated given that many tubular joints in offshore structures are more complex than the simple cases, having more than two intersecting braces within a plane often in conjunction with other planes of braces. Typically these nodes are subject to complex multidirectional loading.

As confidence in the level of understanding for simple joints has grown, so there has been an increasing recognition that a detailed assessment of multiplanar effects represents the logical step forward. The need has been highlighted recently by the findings from preliminary studies which have shown the effects, in some instances, to be considerable.

The nature of multiplanar influences on tubular joints can be appreciated from the simple diagrams in Figure 5.2. It is clear that the compression load in the horizontal brace in the second case will restrain chord deformations compared with the first case. Conversely the tension force in the third diagram will add to the chord ovalisation. As a first step in assessing multiplanar influences, the X joint (or double-tee joint) shown in the last diagram may be considered. In effect the second brace is in a different plane at 180° to the first. This transition from simple, single-sided uniplanar joints, to complex planar joints is an essential link to the multiplanar joints being considered here.

The first step to incorporating multiplanar effects in design guidance was taken by the American Welding Society in its 1985 Edition of the Structural Welding Code (AWS D1.1, 1985). An ovalisation parameter denoted α was adopted to account for the ovalising effect of loading in out-of-plane braces demonstrated in Figure 5.2. The formulation is given in Figure 5.3. This approach is described and assessed in the following sections.

5.2 Review of Existing Design Guidance

5.2.1 API RP2A (WSD and LRFD) 1993

API RP2A (WSD and LRFD, 1993) gives no guidance on the interaction effects due to braces and loads in different planes. *Clause 4.3.3* (API-WSD) gives guidance on detailing congested joints and in the case of spherical joints gives parameters for which planar punching shear concepts may be used. Design is permitted on the basis of a plane by plane assessment for both static strength and SCF evaluations ignoring multiplanar effects.

5.2.2 CIDECT (1991)

This code gives specific guidance for the static strength design of multiplanar joints. A correction factor for various loading and geometric configurations is given as shown in Figure 5.4. These have been derived directly from the work on V joints by Mitri (1987), DT joints by Paul (1988) and double K joints by Makino (1984), all of which are included in the multiplanar joint database (Section 5.3).

Although this guide is aimed primarily at onshore structures the recommendations are based on tests of a reasonable scale and can be considered in relation to offshore structures. Particularly important is the fact that they are related to ultimate (non-linear) data whereas the AWS criterion (based on the ovalising parameter α), has a purely elastic foundation.

5.2.3 CSA (1992)

No specific guidance on multiplanar joints is given.

5.2.4 DnV (1993)

DnV States that multiplanar joints may be assessed according to the planar formulae, but care must be taken to use these in a conservative way. The code notes that the designer should take care where loads in a second plane add to the deformations in the plane under consideration and ensure that this situation is treated conservatively.

5.2.5 HSE (1990)

The HSE Guidance Notes also advocate a plane by plane assessment although the pitfalls of classifying multiplanar joints without due regard to interactions are highlighted in *Clause A21.2.4.c (ii)*. Nevertheless no firm guidelines are given.

5.2.6 NPD (1990)

No specific guidance on multiplanar joints is given.

5.2.7 AWS (1994)

A first step towards accounting for multiplanar effects was taken by Marshall (1982 and 1984) who proposed a general equation to encompass both single and multiplanar non-overlapped joints. Whilst few test results (and none with moment loading) were available against which it could be calibrated, its general form was sufficiently encouraging for the equation to be adopted by AWS in its static strength and fatigue provisions in the Structural Welding Code in 1985.

The AWS formulation centres on the evaluation of an ovalising parameter α, which is calculated in accordance with the procedures in Figure 5.3. Considering each brace as the 'reference brace' in turn, the influence of all other braces is quantified via the summation term. Within this, the cosine 2ϕ function accounts for the out-of-plane influence, Figure 5.5-a, and the exponential decay term expresses the lessening effect as L_f, the distance between brace centre lines increases, Figure 5.5-b. These terms are both unity for the reference brace which appears again in the denominator.

In general, the AWS philosophy has been established from recognition that, for non-overlapping and unstiffened joints, the severity and direction of chord cross-sectional ovalisation plays a major part in governing joint behaviour. The direction of ovalisation is determined from consideration of brace and load type, i.e. axial compression or axial tension. The severity is established from the magnitude of the brace loads and the proximity of all braces with respect to the reference brace. The chord ovalising parameter α accounts for both these aspects. A larger value implies a more severe ovalisation of the chord cross-section, and hence a reduction in the joint strength.

Figure 5.2 presents the results of some example calculations for α for T joints, corner T joints (multiplanar joints with T braces at orthogonal out-of-plane positions) and DT joints to demonstrate the ovalisation severity indicated by these criteria. This suggests that compression loaded DT joints have a 45% increased severity in ovalisation over compression loaded T joints, a difference which is not unexpected in light of evidence from simple joint data. For corner T joints with equal but opposite loads, the degree of ovalisation severity is comparable to a compression loaded DT joint. However, for corner T joints with equal loads of the same sign, the α value is 1.0, indicating that the ovalisation tendency of one brace load is counteracted by the other brace such that the reference brace joint has a greater capacity than the capacity of a simple T joint.

Before assessing the AWS provisions, a number of specific comments on the ovalising parameter may be made:

- Initial support for the formulation is found from the examination of SCF data on multiplanar joints which indicates similar trends to those identified in Figure 5.2.

- The length L_f in Figure 5.3 represents the distance between adjacent planar brace centre lines. The use of a gap parameter, g, ie, correlation with distances between brace ends (appropriately non-dimensionalised), may be more relevant than the exponential decay function adopted by AWS, in line with planar K joint performance implied in both API RP2A (1993) and the HSE Guidance Notes (1990). Furthermore the gap parameter is specified in design and stipulated on fabrication drawings making it a more sensible choice for adoption in analysis.

- The out-of-plane effects are essentially accommodated in α by the cosine 2ϕ term. The use of out-of-plane non-dimensional gap terms may provide a more appropriate representation of capacity variations. For example, a reduced interaction between the same braces at the same angle ϕ would be expected for a larger diameter chord than a small diameter chord. The current AWS formulation implies an identical interaction.

- The α parameter is derived purely from considerations of axial brace loads so the capacity of multiplanar joints subjected to in-plane or out-of-plane moment loads is not treated in any rigorous manner in AWS.

- In addition to being a pioneering attempt at quantifying multiplanar joint capacities the α approach is attractive for its independence from joint classification. The geometrical parameters embodied within the equation are intended to ensure that simple joint equations emerge when all ϕ angles are zero and thus the designer is not required to make subjective decisions regarding joint type. This must be considered a significant advantage in the refinement or development of new (multiplanar) joint equations.

- It should be noted that the α approach is based entirely on elastic considerations. Since the ultimate strength is largely influenced by the elasto-plastic joint behaviour, this approach could result in unsafe designs since information is lacking for a deformation/rotation capacity. More detailed knowledge of the strength and stiffness of multiplanar joints is an essential prerequisite for reliable designs and pushover analyses.

Nevertheless the AWS represents such a major advance over earlier approaches that it is worthy of further detailed study and from its shortcomings a more refined approach may emerge.

5.3 Database on Multiplanar Joints

5.3.1 General

Table 5.1 shows that a considerable amount of data covering several multiplanar joint configurations has become recently available. A substantial proportion of this data is on the axially loaded K-K configuration (experimental), while fewer data cover the axially loaded T-T and DT-DT configurations (experimental, and FE and experimental respectively). Planar joint tests performed for comparison with multiplanar tests have been included in the table providing a useful base case for multiplanar effect assessment. The database is reported in Appendix A3.5.

Joint type	Multiplanar No of tests	ϕ between planes	Reference
K-K	20	60°	Makino et al (1984)
	4	180°	Akiyama (1974)
	96	60°/90°	Mouty & Rondal (1990)
	4	60°	Makino et al (1993)
	18	60°/90°	Paul et al (1992)
T-T	8 (5)	60°-120°	Mitri (1987)
	12	60°-120°	Paul (1988)
DT-DT	7 (2)	90° (FE)	Paul (1989)
	2 (1)	90° (FE)	Sakharov (1989)
	9 (3)	90°	Vegte (1991)
Note: Numbers in brackets refer to planar tests undertaken in the same test series. FE = Finite Element results			

Table 5.1 Summary of tests on multiplanar joints.

5.3.2 K-K Joints

Five sets of data exist all of which have $0.20 < \beta < 0.50$ and ϕ, the angle between the planes, equal to 60° or 90° except for the Akiyama data where ϕ is equal to 180°. These joints are planar but they are still useful to include in order to assess the AWS formulation for multiplanar brace interaction.

All joints but one were loaded under the symmetric loading regime shown in Figure 5.4. The exception, Makino (1993), was loaded asymmetrically.

The series of tests undertaken by Mouty and Rondal (1990) gave strengths that were considerably lower than those tested by Makino and Paul. The testing arrangement used by Mouty and Rondal induced sizeable secondary moments into brace members during testing due to the boundary conditions. This has led to screening these results out of the database.

5.3.3 T-T Joints

Two sets of experimental data are available, those of Mitri (1987) and Paul (1988). These joints have ϕ equal to 60°, 90° and 120° with both braces loaded in compression. Mitri also undertook a series of planar T joint tests against which the multiplanar joints can be compared.

5.3.4 DT-DT Joints

Of the three sets of data, two are based on FE analyses, those of Paul (1989) and Sakharov (1989) where the joints were subject to axial loading. The third data set contains three sets of four joints tested (experimentally) by Vegte (1991), each set containing a planar X joint for reference. The in-plane loading was varied in each of the three sets, one set having axial compression applied, the second in-plane bending and the third out-of-plane bending. Brace loads in the out-of-plane braces in each of the three test series were varied from zero (to assess the effect of addition of the out-of-plane braces) to axial tension and compression, thus enabling the effect of a range of multiplanar loads to be assessed. The β (= 0.6) ratio and other geometric properties were maintained the same for all joints in this series.

5.4 Analysis of Published Formulae

5.4.1 K-K Joints - axial loading

The ratio of the ultimate capacities of the K-K joints compared to the HSE mean formulation for planar K joints is shown in Figure 5.6.

The data generally lie slightly above the mean line for planar K joints indicating that the multiplanar braces and loads do not have a significant effect upon joint strength where the loading remains symmetrical. The Akiyama data where the angle between the bracing planes was 180° can be seen to lie above the HSE mean line, as also can the data point for which asymmetrical loading was applied (Makino, 1993).

The dataset is analysed with respect to the AWS multiplanar formula with the 1.8 safety factor removed in Figure 5.7. As can be seen most of the data lie above the AWS strength prediction with the lowest ratio being equal to 89% of the AWS strength estimate.

The effect of the CIDECT factor for multiplanar K-K joints of 0.9 is shown with respect to the HSE mean fit line in Figure 5.6. Although this factor was applied specifically to account for multiplanar effects on the CIDECT K gap formula, its comparison to the HSE mean line is informative. As can be seen if the 0.9 is applied, most of the data that originally lay below the HSE mean line, now lie above the modified line.

5.4.2 T-T Joints - axial loading

In Figure 5.8 the T-T joints are analysed with respect to the AWS formulation and it can be seen that a significant proportion of the multiplanar data falls below the AWS prediction. These data may be assessed on the basis of the planar T joints tested by Mitri as part of his program (Table 5.2).

β	γ	Planar	ϕ = 60°	ϕ = 90°	ϕ = 120°
0.405	22.2	(T1) 115.2		(V1) 131.5	
0.406	13.4	(T2) 330.5		(V2) 383.7	
0.645	17.2	(T3) 328.7		(V3) 452.9	
0.272	17.3	(T4) 122.3		(V4) 122.0	
0.405	17.2	(T5) 208.6	(V5) 238.8	(V7) 206.3	(V6) 177.4
0.769	17.5				(V8) 458.1

Table 5.2 The Mitri T-T joint data. ϕ = out-of-plane angle

The first noticeable trend in relation to the β = 0.405 joints (T5, V5, V7 and V6) is the increase in strength as the out-of-plane angle (ϕ) decreases. Where ϕ = 90° capacity of the multiplanar T-T joint (V7) is approximately the same as that of the planar T joint. Where ϕ is kept constant at 90° it can be seen that increasing the β ratio increases multiplanar enhancement over the planar capacity (V4/T4 ; V7/T5 ; V3/T3).

Although the Mitri data are mostly above the AWS predictions, it can be seen that much of the Paul data are on the low side when compared to the AWS in Figure 5.8, the two higher β ratio joints in this series are the only data with strengths above the AWS predictions. The Mitri data have short chords (typically α = 4.8) and this may be the cause of the apparent capacity increase between the two sets of data (the Paul data chords have α = 8.9).

For T-T joints under compression loading in both braces, significant multiplanar effects depending on both the out-of-plane angle ϕ and the β ratio exist. These can be seen to be beneficial or detrimental when compared to planar joint capacities. Furthermore although no test data are available, it can be imagined that where one brace is in compression and one brace in tension in a T-T joint then capacity may be reduced below the planar case, although the significance of this will depend on β ratio and ϕ.

The CIDECT modification factor for this joint configuration is 1.0, thus predicted capacities would be the same as those of compression loaded planar T joints. This is clearly not universally the case here, although available evidence confirms that this is conservative with perhaps the exception of ϕ = 120° in the Mitri data.

5.4.3 DT-DT Joints

The data on this configuration suggest that multiplanar effects are more significant than for the K-K and T-T configurations. Since there are data on DT-DT joints subjected to moment as well as axial loading (Vegte, 1991), the data are analysed separately in two sub-sections covering axial loading, and the combination of axial and moment loading.

5.4.3.1 Axial loading

A non-dimensionalised strength plot of the purely axially loaded DT-DT joints is shown with respect to the AWS formulation with the factor of safety removed in Figure 5.9.

Most data (including all the experimental data) for the multiplanar joints lie above the AWS formulation indicating that this formulation is conservative. Examination of the database reveals the addition of an extra plane of braces increases joint strength above that of planar joints and addition of compressive forces to this plane of braces (ie. in the same sense as the uniplanar loading) adds to capacity further. The non-dimensionalised capacities along with β ratio and loading ratios (2nd plane to 1st plane) are shown in Table 5.3.

Joint	β	F_{op}/F_{ip}	Cap/F_yT^2	ϕ	DT-DT/DT	DT-DT/ unloaded DT-DT	CIDECT x planar
T1	0.4	-	10.49	90°	-	-	10.49
T2	0.4	0	10.51	90°	1.00	1.00	10.49
T5	0.4	1.0	13.91	90°	1.32	1.32	13.95
T8	0.4	-1.0	6.83	90°	0.65	0.65	6.99
T2	0.6	0	13.73	90°	-	-	13.75
T4	0.6	0	15.53	90°	1.13	1.00	13.75
T6	0.6	1.0	40.10	90°	2.92	2.58	18.28
T7	0.6	0.75	30.80	90°	2.24	1.98	17.13
T9	0.6	-1.0	10.08	90°	0.73	0.65	9.17
T1	0.53	-	12.16	90°	-	-	12.16
DT1	0.53	1.0	34.60	90°	2.85	-	16.23
DT2	0.53	-1.0	12.90	90°	1.06	-	8.14
X1	0.6	-	12.49	90°	1.00	-	12.49
XX2	0.6	0	15.45	90°	1.24	1.00	12.49
XX3	0.6	0.35	21.48	90°	1.72	1.39	13.93
XX4	0.6	-0.58	13.27	90°	1.06	0.85	10.10

F_{op} = out of-plane F_{ip} = in-plane force

Table 5.3 Axially loaded DT-DT joints

Table 5.3 shows that the greater the β ratio the larger the enhancement due to the addition of an extra plane of braces and the greater the enhancement in strength due to the addition of loading in the same sense in these braces.

However where loading of the opposite sense is present, the reverse occurs. The FE analyses undertaken by Sakharov indicate that the capacity of such a joint is approximately that of an equivalent planar joint (at β = 0.53 and $F_{op} = -F_{ip}$), while the corresponding FE work by Paul indicates that for the same loading ratio, capacity is reduced below that of the planar joint by 27% (at $\beta = 0.6$) and 35% (at $\beta = 0.4$). The available experimental result on this loading configuration indicates a capacity 6% greater than the corresponding planar joint case (at $\beta = 0.6$) but the loading ratio between the planes is not as severe ($F_{op} = -0.58F_{ip}$). Should the magnitude of this ratio increase then it could be reasonably expected that capacity would fall below that of the corresponding planar joint.

Table 5.3 includes the planar capacities adjusted according to the CIDECT multiplanar factor given in Figure 5.4 (planar strength * $(1.0 + 0.33\ F_{op}/F_{ip})$) in order to assess the ability of this factor to predict multiplanar capacities. It is acknowledged in the CIDECT guide that this would be conservative for compression-compression joints. The constant (0.33) was kept the same for both loading combinations (compression-compression and tension compression) to simplify the formulae. For the Vegte and Sakharov data the CIDECT multiplanar adjustment factor gives conservative strength estimates.

5.4.3.2 Moment loading

Two sets of data are available on multiplanar DT-DT joints with one plane under bending loads, the other being unloaded or loaded axially. These comprise the only data on the effects of moment loading on multiplanar joint capacity. No guidance is available currently on the effects of bending on multiplanar joint capacity in either the AWS or CIDECT Codes. Details of these two series of joints are shown in Tables 5.4 and 5.5.

Joint	F_{op}	β	$M_u ip/F_y T^2 d$
X5	Planar	0.6	17.00
XX6	0	0.6	17.12
XX7	242	0.6	20.54
XX8	-213	0.6	16.37

F_{op} = out-of-plane axial force

Table 5.4 DT and DT-DT joints subject to IP moments and axial loads

Joint	F_{op}	β	$M_u op/F_y T^2 d$
X9	- Planar	0.6	7.44
XX10	0	0.6	12.13
XX11	213	0.6	11.39
XX12	-258	0.6	9.54

F_{op} = out-of-plane axial force

Table 5.5 DT and DT-DT joints subject to OP moments and axial loads

From Table 5.4 it can be seen that addition of an unloaded second plane of braces to the in-plane bending loaded joints has little effect on the in-plane bending capacity (X5-XX6). Addition of a compression pre-load to these braces in this second plane increases capacity by 20% while a tensile pre-load acts to reduce in-plane bending capacity slightly. The effect of multiplanar bracing and associated loads is clearly not as significant as for axial loads for the DT-DT joint configuration.

Where the joint series is subject to out-of-plane bending (Table 5.5) slightly different trends emerge. Here the addition of out-of-plane bracing can be seen to enhance joint capacity, the addition of axial loading into these being detrimental (6.1% for the compression case, 21.3% for the tension case). All multiplanar cases however, have capacities above those at which the corresponding planar joint fails.

Therefore it can be seen that the effect of the presence of a second bracing plane and axial loads within such a plane is not as significant on the in-plane and out-of-plane bending strength of multiplanar joints as it was for the axially loaded DT-DT joints.

5.4.4 Implications for other multiplanar joints

5.4.4.1 Axial loading

The aim of this section is, in light of the information contained in the previous sections, to indicate where potential non-conservatism (ie. multiplanar capacities may potentially fall below planar capacities) could occur in the design and assessment of multiplanar joints on the traditional plane by plane basis. The most likely scenario is where the addition of an extra plane of braces, alongside the associated loads acts to increase the deformation induced by the initial plane loading. This is likely to be most severe where such joints are under axial compression in one plane and axial tension in the second as for axially loaded DT-DT joints.

Similar such scenarios can be envisaged in the T-DT and T-T joints in Figure 5.10. However these effects as noted will also depend on the out-of-plane angle, ϕ. For example it can be perceived that where ϕ is reduced towards 0° then the tensile and compressive loads act largely to balance each other, perhaps increasing joint capacity, or at least not reducing it below that of a planar joint.

For K joints under balanced loading the tendency is for the chord to ovalise in two perpendicular directions under the tension and compression brace respectively. The effect of a second plane of bracing of either T or DT configuration on such a K joint is therefore unlikely to be as great as on the DT configuration, particularly if such braces intersect the chord at the centre-point of such a K configuration, as shown in Figure 5.11. The effect of a second set of K braces on a K joint has been discussed already in light of the considerable volume of test data on K-K joints. That agrees with the qualitative analysis here that multiplanar effects on the K-K joint configuration are likely to be less severe than for the DT or T type joint.

5.4.4.2 Moment loading

From the evidence on DT-DT joints discussed above, a second plane of braces with or without axial loads generally increases the capacity over that of the planar configuration, the only reduction in strength to below that of the corresponding planar configuration is 4% (Joint XX8 of the Vegte data). This evidence would suggest that addition of multiplanar braces and associated forces has little impact on in-plane or out-of-plane bending strength compared to the planar case. Where the impact is of significant magnitude the multiplanar effects generally increase the capacity over that of planar configurations.

The possible geometries and loading scenarios are limitless and guidance for all cases is difficult to develop. However by using qualitative analysis the designer may become aware of potential problems and take measures to ensure design of multiplanar connections is conservative.

5.5 Conclusions and Recommendations

The available experimental evidence and design recommendations have been reviewed for axially loaded K-K joints. The AWS multiplanar formulation gives largely conservative results (safety factor removed). The most under-conservative prediction is approximately 12% (one test). Most of the multiplanar data lie above predictions based on the mean HSE formula for planar K joints. The 0.9 reduction factor recommended in the CIDECT Code can be seen to slightly over-penalise the data.

For axially loaded T-T joints it can be seen that the AWS formulation over-predicts most of the Paul data and under-predicts the majority of the Mitri data. The Mitri joints have short chords ($\alpha = 4.8$) which enhance the capacity in comparison with joints having longer chords. The AWS formulation is slightly under-conservative for this multiplanar joint. CIDECT proposes a modification factor of 1.0, based on the Mitri data. With the more recent Paul T-T data ($\alpha = 8.9$) showing lower capacities, this factor could lead to under conservative predictions of static strength for this joint and loading type.

For axially loaded DT-DT joints, the AWS gives conservative predictions which reflect the increase and decrease in capacity caused by the multiplanar loading in the available FE and experimental data. Similarly the CIDECT modification factor can be seen to reflect conservatively the multiplanar loading effects (Table 5.3). For the case of compression loading in both bracing planes the CIDECT modification is somewhat over conservative. Therefore, the AWS and CIDECT formulae may be seen to reflect the multiplanar behaviour of DT-DT joints in a conservative and realistic way. Both may be considered more suitable for assessment and design of this joint type than the traditional plane by plane approach.

For moment loaded joints, the limited available data suggest that for most cases the presence of a second plane of braces and associated loads increases bending strength capacity above that of the equivalent planar case. Where multiplanar capacity falls below the planar equivalent this is only by a small magnitude (4% Joint XX8). In the absence of more comprehensive information the traditional plane by plane assessment is considered appropriate for design of moment loaded multiplanar joints.

For other configurations where test or FE evidence is unavailable consideration should be given to potential under conservatism in design, in particular where deformations in a second plane add to deformations in the original plane. Some potentially unconservative situations are discussed in Sections 5.4.4.1 and 5.4.4.2.

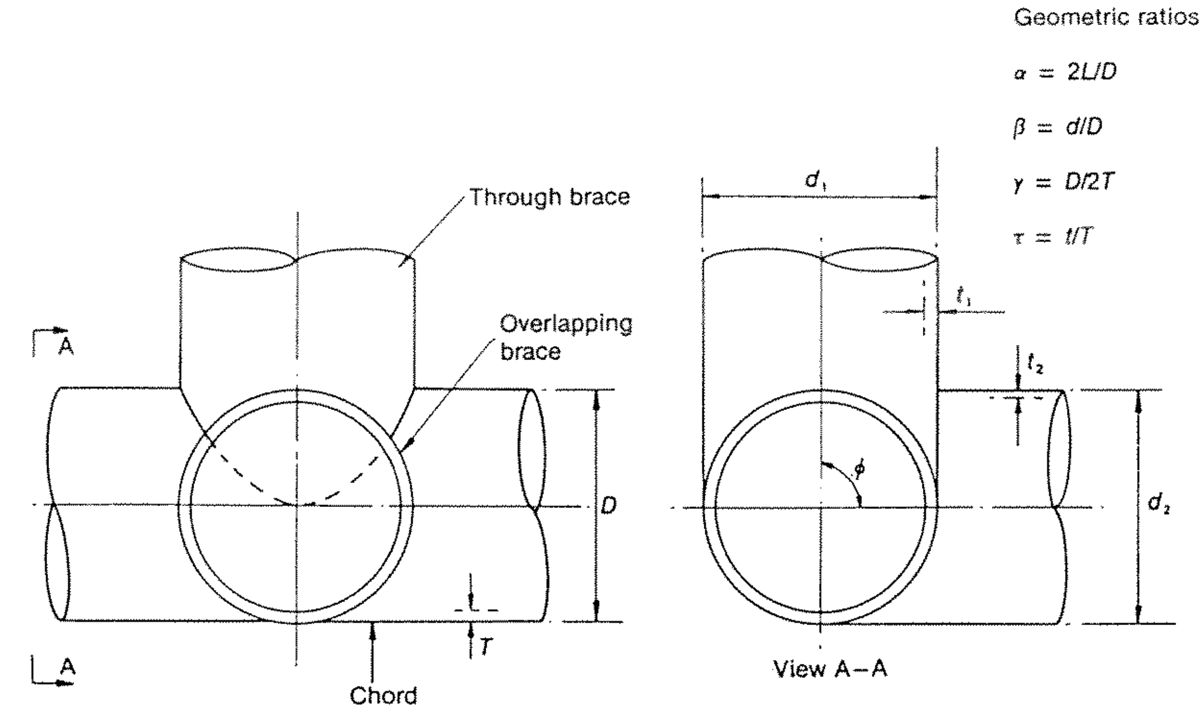


Figure 5.1 Multiplanar overlapping joint: Geometric notation

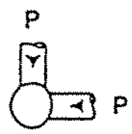
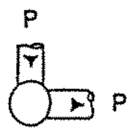
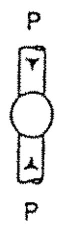
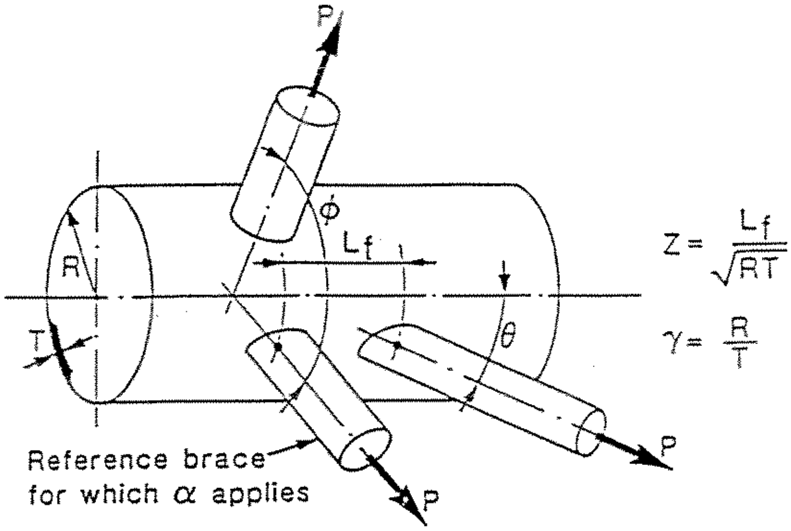
Joint type and load case	Value of α_o
	1.7
	1.0
	2.4
	2.4

Figure 5.2 The influence of out-of-plane braces and loading



$$\alpha = 1.0 + 0.7 \frac{\sum_{\substack{\text{All braces}\\ \text{at a joint}}} P \sin\theta \cos 2\phi \exp - \frac{Z}{0.6\gamma}}{[P \sin\theta]_{\text{Reference brace for which } \alpha \text{ applies}}}$$

$$\alpha \geq 1.0$$

Figure 5.3 The α formulation in AWS D1.1 (1994)

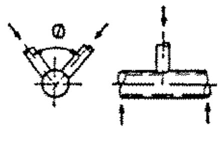
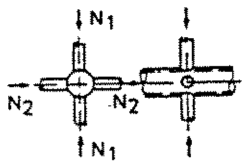
Type of joint	correction factor to uni-planar joint (limits according to Fig. 8) $60^\circ \leq \phi \leq 90^\circ$
TT 	1.0
XX 	$1 + 0.33 \frac{N_2}{N_1}$ Note: take account of the sign of N_2 and N_1 ($N_1 \geq N_2$)
KK 	0.9

Figure 5.4 CIDECT correction factors for multiplanar joints (1991)

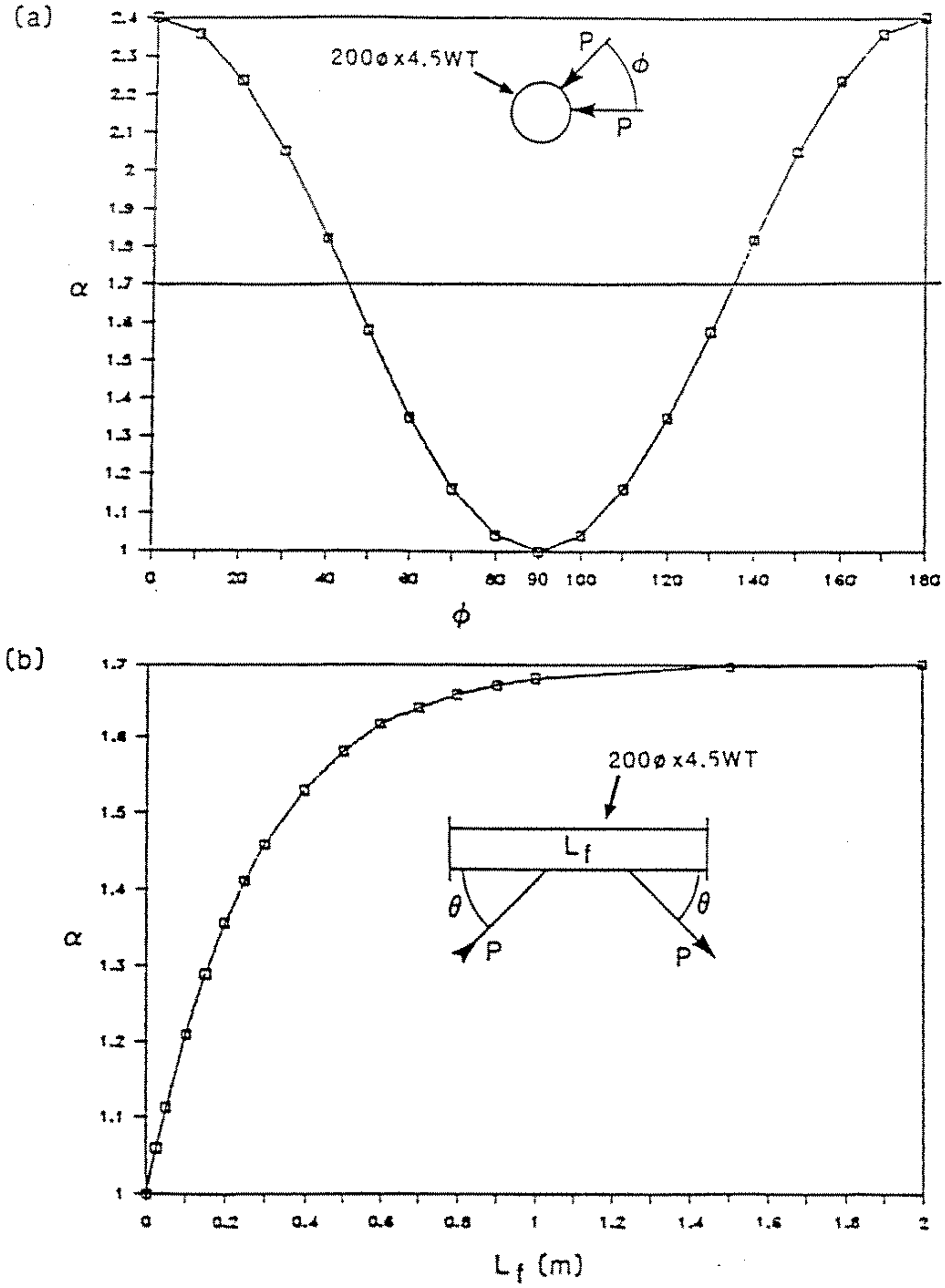


Figure 5.5 Variation of α ovalisation with out-of-plane angle, ϕ, and brace separation, L_f

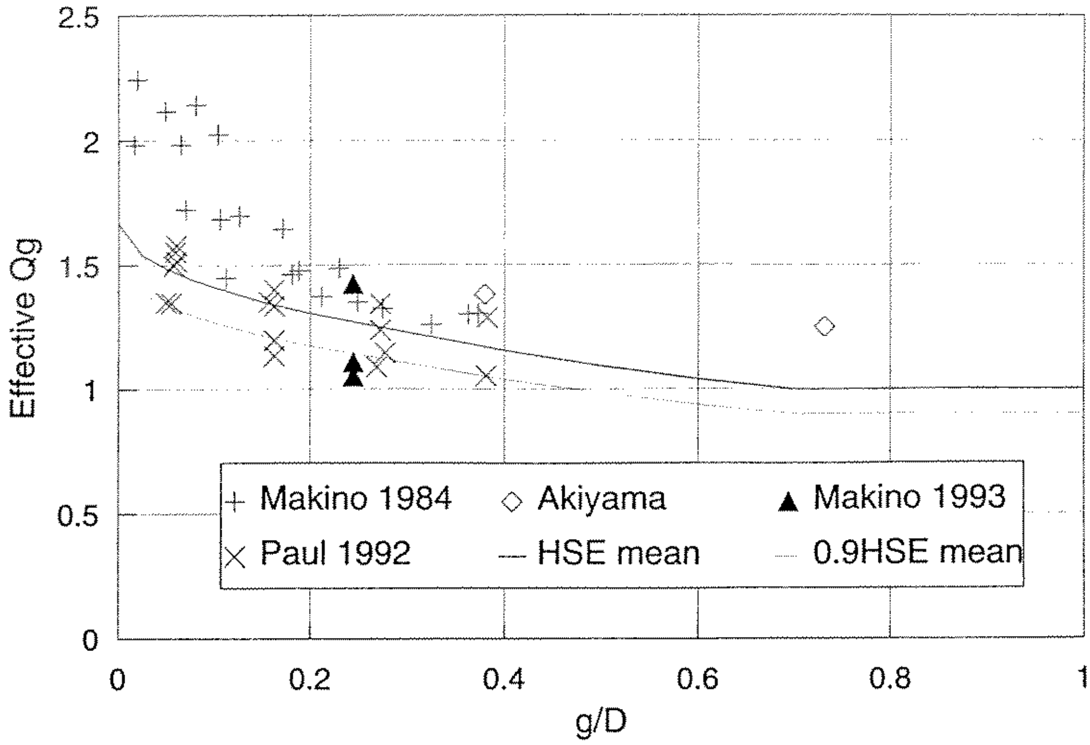


Figure 5.6 Comparison of multiplanar K-K joint dataset effective Q_g for planar HSE mean formulation against g/D

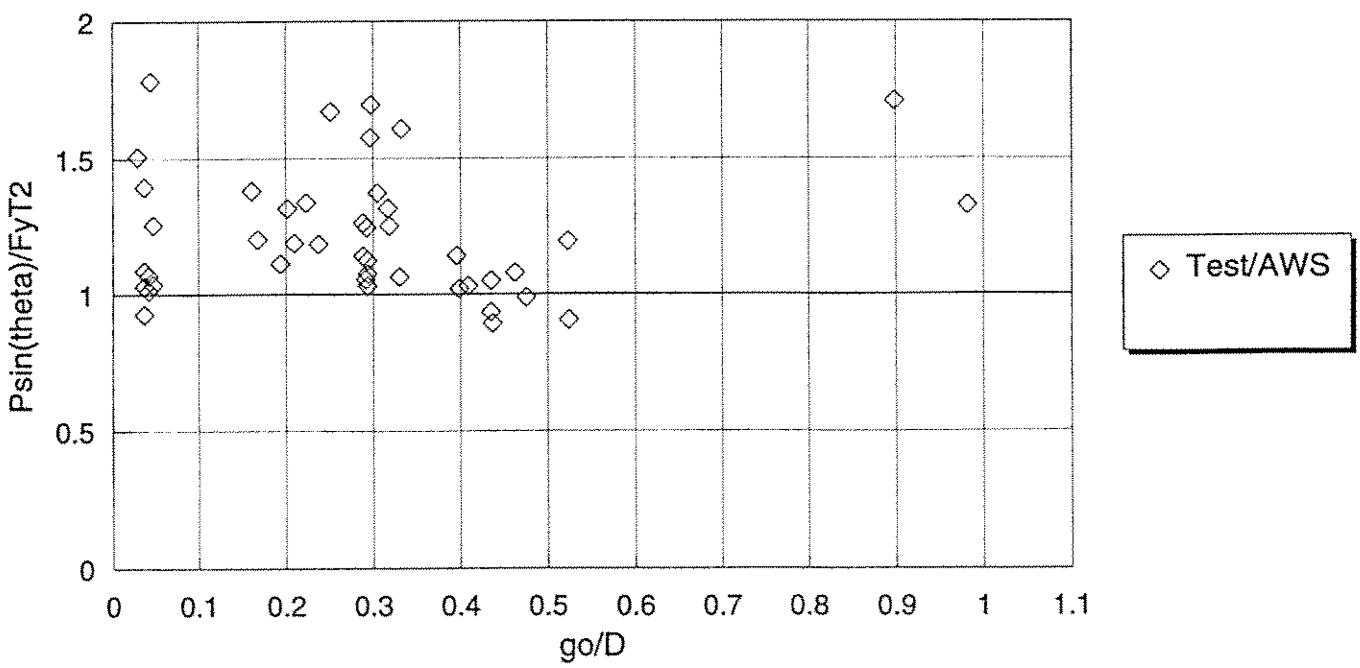


Figure 5.7 Comparison of measured to predicted strengths of K-K joints with the AWS vs g/D

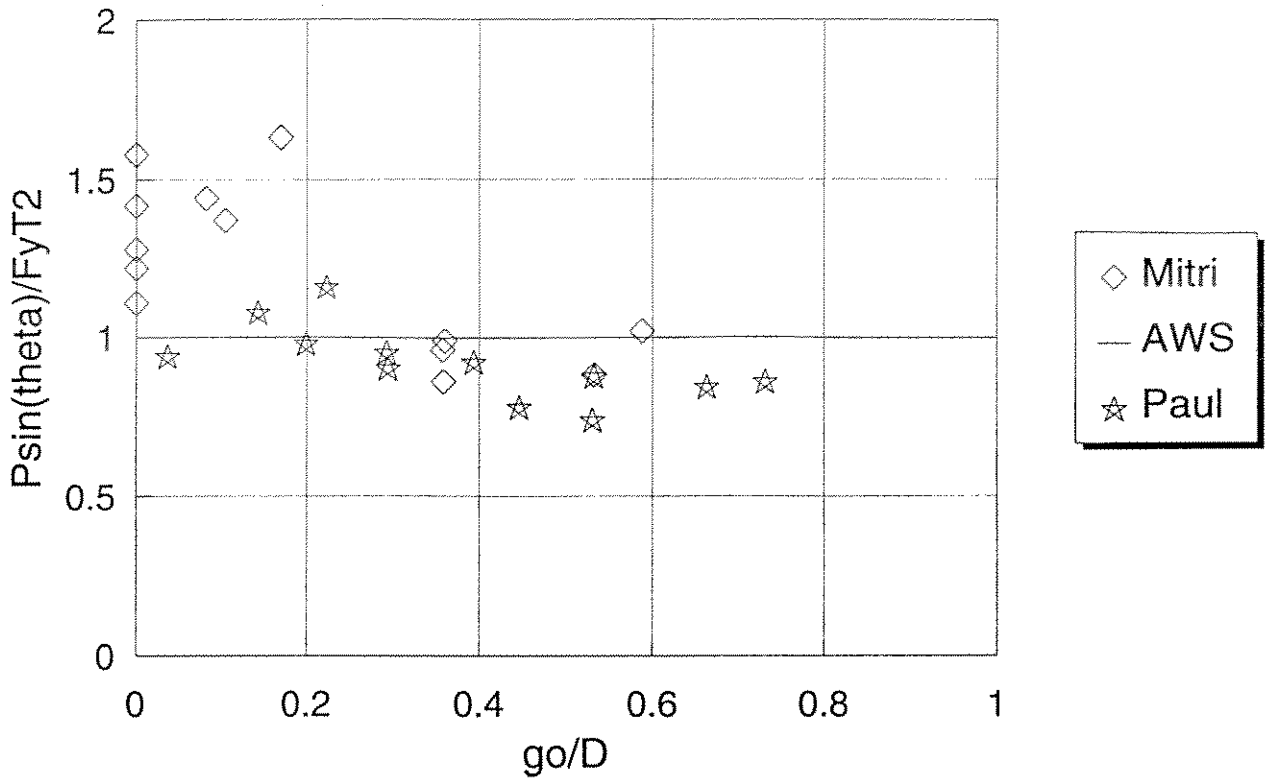


Figure 5.8 Comparison of measured to predicted strengths for the multiplanar TT joints with the AWS vs out-of-plane gap ratio (go/D)

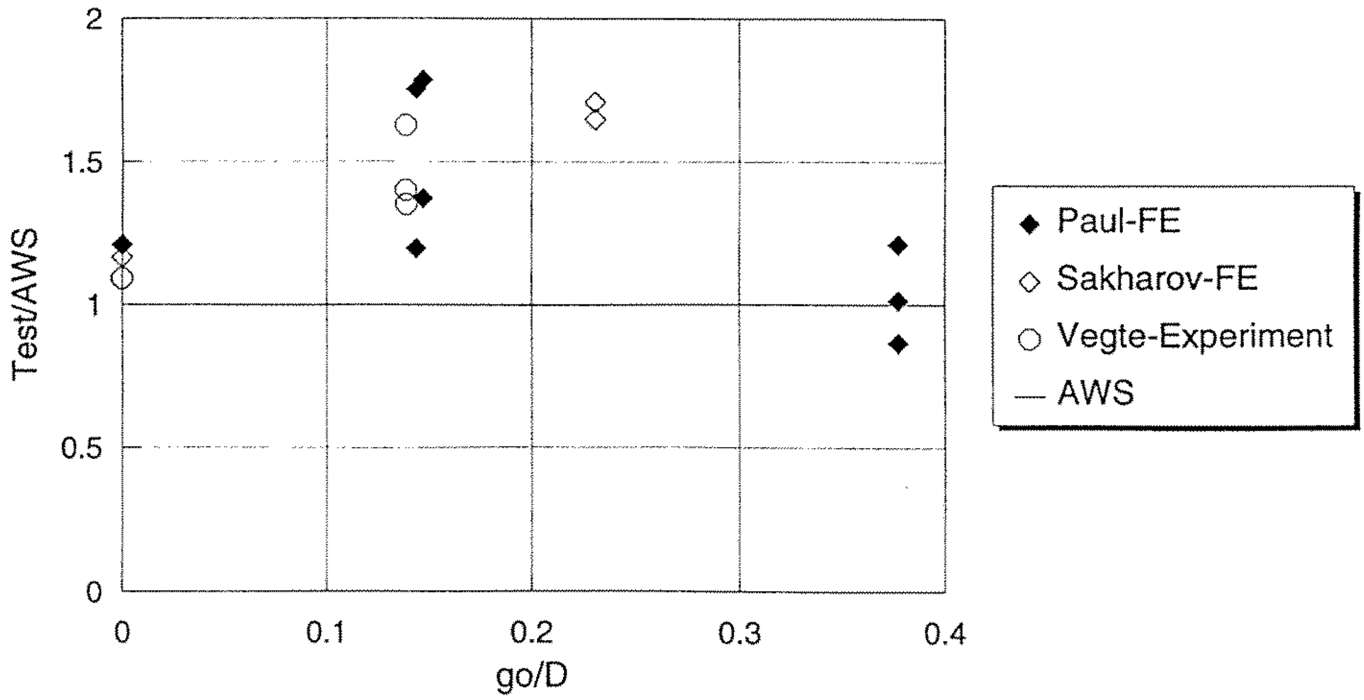


Figure 5.9 Comparison of axially loaded multiplanar XX joint dataset with the AWS vs out-of-plane gap ratio (go/D)

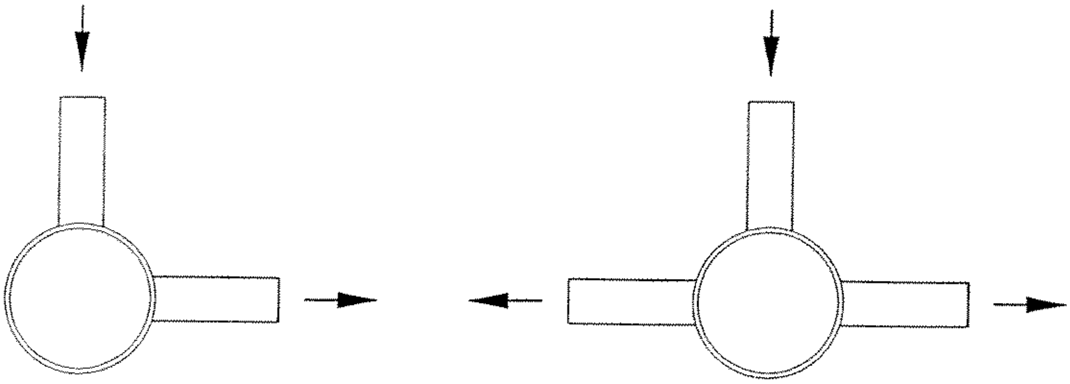


Figure 5.10 Multiplanar TT and T-DT joints subject to axial loads of the opposite sense

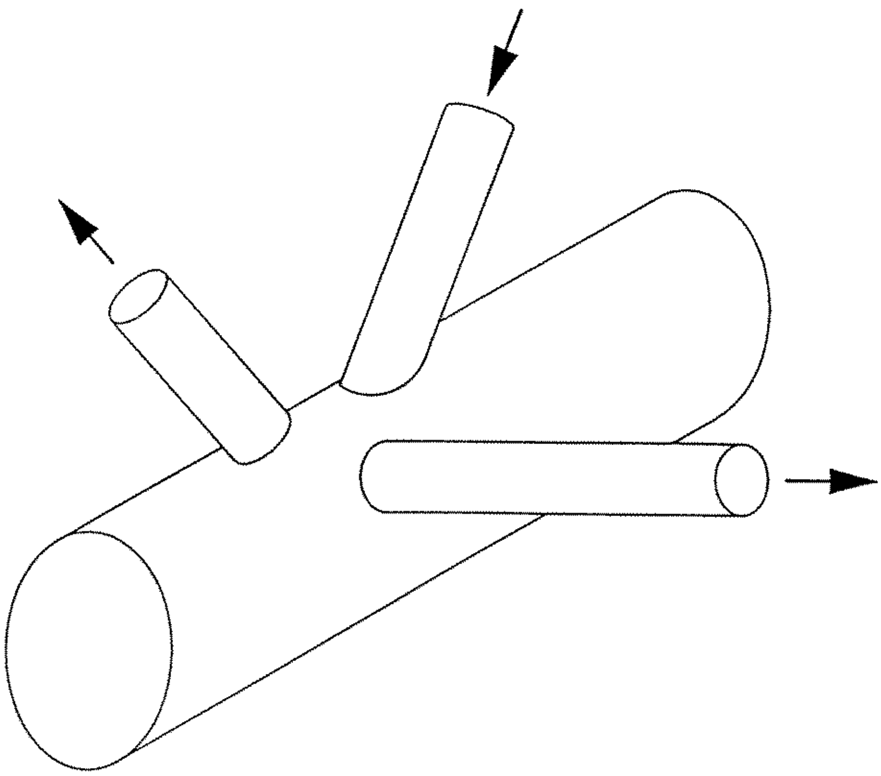


Figure 5.11 A multiplanar K-T joint

6. STATIC STRENGTH OF RING STIFFENED JOINTS

6.1 General

Internally ring stiffened joints are defined as those with complete annular stiffeners welded internally into the chord, in the region of the brace/chord intersection. An example of a ring stiffened K joint and definitions of relevant parameters are illustrated in Figure 6.1. Stiffeners may be of any uniform cross section and may be of complete diaphragm configuration.

Ring stiffeners increase the resistance of chords to radial deformation and any change in ovality. Therefore, they may be used to enhance the static strength of some joint types such as X joints and highly loaded leg launch runner joints. They are particularly efficient for large diameter thin wall chords where excessively thick cans might otherwise be required. In addition ring stiffened joints have generally lower stress concentration factors than simple joints.

It should be noted that since the welding of stiffeners inside some chord members is difficult and time consuming, the criteria for use of internal ring stiffeners should be assessed from both the fabrication and design points of view. Further information is given in Chapter 2.

6.2 Review of Existing Design Codes

Apart from general statements, none of the design codes give direct or definitive guidance on static strength computations for ring stiffened joints. This is consistent with the almost complete lack of data on such joints.

API-RP2A (WSD and LRFD, 1993)

A general paragraph entitled *'Other Complex Joints'* (in both WSD and LRFD versions of API-RP2A) states that such joints (includes internally stiffened joints) may be designed on the basis of appropriate experimental or in-service evidence. In the absence of such evidence, an appropriate analytical check is recommended as follows:

'This check may be done by cutting sections which isolate groups of members, individual members, and separate elements of the joint (i.e. gussets, diaphragms, stiffeners, welds in shear, surfaces subjected to punching shear), and verifying that a distribution of stress can be assumed that satisfies equilibrium without exceeding the allowable stress of the material'.

Further reference to stiffened joints is made in the Section entitled *'Load Transfer Across Chords'* where the codes states: *'Special consideration is required for more complex joints. For multiple branches in the same plane, dominantly loaded in the same sense, the relevant crushing load is* $\underline{\Sigma P_i}$ *Sin* $\underline{\phi_i}$. *An approximate closed ring analysis may be employed, including plastic analysis with appropriate safety factors, using an* *effective chord length as shown in Figure 4.3.4-1* (Figure 6.2).

Any reinforcement within this dimension (e.g. diaphragms, rings, gussets or the stiffening effect of out of plane members) may be considered in the analysis, although its effectiveness decreases with distance from the branch footprint'. It is further recommended that no chord check is necessary for joints which have *'two or more appropriately located diaphragms at each branch'* at least as thick as the wall thickness of the corresponding branch member; such joints need only be checked for local capacity. The code recommends that, for cross joints with diaphragms, the local capacity may be calculated using the provisions for simple joints (Section 3) with Q_u taken as $(3.4 + 19\beta)$.

AWS (1994)

This codes recognises the use of stiffeners by stating that *'general collapse is particularly severe in cross connections and connections subjected to crushing loads. Such connections may be reinforced by increasing the main member thickness, or by use of diaphragms, rings or collars'.* However, no design guidance is given. The statement draws attention to leg launch runner joints, which, although not of DT/X geometric configuration, behave as cross joints and should be designed accordingly.

CSA (1992)

Guidance on *complex joints*, defined as *those in which internal or external stiffeners are employed* is restricted to the following statements:

i) *In cases where stiffeners must be introduced to increase the chord strength, the minimisation of local stress-raising effects should be considered in the stiffener design and positioning.*

ii) *Resistances of complex joints shall be calculated by lower bound analysis or other rational methods of analysis, or shall be determined by experimental tests.*

CIDECT (1991)

The CIDECT code makes no reference to the static strength design of internally ring stiffened joints.

DnV (1993)

With reference to joints stiffened by gussets, diaphragms, ring stiffeners or by grouting, Clause *E 105* states that such joints *may be used to obtained an enhanced performance. Such enhanced performance is to be documented by detailed analysis (FEM-analysis) model tests or parametric formulae, where appropriate.* In addition, Clause *E 500* on the static strength of complex joints, not covered by explicit design guidance, contains a "Guidance note" on performing approximate analytical checks which is effectively similar to that of API-RP2A.

HSE (1990)

Referring to joint types such as stiffened joints, cast joints, and grouted joints, Clause *21.2.4* states that a combination of test data, analytical techniques or conservative estimates of strength may be adopted for designing such joints, subject to Certifying Authority approval. It also recommended that care must be exercised when designing such joints on the basis of a limited test programme.

NPD (1990)

Guidance on the design of complex joints are restricted to general statements broadly similar to those in DnV (1993).

6.3 Review of Published Information

6.3.1 Marshall (1992)

In his thorough design guide entitled 'Design of welded tubular connections', Marshall (1992), describes in some detail a practical design procedure for ring stiffened joints using as an example joints in the Bullwinkle Jacket. Early design calculations that can thicknesses of nearly 7 inches would be required for simple unstiffened joints. Since this exceeded the cold forming capacity of most fabricators, an alternative stiffened design was investigated, which allowed the reduction of joint can thickness to around 4 inches. The design procedure is reported to include consideration of the following:

i) Punching shear in shell: Application of the punching shear concept (derived for simple joints) to stiffened joints.

ii) Membrane loads in shell: Checking the capacity of the cylindrical shell to carry axial membrane stresses, including the interaction of these with punching shear in the shell.

iii) Demand/Capacity in Ring/Diaphragm: Design of the ring stiffeners to carry the applied loads.

With regard to the design of ring stiffened joints in general, Marshall states the following: ' Stiffening can be designed with clearly identifiable load paths, so that the designer is not dependent on finite element analysis or empirical formulas, with their potential for latent errors and mis-application. Being able to conceptualise also helps the formulation of design strategies, as opposed to a trial-and-error approach. A stiffened joint can be a challenging structure itself. A design approach which consists of cutting sections and taking free bodies may be loosely justified by the lower bound theorem of plasticity, provided that material selection and detailing are such that yielding can occur without premature failure by local overstraining, brittle fracture, or local buckling. Success of the method depends on the perceptiveness and thoroughness with which each part of the connection is examined. It follows that stiffened joints require more engineering attention than simple joints. Also stiffened joints usually end up being more conservatively designed'.

6.3.2 Sawada et al (1979)

This paper reports static and fatigue tests on T joints stiffened using one ring welded inside the chord along the brace centreline. Static strength data are reported for two unstiffened joints and seven ring stiffened joints (Table 6.1).

The authors suggest that the strength of the stiffened joints may be estimated using the 'cut and try' method based on the lower bound theorem of plasticity. The static strength of a stiffened joint is expressed as the sum of the strength of the joint in the unstiffened condition (ie. as a simple joint) and the shear strength of the ring stiffener , assuming that the ring shears in two planes. The method is illustrated in Figure 6.3 and may be expressed as follows:

$$P_{u,stiffened} = P_{u,unstiffened} + 2H_s t_s F_{y,s}/\sqrt{3}$$

where H_s, t_s, and $F_{y,s}$ are the width, thickness and yield strength of the stiffener.

Application of this method with $P_{u,unstiffened}$ based on an empirical equation for simple T/Y joints proposed by Akiyama et al (JSSC, 1974), is reported to result in predictions in good agreement with the measured strength of the stiffened joints. Therefore the authors suggest that the above method is sufficiently accurate for engineering purposes.

Spec.	Joint properties			Ring properties			Strengths				Strength ratios	
	T mm	γ	F_y N/mm²	H_s mm	t_s mm	$F_{y,s}$ N/mm²	(1) P_{meas} kN	(2) P_{pred} HSE kN	(3) P_{pred} HSE# kN	(4) HSE# + $2H_s t_s F_{ys}/\sqrt{3}$ kN	(1)/(3)	(4)/(1)
R-0-1	9.93	35.8	389	NA	NA	NA	385	491	385	NA	NA	NA
R-0-2	10.38	34.3	363	NA	NA	NA	396	501	393	NA	NA	NA
R-1-1	10.38	34.3	363	100	8.21	439	876	501	393	809	2.23	1.08
R-1-2	10.27	34.6	368	100	8.21	439	798	497	390	806	2.05	0.99
R-1-3	9.44	37.7	394	100	8.30	338	806	450	353	677	2.28	1.19
R-2	10.06	35.3	385	100	5.90	257	606	499	392	567	1.55	1.07
R-3	10.27	34.6	368	100	10.16	273	903	497	390	712	2.32	1.27
R-4	9.93	35.8	389	80	8.21	439	791	491	385	718	2.05	1.10
R-5	10.06	35.3	386	120	8.21	439	963	500	392	891	2.46	1.08

All joints have a T configuration and were tested under compression loading
All joints have: D = 711.2mm; d = 318.5mm; β = 0.45; τ = 0.7; L = 3600mm
R-0-1 and R-0-2 are unstiffened joints
Each of R-1(1-3), R-2, R-3, R-4 and R-5 contained a centrally positioned ring stiffener
H_s and t_s are, respectively, the width and thickness of the stiffener
F_y and $F_{y,s}$ are, respectively, the yield strength of chord and stiffener
(1) = Measured strength
(2) = Predicted strength based on the HSE mean equations
(3) = (2) * 0.785. The correction factor 0.785 ≈ average of (1)/(2) for R-0-1 and R-0-2
(4) = (3) + $2H_s t_s F_{y,s}/\sqrt{3}$. The second term represents the stiffener shear strength

Table 6.1 Experimental results for ring stiffened T joints subject to axial compression (Sawada et al, 1979)

Table 6.1 shows predictions of the strength of the stiffened joints, $P_{u,stiffened}$, with $P_{u,unstiffened}$ evaluated using the HSE mean equation for compression loaded T/Y joints, corrected on the basis of the measured strengths of the two unstiffened joints. It can be seen clearly that the predictions are in good agreement with the measured strength of the stiffened joints.

With regard to the strength enhancement due to stiffening, Table 6.1 shows that the strength ratio of stiffened joints to simple (unstiffened) joints is in the range 1.55-2.46. This implies a strength enhancement between 55% and 146%.

6.3.3 Murthy et al (1992)

This paper reports data on the effects of ring stiffeners on the static strength, fatigue and stress concentration factors of T and Y joints. The stiffened joints had three ring stiffeners welded inside the chord under the saddle and two crown positions. Four static strength tests were performed on compression loaded two stiffened T joints (β = 0.7; γ = 13.5 and 16.9) and two nominally identical unstiffened joints. The measured strength enhancement due to stiffening is 67% for the γ = 16.9 joint and 73% for the γ = 13.5 joint (Table 6.2). A number of important parameters are not reported including:

- The yield stress of the chord, brace and rings
- The failure criterion used in determining the capacity of the stiffened joints and the corresponding load deformation data. It is reported that the stiffened joints were 'still intact even at failure load and can still have a residual strength'.

The lack of important information precludes further evaluation of the data.

Spec.	Joint properties							Ring properties			Measured Strength	Measured strength ratio: Stiffened / unstiffened
	D mm	d mm	T mm	t mm	β	γ	F_y N/mm²	H_s mm	t_s mm	$F_{y,s}$ N/mm²	kN	
TUS1	327	220	9.7	5.8	0.67	16.9	---	NA	NA	NA	527	NA
TUS2	324	219	12.0	8.2	0.68	13.5	---	NA	NA	NA	1020	NA
TS1	327	220	9.7	5.8	0.67	16.9	---	70	10	---	878	1.67
TS2	324	219	12.0	8.2	0.68	13.5	---	75	12	---	1765	1.73

All joints have a T configuration and were tested under compression loading
All joints have a chord length equal to 1800mm
TUS1 and TUS2 are unstiffened joints
Each of TS1 and TS2 contained three internal ring stiffeners: One was positioned under the saddle and one under each of the crown locations.
H_s and t_s are, respectively, the width and thickness of the stiffener
F_y and $F_{y,s}$, the yield strengths of chord and stiffeners are not reported

Table 6.2 Experimental results for ring stiffened T joints subject to axial compression (Murthy et al, 1992)

6.4 Failure Modes

Typical load-deformation characteristics for axially loaded stiffened and unstiffened joints are reported by Sawada et al (1979). These indicate that internal ring stiffening can increase the static strength significantly. In addition, the maximum loads the joints can sustain are reached at roughly the same deformation levels, indicating that carefully selected ring stiffener size and position may not affect the ductile properties of the joint. Failure usually occurs either by elastoplastic buckling of the chord section following flexural-torsional buckling of the ring stiffeners, or local buckling of the brace wall in the vicinity of the joint. The second failure mode would suggest that for heavily stiffened joints, brace buckling could be the limiting criterion in design.

No ultimate load tests have been carried out for moment loaded ring stiffened joints.

6.5 Conclusions and Recommendations

Stiffener positions

The following stiffener positions are recommended for axially loaded joints:

i) One ring stiffener: Locate at the saddle position

ii) Three ring stiffeners: Locate at the saddle and two crown positions.

iii) Greater than three ring stiffeners: Locate three of the rings as in configuration ii).

The rings may be positioned at some characteristic distance apart within the brace footprint provided that some valid evidence on their benefit is available.

No data are available on moment loaded joints for the development of any detailed guidance on stiffener positions. Based on simple engineering judgement, it is recommended that the position of stiffeners should reflect the principal load paths for the transfer of moments from brace to chord: stiffeners should therefore be located at the crown and saddle positions for in-plane and out-of-plane moment loaded joints respectively.

Joint design

Insufficient data are available to develop design guidance. It is recommended that in the absence of experimental or numerical evidence, ring stiffeners should be designed to transmit all brace loads. Formulae presented by Young (Roark's formulas for stress and strain, 1989) for ring analysis may be used for this purpose. The appropriate elements of ring stiffened joints may be designed on the basis of the allowable stress approach. Procedures discussed by Marshall (1992) may be particularly useful. Alternatively, the use of nonlinear finite element analysis is recommended. In particular finite element analysis is ideally suited to sensitivity studies to investigate the effects of individual parameters such as the geometry, location or number of stiffeners.

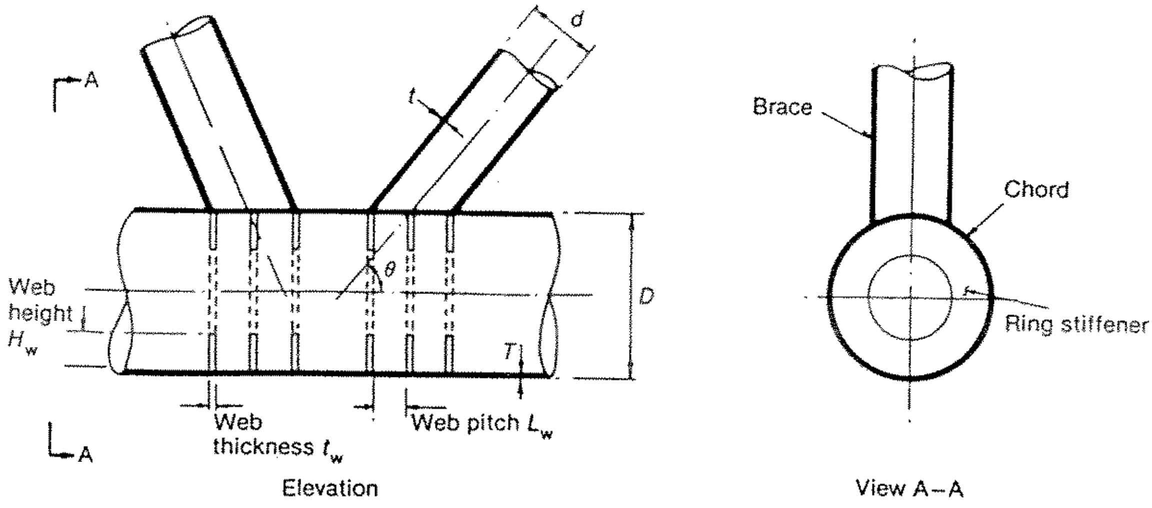


Figure 6.1 Internally ring-stiffened joint: Geometric notation

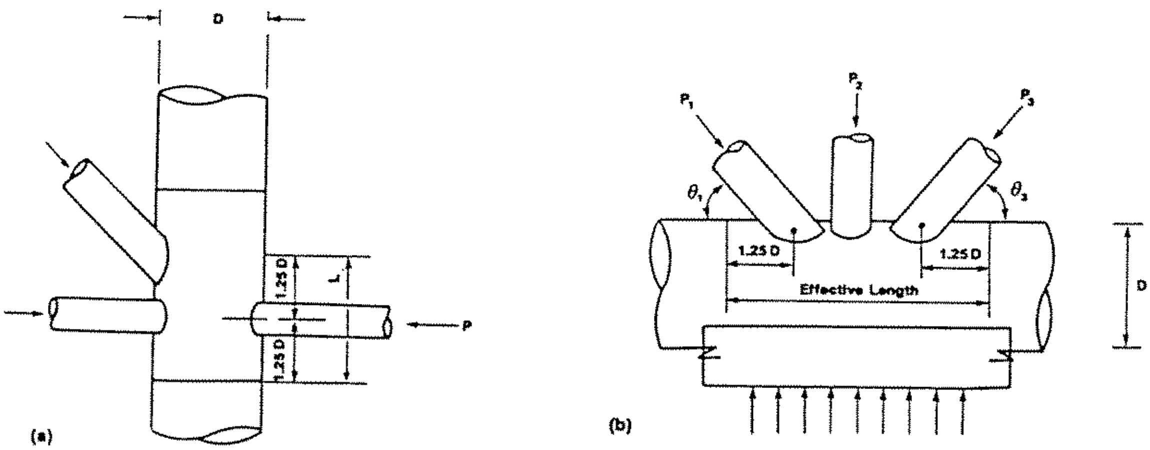


Figure 6.2 Definition of effective chord length (API-RP2A, 1993)

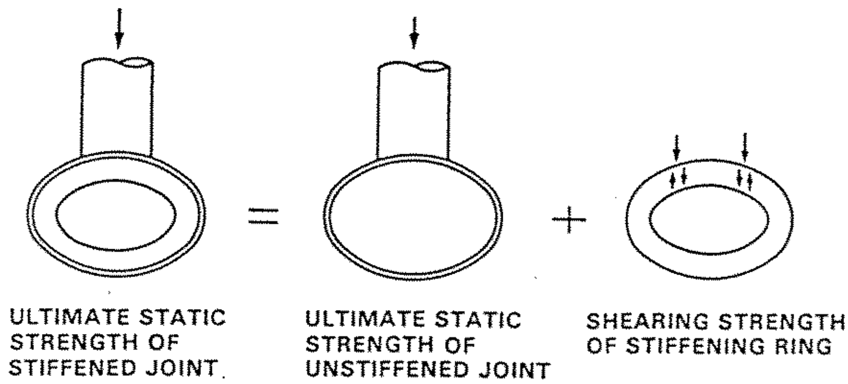


Figure 6.3 Method for estimating the ultimate static strength of a stiffened joint (Sawada et al, 1979)

7. STATIC STRENGTH ASSESSMENT OF CAST JOINTS

7.1 General

Cast joints are formed using a casting process as illustrated in Figure 7.1. They can be of any geometry and of variable wall thickness. An example of a multiplanar cast joint is given in Figure 7.2

Cast joints are a recent development of foundry practice in relation to offshore activities. These developments have been made possible by improvements in steel processing, micro alloying and casting design which allowed steel manufacturers to produce sound castings of suitable quality and composition for use in offshore environments.

There are two basic design methods:

1. Direct substitution of a welded joint using a casting. The basic joint geometry is retained with slight modifications to take advantage of some of the aspects of casting technology. Therefore, the basic design approach may be considered broadly similar to that of welded joints.

2. Optimised cast joints (manufacturers' term). This method exploits fully the advantages of cast joints by employing variable thicknesses and geometries to optimise joint performance. As these modifications to the geometry are substantial, a radical change in design approach from that of welded joints would be required.

In practice, it is advantageous to combine the two approaches.

Figure 7.3 illustrates some types of casting which have been proposed by various investigators.

The use of castings for tubular joints offers obvious advantages such as a homogeneous integral component free from stress raisers associated with welded joints and with significantly lower residual stresses. In addition, the thickness of the casting can be varied to accommodate any areas of high stress. Castings also offer the opportunity to place padears or launch rails as an integral part of the joint.

The basic advantages of cast steel joints may be summarised as follows (Walker at al, 1980):

1. Greatly improved fatigue resistance due to the essentially isotropic nature of the casting.

2. Significant reduction in platform construction costs and greatly reduced in-service inspection and maintenance.

3. No need for stiffeners, because of inherent high stiffness and low stress concentration factors.

4. Improved joint efficiency resulting from absence of fabrication problems, and greater design flexibility.

5. Ability to cast thick-section joints and avoid complex problems associated with internal stiffening.

7.2 Review of Existing Design codes

Some design guides include general statements on cast joints with regard to fatigue design (eg. HSE Guidance Notes, 1990). However, no guidance is given on static strength design.

7.3 Review of Published Formulae

The two following alternative methods have been proposed for determination of the static strength of cast joints. The first, based on a modified API "punching shear" model, applies to direct substitution of casting; while the second, based on a theoretical approach, is intended for overlapping cast joints.

7.3.1 Modified API punching shear

This approach account for the enhancement in static strength in cast joints when compared to equivalent welded joints by the increase in effective shear area provided by the fillet radii. A modified API punching shear equation has been derived by "River Don Casting Ltd":

$$f_p = (f_a \sin\theta / K_a + f_b / K_b)\ t / [T + (2\Delta x_t T / d)]$$

where

- f_p is the applied punching shear stress
- f_a is the applied axial stress
- f_b is the applied bending stress
- θ is the included angle of the joint
- T is the chord wall thickness
- t is the brace wall thickness
- d is the brace diameter
- Δx_t is the length from the fillet radii tip to the centre of the brace wall shell
- K_a, K_b are constants relating to the footprint of the brace

It should be noted that the above modified API formula is based on early versions of API which have subsequently been revised.

7.3.2 Theoretical parametric equations

Based on theoretical load transfer mechanisms and allowable AISC stresses, parametric equations for the static strength of overlapping cast joints under axial loading have been proposed by Nakamura et al (1985). Depending on joint configuration, three modes of failure (membrane, 'scratching' (defined as a shear failure between the braces and the chord), and shearing between braces), were identified and are shown in Figure 7.4. Joint types and geometric notations are illustrated in Figures 7.5 and 7.6, respectively. The design equations for each failure mode are as follows:

Mode of Failure	Joint Type	Axial Ultimate Strength
Membrane failure	K, KT YT	$F_y\ T\ (0.4\ 1c+0.3d)\ \cos^{-1}\theta$ $F_y\ T\ (0.8\ 1c+0.6d)\ \cos^{-1}\theta$
Scratching failure	K, KT YT	$0.2\ F_y\ t_{sc}\ 1c\ \cos^{-1}\theta$ $0.4\ F_y\ t_{sc}\ 1c\ \cos^{-1}\theta$
Shearing failure between braces	K, KT, YT	$0.4\ F_y\ t_{ss}\ 1_s\ \gamma_s^{-1}\ \cos^{-1}\theta$

where

- F_y is the yield stress
- T is the chord wall thickness
- d is the brace diameter
- 1c is the projected length of the intersection between chord and braces (see Figure 7.5)
- 1s is the effective projected intersection length between braces and is defined as follows:

  $1s = 1_{yy}$ if 1_{yy} exists
  $1s = 1_{yt}$ if 1_{yy} is absent (Figure 7.6)

- t_{sc}, t_{ss} are average brace wall thicknesses along the intersections between brace and chord and between stubs, respectively.

It should be noted that the parametric equations cover axial loading only.

7.4 Review of Available Test Data

No static strength tests on cast joints are known to exist. This lack of data precludes evaluation of the above formulae.

7.5 Conclusions and Recommendations

It is recommended that if cast joints are considered, the designer should seek specialist advice. This is especially true for optimised cast joints where radical design criteria are followed. Alternatively, non-linear finite element analysis may be used but due consideration should be given to the geometric and material characteristics of cast joints including the effects of casting geometry, stress-strain characteristics, and casting defects.

In addition, it should be remembered that the performance of a cast joint beyond first yield may not correspond to the load redistribution which is achieved in welded joints. The post yield behaviour of cast joints should be investigated in order to ensure that the safety factors against total collapse are comparable to those of welded joints.

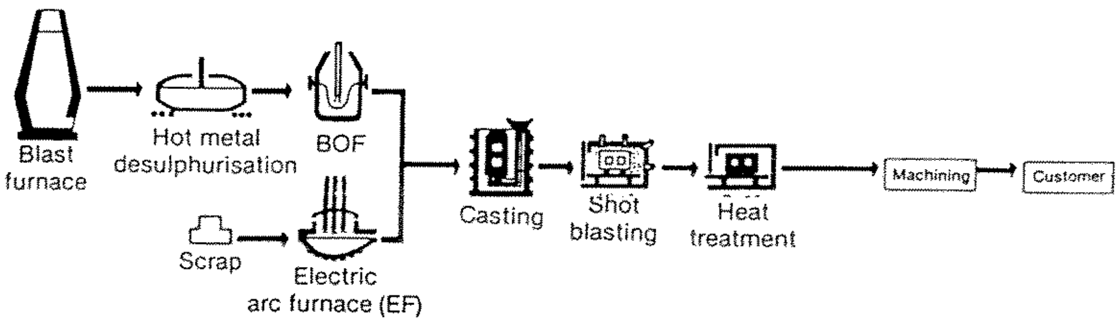


Figure 7.1 Cast joints: Typical casting process

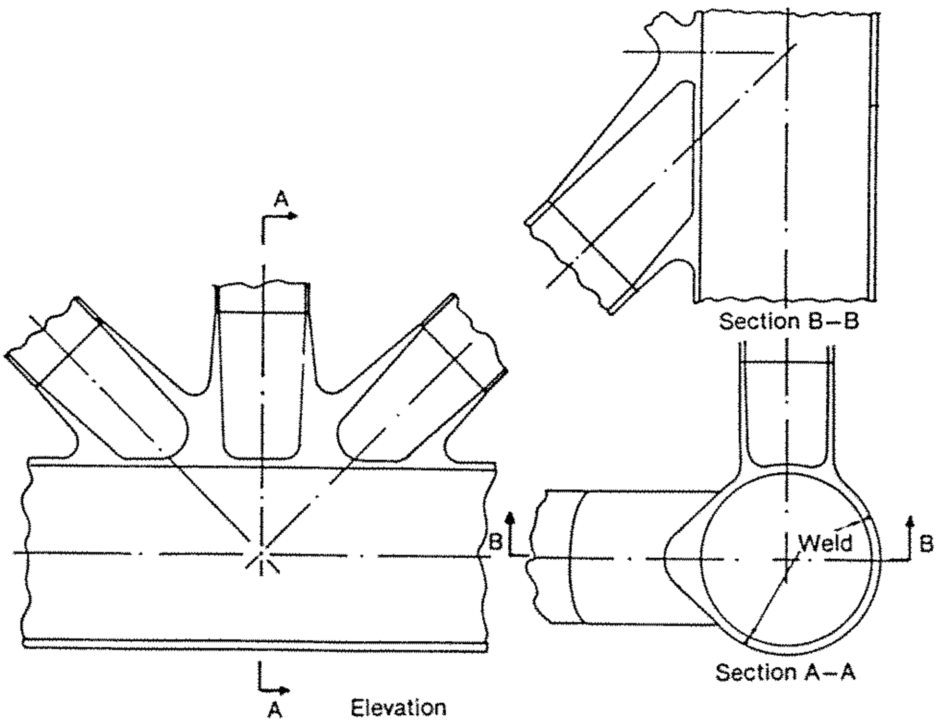


Figure 7.2 Substitution cast joint

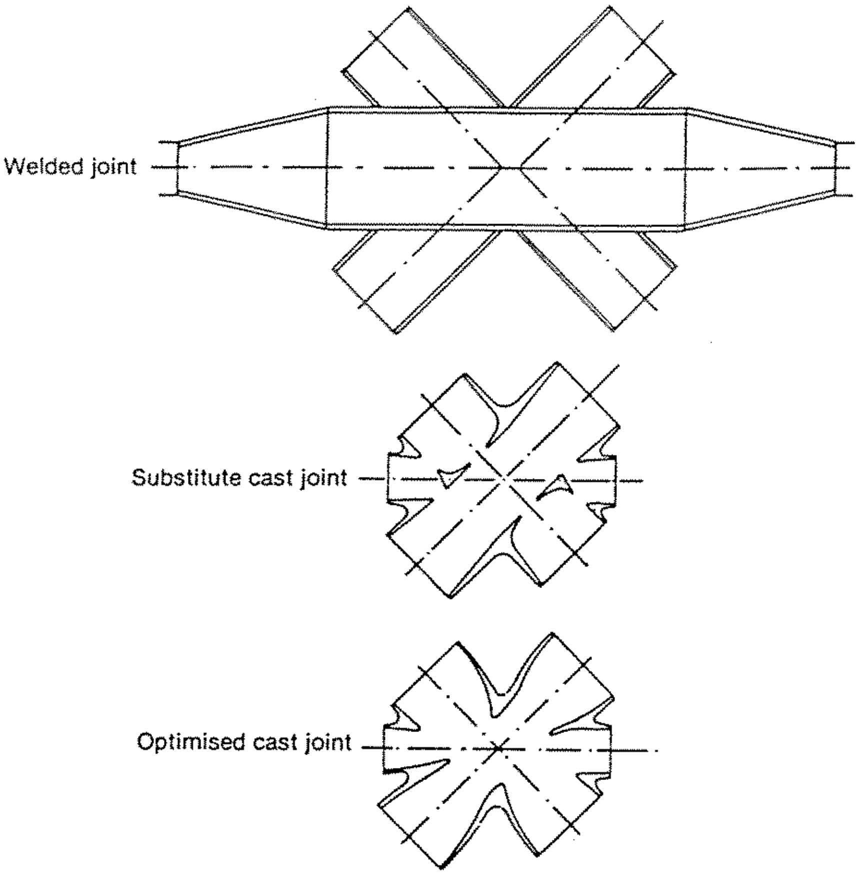


Figure 7.3 Comparison of welded and cast joints

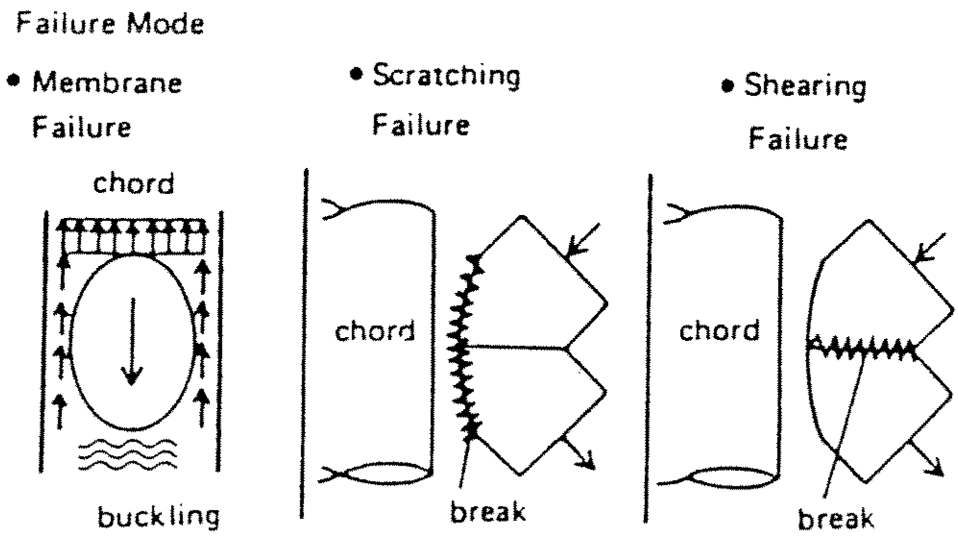


Figure 7.4 Failure modes for overlapped nodes

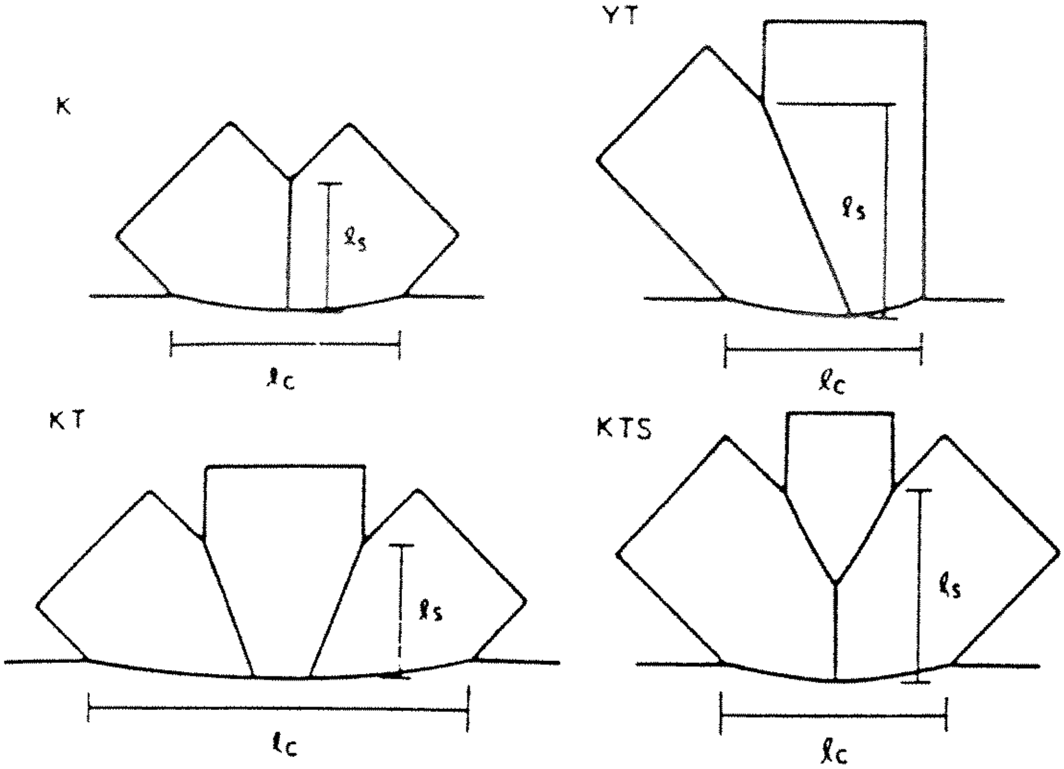
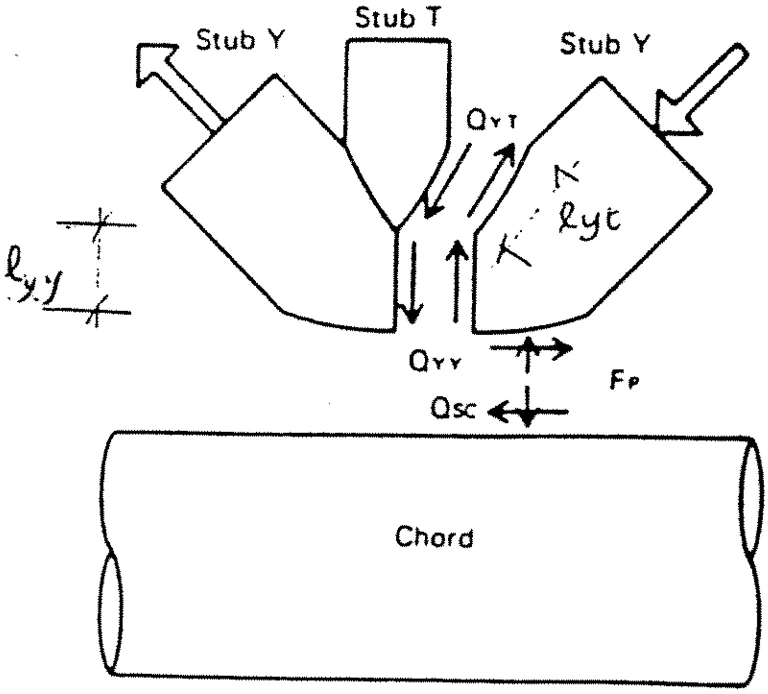


Figure 7.5 Node types and overlapped ratio



Fp	:	Punching Force
Qsc	.	Scratching Force
QYY	:	Shearing Force between Stub Y and Stub Y
QYT	:	Shearing Force between Stub Y and Stub T
Stub Y	:	Diagonal Stub to Chord
Stub T	:	Normal Stub to Chord

Figure 7.6 Forces interaction

8. STATIC STRENGTH OF COMPOSITE JOINTS

8.1 General

Composite joints are defined as those in which the chord member is either fully filled with a cementitious material (eg. grout) or in which the chord member contains a pile and a grouted annulus. Sometimes the pile is filled with grout to provide additional strength. The nondimensional parameters relevant to composite joints are illustrated in Figure 8.1.

Composite joints provide enhanced strength due to the restraint provided by the grout which reduces chord wall deformation. They offer an additional advantage over internally or externally stiffened joints in that less fabrication effort is required. grouting technology is well proven and grouting works can be executed with confidence.

Historically, composite joints have often occurred in offshore steel jacket structures not through specific design requirements but as a by-product of the foundation system. In a shallow water jacket structure, foundation piles are often driven through the main leg members. The annulus between the pile and leg is filled with a cement grout. Brace members welded to such legs form composite joints which exhibit greater static strength than simple joints due to the composite behaviour of the cement grout, pile and chord. Composite joints are also formed in deep water skirt-piled structures.

When composite joints are formed as a by-product rather than in order to satisfy specific design requirements, the enhancement in strength is often assessed only as part of a re-analysis of the structure during its service life. However, the incorporation of composite joints in the initial design phase can result in significant cost savings (Billington and Tebbett, 1983). Filling the tubular chord (and/or brace) members with a cementitious material results in the efficient use of materials in applications most suited to their mechanical properties. The cementitious material is contained and therefore greater strength and ductility may be achieved. The steel tubular is the containment medium and is therefore predominantly subjected to hoop tension, and the cementitious filling minimises any tendency for buckling of the steel shell. Billington (1981) summarises the improvements obtained by composite construction in offshore jacket structures as follows:

1. Axial and bending capacities are greatly enhanced.
2. Increased resistance to external hydrostatic pressure is provided, thus reducing or eliminating the need for internal or external stiffeners.
3. Energy absorption characteristics are greatly improved.
4. SCFs are considerably reduced, leading to enhanced fatigue endurance.

8.2 Review of Existing Design Codes

No definitive guidance or formulae for the static strength design of composite joints are given in any code. Some codes include general statements mostly under the general heading "Complex joints". These are reviewed in Section 6.2.

8.3 Review of Published Information

8.3.1 Wimpey-BP Programme

This testing programme was undertaken as a part of structural reappraisals of existing platforms. A total of twenty reduced scale T shaped joints were tested. The dimensions of the specimens, grouped in either Series A or W, are shown in Table 8.1. Specimens in series A and W represent existing joints in the ADMA and West Sole structures, respectively. Each series contained ten specimens, five were grouted and five remained ungrouted. All grouted specimens contained a centrally positioned pile and a grouted annulus, but in addition, those in Series A contained a grout filling in the pile member. In each series, two specimens (one grouted) were tested under tension, four specimens (two grouted) were tested under compression and a similar set was tested under in-plane-bending.

Some data on the Series A tests were published by Tebbett et al in 1979 and reported in the UEG Design Guide in 1985. Results of the full programme, documented in two Wimpey reports (Wimpey, 1977), have been recently made available to the Tubular Joints Group by BP. Data on measured capacities and failure modes are given in Table 8.2 and discussed in Section 8.4.

Series	D	T	d	t	L	β	γ	F_y	F_t	F_{yb}	T_p	D_p	Grout F_{cu}
A	508	7.94	168.3	7.94	2032	0.33	32.0	335	463	312	17.46	317.5	67.1
W	508	12.7	193.7	6.35	2032	0.38	20.0	338	462	256	7.94	457.2	65.7

Table 8.1 Geometric and material properties for grouted and ungrouted T joints (units mm & N/mm^2), (Wimpey, 1977)

Tebbett et al (1979), commenting on the results of Series A, proposed the following approach to design fully grouted joints which depends on whether brace stresses are compressive or tensile:

<u>Compressive brace stresses only</u>: These result from axial compression or combined bending and compression where $|f_a| \geq |f_b|$, where f_a and f_b are the axial and bending stresses respectively. For this case it is suggested that "punching shear" need not be considered for a fully grouted joint, and that the design of the joint will be controlled either by the permissible brace stresses or by the fatigue performance.

Partially or wholly tensile brace stresses: These result from axial tension, pure bending or combinations of bending and axial tension or compression where $|f_a| \le |f_b|$. For these cases it is suggested that the joint should be designed against "punching shear". For joints having the same geometry as the specimens tested, Tebbett recommends that a 60% enhancement be applied for design purposes.

Design for "punching shear", referred to above, applies to the procedures of the Seventh Edition of API-RP2A (1976).

Joint ID	Load Type	Grouted Annulus	Grouted Pile	Measured Strength Axial: kN IPB: kN.m	Grouted / Ungrouted Strength	Reported Failure Mode
A11	tens.	No	No	470.3		cw
A12	tens.	Yes	Yes	815.1	1.73	cw
A13	comp.	No	No	259.1		a
A14	comp.	Yes	Yes	1663.0	average= 6.73	B
A15	comp.	No	No	240.1		a
A16	comp.	Yes	Yes	1698.9		B
A17	ipb	No	No	36.95		a,cw
A18	ipb	Yes	Yes	68.33	average= 1.77	cw
A19	ipb	No	No	35.94		a,cw
A20	ipb	Yes	Yes	60.74		cw
W1	tens.	No	No	1151.8		a
W2	tens.	Yes	No	1280.4	1.11	cw
W3	comp.	No	No	668.6		a
W4	comp.	Yes	No	1072.1	average= 1.61	a
W5	comp.	No	No	668.6		a
W6	comp.	Yes	No	1079.1		a
W7	ipb	No	No	77.44		a,B,cw
W8	ipb	Yes	No	86.05	average= 1.09	a,B,cw
W9	ipb	No	No	78.96		a,B,cw
W10	ipb	Yes	No	84.02		a,B,cw

Nomenclature of failure modes:
a: Local plastic deformation of chord wall,
B: Yield or buckle of brace member, and
cw: Cracks at weld toe.

Table 8.2 Strengths of grouted joints subject to compression, tension and in-plane bending loads (Wimpey, 1977)

8.3.2 Tebbett (1982)

In this paper Tebbett discusses the reappraisal of steel jacket structures allowing for the composite action of grouted piles, highlighting the benefits of the associated composite joints with regard to static strength, stress concentration factors and fatigue. Tebbett also reports that a major testing programme (over 70 tests) was underway at Wimpey Laboratories to produce design guidance on composite joints. Findings from this programme remain confidential, but Tebbett presents a set of five graphs produced in the preliminary stages of the programme providing information mainly on the static strength of fully grouted joints. These graphs are reproduced in Figures 8.2-8.6 and discussed in Section 8.4.

8.3.3 Le Meur et al (1994)

This paper reports some findings from a recent research programme which included experimental and analytical investigations into the static and fatigue strengths of composite joints (grouted annulus only). A total of Five static strength tests were performed on two T and three DT joints. One T joint was tested under in-plane bending and the other under out-of-plane bending, while two of the DT joints were subjected to tension and one to compression. The geometric and material properties, reported in the paper, are reproduced in Table 8.3.

The observed ultimate strengths are reported to be much higher than predictions of ungrouted strength based on the ARSEM parametric formulae (1987), which are effectively the equations of EuroCode 3 and CIDECT. Predictions of grouted strength were also evaluated by substitution of an equivalent chord wall thickness, T_{eq}, in the aforementioned formulae. This modification resulted in higher predictions (Table 8.4) but the authors suggest that the use of "specific" design formulae (undefined in the paper) would be more appropriate to take full advantage of the composite technique. T_{eq} was estimated using a formula based on Lloyds recommendations and reported in Part F of the UEG Design Guide (1985). Since the formula does not account for strength of the grout (F_{cu}), it is not clear how its application could result in different predictions for the tension loaded DT joints (Table 8.4).

D	T	d	t	L	β	γ	F_y	F_t	F_{yb}	T_p	D_p	Grout F_{cu}
508	9.5	210	10	1800	0.41	26.7	---	---	---	8.8	406.4	30 & 75

Table 8.3 Geometric and material properties of grouted T and DT joints (units mm & N/mm^2), (Le Meur, 1994)

A number of graphs showing comparisons of the recorded load-deformations curves and those predicted using nonlinear finite element analyses are given. It is suggested that such numerical simulations could be an effective tool to complement data from experiments, provided that the numerical modelling is carefully performed. However, it is noted that the analysis of a large number of grouted joints within the context of a design project would require a skilful team with vast computer resources. In this respect, it is suggested that numerical simulation seems at present at the bounds of engineering feasibility, and that the development of conventional design formulae or simplified numerical approaches would still be of great interest.

Joint	F_{cu} of grout N/mm^2	Loading	Experimental failure load Axial (kN) Moment (kN.m)	Predicted ungrouted strength (ARSEM 1987)	Predicted grouted strength (ARSEM 1987) with T_{eq}
DT	30	Comp.	1270	656	793
DT	30	Tension	1100	656	793
DT	75	Tension	1696	656	1180
T	30	IPB	≈103	---	≈83
T	30	OPB	≈66	---	≈45

Table 8.4 Measured and predicted strengths of grouted T and DT joints (Le Meur, 1994)

8.4 Review of Available Test Data

8.4.1 General

As reported earlier, a major test programme was undertaken in the early 1980s at Wimpey Laboratories to produce design information on static strength, stress analysis and fatigue of composite joints (Tebbett, 1982). In addition, it is stated in the UEG Design Guide (1985) that another programme was underway (probably in the early 1980s) at Det norske Veritas. This is reported to include some 24 tests on double-skin grout-reinforced joints. Results from both these programmes and from the recent French Programme (Le Meur, 1994) remain confidential. Since the limited published information does not allow a comprehensive design approach to be formulated, it is intended in the following section to review the broad design aspects for composite joints with reference to the data summarised in Section 8.3.

8.4.2 Failure modes

Composite joints can fail in a number of modes depending on load type, infill material type and joint configuration. In the absence of brace member failure, the failure modes described below may occur.

Typical load deformation curves for axially loaded grouted and ungrouted specimens are given in Figure 8.7. The increase in strength under compression or tension loading is governed by the load transfer mechanism. Compression loaded joints show a very large enhancement due to load transfer in bearing to the grout through the chord wall at the brace/chord intersection. For some compression loaded T joints an overall bending failure of the grouted chord may occur.

For tension loaded joints a similar enhancement in strength is noticed, as shown in Figure 8.7. Here the grout acts as a filler preventing ovalisation of the chord. The increase in strength is again due to load transfer, in bearing, to the grout. However, this load transfer does not occur under the brace member. failure usually occurs when local deformation of the chord wall under the loaded brace takes place. Examination of failed specimens shows usually that a gap between the chord and the grout has developed.

For moment loaded joints the failure mechanism is different to that of simple joints. Inward deformation of the chord wall is prevented and the centre of rotation at failure is displaced by half the brace diameter from the position expected for ungrouted joints. The mechanism of failure is therefore that of yield followed by extensive cracking of the chord wall, propagating from the tension side of the joint.

8.4.3 Comments on available data

The available data, summarised in Section 8.3, allow the following general comments to be made:

Fully grouted T joints: Compression

- Strength enhancement of specimens A13-A16 (β = 0.33, γ = 32) is in excess of 500% (Table 8.2). Strength of the grouted specimens A14 and A16 is limited by the brace member capacity.

Fully grouted T joints: Tension

- Strength enhancement of specimens A11-A12 (β = 0.33, γ = 32) is approximately 73% (Table 8.2).

- Figure 8.2 suggests that for $0.33 < \beta < 0.53$ and $\gamma = 20$, $P_{u,g}/F_yT^2$ may be approximated by the linear relationship: $(175\beta - 30)$.

- Figure 8.3 suggests that for $\beta = 0.33$ and $20 < \gamma < 42$, $P_{u,g}/F_yT^2$ may be approximated by the linear relationship: $(0.83\gamma + 12.5)$.

Fully grouted T joints: IPB

- Strength enhancement of specimens A17-A20 (β = 0.33, γ = 32) is approximately 77% (Table 8.2).

Fully grouted T joints: OPB

- Figure 8.4 suggests that for $0.35 < \beta < 0.58$ and $\gamma = 32$, $M_{u,g}/F_yT^2d$ may be approximated by the linear relationship: $(139\beta - 34)$.

- Figure 8.5 suggests that for $\beta = 0.33$ and $20 < \gamma < 42$, $M_{u,g}/F_yT^2d$ may be approximated by the linear relationship: (0.44γ).

Annulus only grouted T joints: Compression

- Strength enhancement of specimens W3-W6 (β = 0.38, γ = 20) is approximately 61% (Table 8.2).

Annulus only grouted T joints: Tension

- Strength enhancement of specimens W1-W2 (β = 0.38, γ = 20) is only about 11% (Table 8.2).

- Figure 8.6 suggests that for β = 0.38, γ = 20 and γ_g = 18.6, $P_{u,g}/F_yT^2$ decreases as γ_P (=$D_P/2T_P$) increases.

Annulus only grouted DT joints: Tension

- Increasing the grout strength, F_{cu}, appears to result in a substantial strength enhancement of DT joints with β = 0.41 and γ = 27 (Table 8.4).

Annulus only grouted T joints: IPB

- Strength enhancement of specimens W7-W10 (β = 0.38, γ = 20) is only about 9% (Table 8.2). However, strength of the grouted joints W8 and W10 may have been limited by brace member failure.

8.5 Conclusions and Recommendations

Published data on the static strength of composite joints are available for a very limited range of joint configuration and loading. These data may be useful for the design of similar joint geometries and load types. Alternatively, non-linear finite element analysis may be used provided that the numerical modelling is performed carefully and calibrated using reliable test data.

In the absence of appropriate data, it is recommended to seek specialist advice.

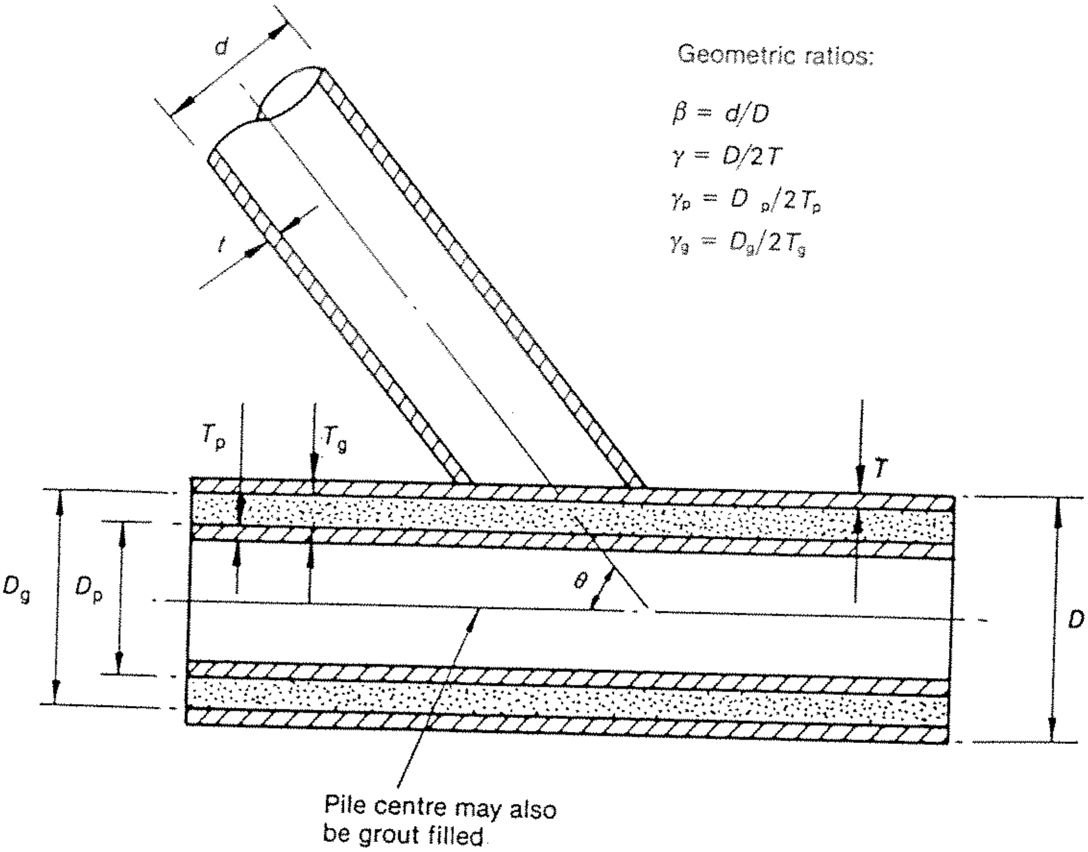


Figure 8.1 Composite joints: Geometric notation

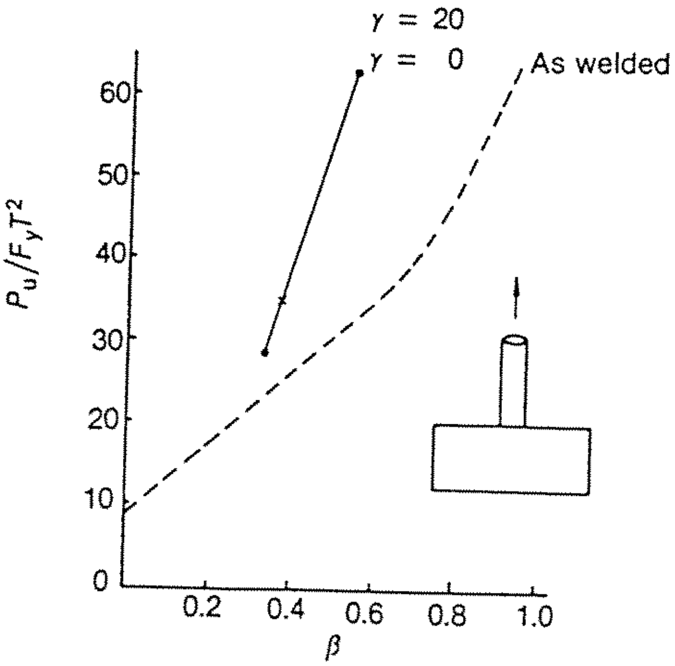


Figure 8.2 Fully grouted joint under axial tension: Ultimate strength results given by Tebbett (1982)

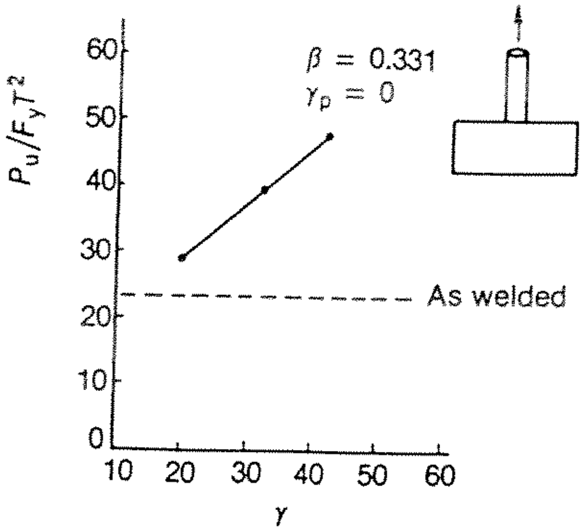


Figure 8.3 Fully grouted joint under axial tension: Ultimate strength results given by Tebbett (1982)

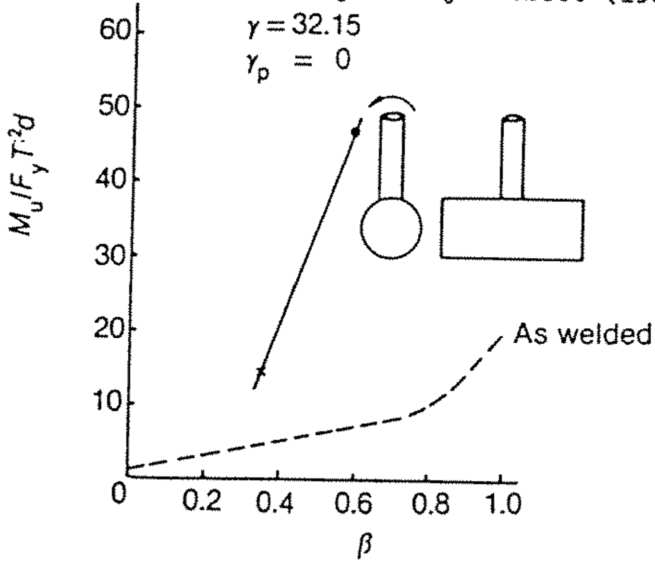


Figure 8.4 Fully grouted joint under out-of-plane moment: Ultimate strength results given by Tebbett (1982)

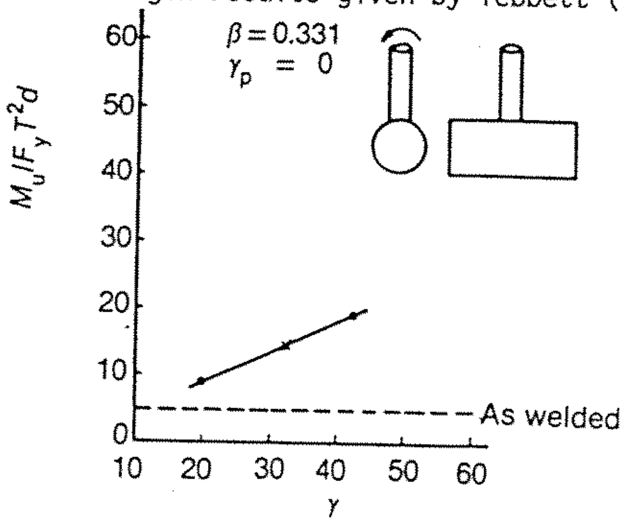


Figure 8.5 Fully grouted joint out-of-plane moment: Ultimate strength results given by Tebbett (1982)

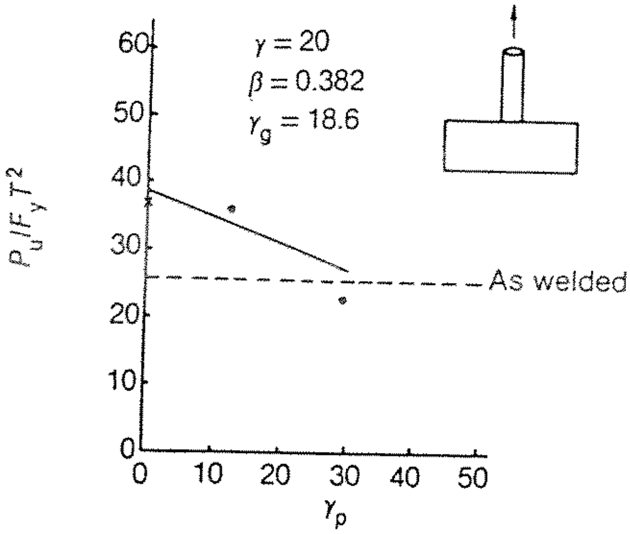


Figure 8.6 Grouted annulus joint under axial tension: Ultimate strength results given by Tebbett (1982)

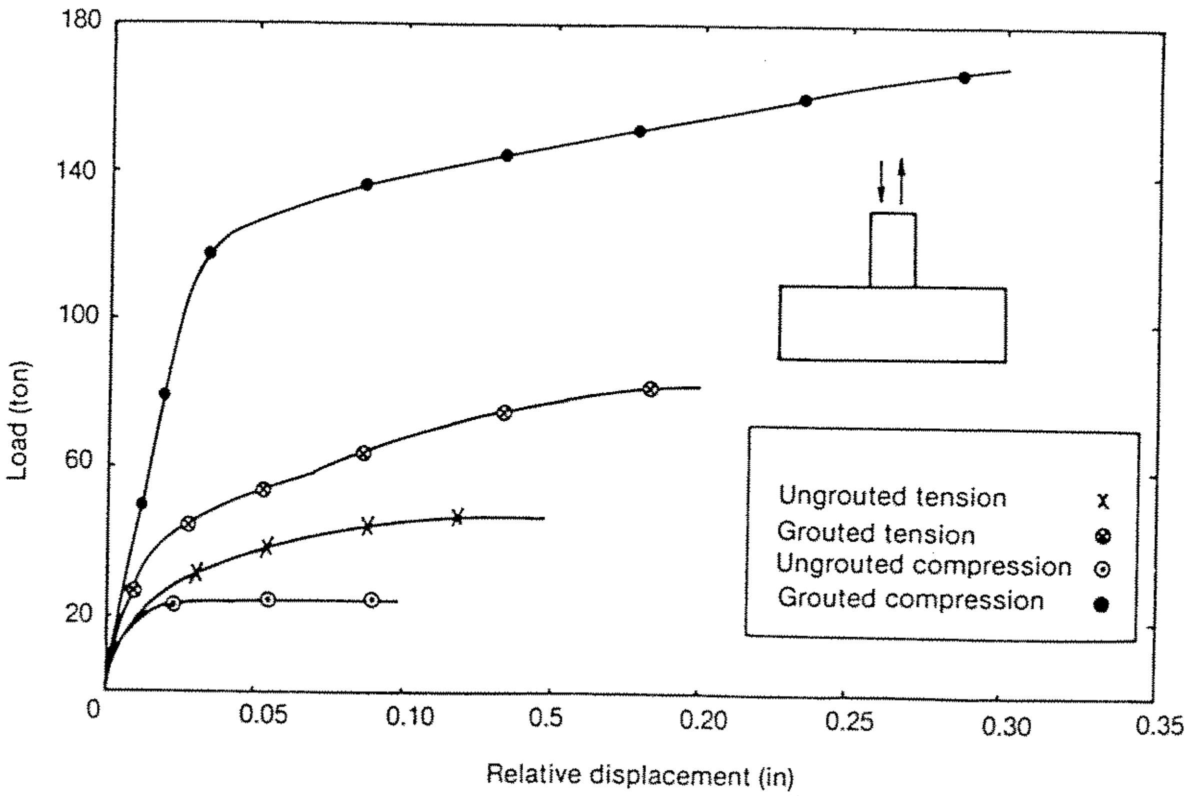


Figure 8.7 Typical load-deformation curves for axially loaded composite joints

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APPENDIX A3.1 FULL DATABASE ON SIMPLE JOINTS

Database on Simple Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Thetac (deg.)	Thetar (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm2)	Static (N/mm2)	(N/mm2)	Dynamic (N/mm2)	Static (N/mm2)	Mps (KN-m)	Pu (KN)	Ppc (KN)	Mu (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
T&Y-COMPRESSION																													
KANATANI	C-A-1	T	139.8	139.8	6.50	6.50		400	90		5.72	1.00	10.75	1.00		324		500	324	291		433.5			P	Yes	L = L2		
(1964, 1966)	C-A-2	T	139.8	114.3	6.50	4.30		400	90		5.72	0.82	10.75	0.66		324		500	382	353		334.4			U	No	TF = 12		
	C-A-3	T	139.8	101.6	6.50	3.90		400	90		5.72	0.73	10.75	0.60		324		500	392	363		288.3			P	Yes			
	C-A-4	T	139.8	76.3	6.50	3.20		400	90		5.72	0.55	10.75	0.49		324		500	402	374		203.5			U	No	Flange is		
	C-A-5	T	139.8	48.6	6.50	2.40		400	90		5.72	0.35	10.75	0.37		324		500	422	396		130.4			P	Yes	reinforced		
	C-B-1	T	139.8	139.8	6.50	6.50		400	90		5.72	1.00	10.75	1.00		343		480	324	291		549.2			U	No			
	C-B-2	T	139.8	101.6	6.50	3.20		400	90		5.72	0.73	10.75	0.49		343		480	324	291		317.3			U	No	Ftc is an average	BF, Out	
	C-B-3	T	139.8	89.1	6.50	3.20		400	90		5.72	0.64	10.75	0.49		343		480	402	374		269.7			U	No	estimate for		
	C-B-4	T	139.8	48.6	6.50	2.30		400	90		5.72	0.35	10.75	0.35		343		480	461	440		147.1			U	No	CB1-CB6		
	C-B-5	T	139.8	42.7	6.50	2.30		400	90		5.72	0.31	10.75	0.35		343		480	324	291		131.9			U	No		BF, Out	
	C-B-6	T	139.8	34.0	6.50	2.30		400	90		5.72	0.24	10.75	0.35		343		460	451	429		115.5			U	No	Fyb is LB for	BF, Out	Out
	C-D-1	T	139.8	139.8	4.80	4.80		400	90		5.72	1.00	14.56	1.00		402		461	402	374		355.0			U	No	CB1, CB2,		
	C-D-2	T	139.8	114.3	4.80	4.30		400	90		5.72	0.82	14.56	0.90		402		461	382	353		253.0			U	No	CB5, CD2,		
	C-D-3	T	139.8	101.6	4.80	4.10		400	90		5.72	0.73	14.56	0.85		402		461	402	374		220.7			U	No	CC1, CAE,		
	C-D-4	T	139.8	76.3	4.80	4.10		400	90		5.72	0.55	14.56	0.85		402		461	451	429		159.9			U	No	and CBE		
	C-D-5	T	139.8	48.6	4.80	2.30		400	90		5.72	0.35	14.56	0.48		402		461	461	440		102.2			U	No			
	C-A-D	T	165.2	76.3	7.20	4.00		400	90		4.84	0.46	11.47	0.56		324		412	412	385		214.8			U	No	Beam bending		Alpha
	C-A-E	T	165.2	60.5	7.20	3.80		400	90		4.84	0.37	11.47	0.53		324		412	284	251		203.0			U	No	failure and	BF, Out	Alpha
	C-B-D	T	139.8	76.3	6.50	4.00		400	90		5.72	0.55	10.75	0.62		284		431	412	385		210.9			U	No	buckling of small		
	C-B-E	T	139.8	60.5	6.50	3.80		400	90		5.72	0.43	10.75	0.58		284		431	284	251		165.7			U	No	braces are		
	C-E-3	T	139.8	101.6	6.50	5.40		600	90		8.58	0.73	10.75	0.83		324		500	382	353		242.2			U	No	suspected in the		
	C-E-2	T	139.8	101.6	6.50	5.40		400	90		5.72	0.73	10.75	0.83		324		500	382	353		291.3			U	No	CA1-CD5 series		
	C-E-1	T	139.8	101.6	6.50	5.40		200	90		2.86	0.73	10.75	0.83		324		500	382	353		429.5			U	No			Alpha, Out
	C-C-1	T	114.3	114.3	4.30	4.30		400	90		7.00	1.00	13.29	1.00		412		490	382	353		248.1			U	No			
	C-C-2	T	114.3	89.1	4.30	3.20		400	90		7.00	0.78	13.29	0.74		412		490	402	374		160.8			U	No			
	C-C-3	T	114.3	76.3	4.30	3.20		400	90		7.00	0.67	13.29	0.74		412		490	402	374		134.8			U	No			
	C-C-4	T	114.3	60.5	4.30	3.30		400	90		7.00	0.53	13.29	0.77		412		490	392	363		103.5			U	No			
	C-C-5	T	114.3	34.0	4.30	2.30		400	90		7.00	0.30	13.29	0.53		412		490	451	429		67.7			U	No			
JSSC (1972)	I-CB-40-0.2	T	165.5	42.7	4.70	3.30		826	90		9.98	0.26	17.61	0.70		441		532	343	311		84.4			P	Yes	L = L1		
and	I-CB-40-0.4	T	165.2	76.3	4.70	2.90		826	90		10.00	0.46	17.57	0.62		441		532	373	343		116.7			P	Yes	Ftc from		
AKIYAMA (1974)	I-CB-70-0.2	T	318.4	60.5	4.50	3.00		1593	90		10.01	0.19	35.38	0.67		412		533	333	301		58.9			P	Yes	Ochi (1984)		
	I-CB-70-0.4	T	318.5	139.8	4.50	4.40		1593	90		10.00	0.44	35.39	0.98		412		533	343	311		102.0			P	Yes			
	I-CB-100-0.2	T	456.9	89.1	4.90	3.00		2286	90		10.01	0.20	46.62	0.61		392		530	363	332		63.8			P	Yes			Gamma
	I-CB-100-0.4	T	457.6	165.2	4.90	4.70		2286	90		9.99	0.36	46.69	0.96		392		530	441	417		98.1			P	Yes			Gamma
	I-CB'-40-0.4	Y	164.9	76.2	4.70	2.90		826	45		10.02	0.46	17.54	0.62		432		530	373	343		186.4			P	Yes			
	I-CB'-70-0.4	Y	318.5	139.8	4.50	4.40		1593	45		10.00	0.44	35.39	0.98		412		530	343	311		175.6			P	Yes			
	I-CB'-100-0.4	Y	457.6	165.2	4.90	4.70		2286	45		9.99	0.36	46.69	0.96		392		530	441	417		154.0			P	Yes			Gamma
AKIYAMA (1974)	IR-70-0.4(1)	T	318.5	139.8	4.50	4.40		1593	90		10.00	0.44	35.39	0.98		412		510		0		85.8			U	No	Ftc from		
	IR-100-0.4(1)	T	457.6	165.2	4.90	4.70		2286	90		9.99	0.36	46.69	0.96		417		549		0		98.1			U	No	Ochi (1984)		Gamma
WIMPEY (1977)	A13	T	508.0	168.3	7.94	7.94		1473	90		5.80	0.33	31.99	1.00		335		463	312	279		259.1			PL	Yes	L = L1		
and	A15	T	508.0	168.3	7.94	7.94		1473	90		5.80	0.33	31.99	1.00		335		463	312	279		240.1			PL	Yes	L4 = 2032		
TEBBETT (1979)	W3	T	508.0	193.7	12.70	6.35		1473	90		5.80	0.38	20.00	0.50		338		462	256	224		668.6			P?	Yes			
	W5	T	508.0	193.7	12.70	6.35		1473	90		5.80	0.38	20.00	0.50		338		462	256	224		668.6			P?	Yes			
YAMASAKI	SM-A	T	641.1	256.2	16.00	12.40		3000	90		9.36	0.40	20.03	0.78		392		557		0		1083.0			U	No	L = L4		
(1979, 1980)	SM-B	T	642.5	384.0	16.20	12.20		3000	90		9.34	0.60	19.83	0.75		392		557		0		1553.9			U	No			
	SM-C	T	642.3	512.5	16.00	12.20		3000	90		9.34	0.80	20.07	0.76		392		557		0		2099.3			U	No			
	SR-A	T	641.8	255.5	16.00	12.00		3000	90		9.35	0.40	20.06	0.75		366		524		0		953.5			U	No			
	SH-A	T	643.4	255.8	16.00	13.00		3000	90		9.33	0.40	20.11	0.81		728		827		0		1996.3			U	No			
	T-O	T	1400.0	800.0	26.00	12.00		7000	90		10.00	0.57	26.92	0.46		280		458	300	267		3242.2			P	No	L = L2		Fyc, Out
SAWADA (1979)	R-O-1	T	711.2	318.5	9.93	7.06		3600	90		10.12	0.45	35.81	0.71		389		459	411	384		385.5			P	Yes	L = L4		
	R-O-2	T	711.2	318.5	10.38	7.06		3600	90		10.12	0.45	34.26	0.68		363		437	411	384		396.3			P	Yes			
MITSUI (1973)	T-1	T	101.6	48.6	3.07	3.50		365	90		7.19	0.48	16.55	1.14		370		451		0		61.3			U	No			
	T-2	T	101.6	48.6	4.14	3.50		365	90		7.19	0.48	12.27	0.85		414		458		0		89.7			U	No	Ftc from		
	T-3	T	101.6	48.6	5.82	3.50		365	90		7.19	0.48	8.73	0.60		424		472		0		148.6			U	No	Ochi (1984)		
	T-5	T	165.2	89.1	4.51	3.50		527	90		6.38	0.54	18.31	0.78		417		535		0		137.3			U	No			
	T-6	T	165.2	89.1	4.24	3.50		527	90		6.38	0.54	19.48	0.83		236		431		0		72.9			U	No			

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Database on Simple Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Theta (deg.)	Thetar (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm^2)	Static (N/mm^2)	(N/mm^2)	Dynamic (N/mm^2)	Static (N/mm^2)	M_{re} (KN-m)	P_u (KN)	P_{rc} (KN)	M_u (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
WASHIO (1968)	T-3.2-E-90-1	T	101.6	48.6	3.29	3.20		300	90		5.91	0.48	15.44	0.97		380		452		0		66.7			U	No	L = L2		
checked in	T-3.2-E-90-2	T	101.6	48.6	3.29	3.20		300	90		5.91	0.48	15.44	0.97		380		452		0		66.7			U	No	Flange is		
TOGO (1967)	T-3.2-E-90-3	T	101.6	48.6	3.29	3.20		300	90		5.91	0.48	15.44	0.97		380		452		0		63.8			U	No	reinforced		
	T-3.2-E-60-1	Y	101.6	48.6	3.29	3.20		346	60		6.81	0.48	15.44	0.97		380		452		0		71.6			U	No			
	T-3.2-E-60-2	Y	101.6	48.6	3.29	3.20		346	60		6.81	0.48	15.44	0.97		380		452		0		72.6			U	No			
	T-3.2-E-60-3	Y	101.6	48.6	3.29	3.20		346	60		6.81	0.48	15.44	0.97		380		452		0		75.5			U	No	Flanges		
	T-3.2-E-60-1*	Y	101.6	48.6	3.29	3.20		300	60		5.91	0.48	15.44	0.97		380		452		0		73.6			U	No	are stiffed		
	T-3.2-E-60-2*	Y	101.6	48.6	3.29	3.20		300	60		5.91	0.48	15.44	0.97		380		452		0		72.6			U	No			
	T-3.2-E-60-3*	Y	101.6	48.6	3.29	3.20		300	60		5.91	0.48	15.44	0.97		380		452		0		69.7			U	No			
TOPRAC (1963)	C-12	T	219.1	114.3	4.76			991	90		9.05	0.52	23.01	0.00		248				0		88.9			P?	Yes	Fyc is nominal		Out
	C-18	T	219.1	114.3	7.14			991	90		9.05	0.52	15.34	0.00		248				0		249.1			P?	Yes	Outliers by		Out
	C-26	T	219.1	114.3	10.32			991	90		9.05	0.52	10.62	0.00		248				0		444.8			P?	No	Ochi (1984)		Out
	E-16	T	323.9	114.3	6.35			1143	90		7.06	0.35	25.50	0.00		248				0		186.8			P?	No			Out
	E-24	T	323.9	114.3	9.53			1143	90		7.06	0.35	16.99	0.00		248				0		298.0			P?	No			Out
	E-32	T	323.9	114.3	12.70			1143	90		7.06	0.35	12.75	0.00		248				0		498.2			P?	No			Out
	G-19	T	457.2	114.3	7.54			1143	90		5.00	0.25	30.32	0.00		248				0		200.2			P?	No			Out
	G-24	T	457.2	114.3	9.53			1143	90		5.00	0.25	23.99	0.00		248				0		266.8			P?	No			Out
	G-32	T	457.2	114.3	12.70			1143	90		5.00	0.25	18.00	0.00		248				0		462.6			P?	No			Out
REF (34) in	60	T	500.0	114.3	12.70	4.50		1870	90		7.48	0.23	19.69	0.35		360		517		0		406.0			U	No	From		Ref
Ochi (1984)	61	T	500.0	200.0	12.70	6.40		2370	90		9.48	0.40	19.69	0.50		360		546		0		627.6			U	No	Ochi (1984)		Ref
	62	T	500.0	250.0	12.70	6.40		2370	90		9.48	0.50	19.69	0.50		360		546		0		755.1			U	No			Ref
	63	T	500.0	350.0	12.70	6.40		1870	90		7.48	0.70	19.69	0.50		360		517		0		961.1			U	No			Ref
	64	T	500.0	200.0	6.40	6.40		2370	90		9.48	0.40	39.06	1.00		392		539		0		191.2			U	No			Ref
REF (37) in	20	T	508.0	216.3	6.24	6.70		2180	90		8.58	0.43	40.71	1.07		365		478		0		171.4			U	No	From		Ref, Gamma
Ochi (1984)	70	T	165.6	34.3	4.56	2.40		496	90		5.99	0.21	18.16	0.53		284		397		0		43.4			U	No	Ochi (1984)		Ref
	71	T	165.4	49.1	4.57	3.50		504	90		6.09	0.30	18.10	0.77		284		397		0		53.9			U	No			Ref
	72	T	165.3	60.8	4.58	3.40		502	90		6.07	0.37	18.05	0.74		284		397		0		65.7			U	No			Ref
	73	T	165.3	76.2	4.57	3.50		502	90		6.07	0.46	18.09	0.77		284		397		0		78.4			U	No			Ref
	74	T	164.9	89.8	4.55	4.30		504	90		6.11	0.54	18.12	0.95		284		397		0		96.9			U	No			Ref
	75	T	166.2	102.2	4.54	2.80		505	90		6.08	0.61	18.30	0.62		284		397		0		120.1			U	No			Ref
	76	T	165.4	61.0	4.55	2.80		495	90		5.99	0.37	18.18	0.62		284		397		0		64.0			U	No			Ref
	77	T	165.7	60.3	4.54	3.20		494	90		5.96	0.36	18.25	0.70		284		397		0		62.9			U	No			Ref
	78	T	166.1	89.3	4.51	3.60		496	90		5.97	0.54	18.41	0.80		284		397		0		101.3			U	No			Ref
	79	T	166.1	101.9	4.48	5.70		495	90		5.96	0.61	18.54	1.27		284		397		0		116.2			U	No			Ref, Tau, Out
	80	T	166.2	48.8	7.31	3.50		501	90		6.03	0.29	11.37	0.48		358		496		0		154.9			U	No			Ref
	81	T	165.9	60.6	7.29	2.70		496	90		5.98	0.37	11.38	0.37		358		496		0		186.3			U	No			Ref
	82	T	165.9	60.2	7.38	3.00		497	90		5.99	0.36	11.24	0.41		358		496		0		188.8			U	No			Ref
	83	T	166.2	60.9	7.34	3.50		498	90		5.99	0.37	11.32	0.48		358		496		0		180.9			U	No			Ref
	84	T	166.1	76.8	7.26	3.50		496	90		5.97	0.46	11.44	0.48		358		496		0		225.6			U	No			Ref
	85	T	166.0	88.7	7.25	3.50		496	90		5.98	0.53	11.45	0.48		358		496		0		266.3			U	No			Ref
	86	T	166.3	89.0	7.32	4.10		495	90		5.95	0.54	11.36	0.56		358		496		0		261.3			U	No			Ref
	87	T	166.3	101.2	7.34	3.20		500	90		6.01	0.61	11.33	0.44		358		496		0		304.5			U	No			Ref
	88	T	166.5	101.8	7.34	4.20		494	90		5.93	0.61	11.34	0.57		358		496		0		304.5			U	No			Ref
DEn (1989)	1.1	Y	508.0	406.0	12.50	12.50		1575	45		6.20	0.80	20.32	1.00		340		483	483	465		2346.0			P	Yes	L = L3		
JISSP	1.3	T	508.0	406.0	12.70	12.70		1575	90		6.20	0.80	20.00	1.00		339		500	500	485		1633.0			PL	Yes	L4 = 2032		
	1.4	T	508.0	508.0	12.40	12.40		1575	90		6.20	1.00	20.48	1.00		334		476	476	457		2328.0			PL	Yes			
	1.5	T	508.0	406.0	8.00	8.00		1575	90		6.20	0.80	31.75	1.00		307		444	444	421		674.0			PL	Yes			
	1.6	T	508.0	508.0	8.00	8.00		1575	90		6.20	1.00	31.75	1.00		322		447	447	424		1180.0			PL	Yes			
	1.7	Y	508.0	406.0	8.00	8.00		1575	45		6.20	0.80	31.75	1.00		312		427	427	402		985.0			P	Yes			
	1.8	Y	508.0	508.0	7.90	7.90		1575	45		6.20	1.00	32.15	1.00		276		419	419	393		1435.0			PL	Yes			
MITRI (1987)	T1	T	219.8	89.0	4.94	4.78		529	90		4.81	0.40	22.25	0.97		335		465		0		115.2			P	Yes	L = L4		Alpha
and	T2	T	219.7	89.3	8.21	4.78		529	90		4.81	0.41	13.38	0.58		400		482		0		330.5			(PL)	Yes	Fillet welded		Alpha
SCOLA (1989)	T3	T	219.7	141.8	6.40	6.55		581	90		5.29	0.65	17.16	1.02		327		458		0		328.7			NOT P	Yes	Chord reinforced		Alpha, Out
	T4	T	219.8	48.7	6.37	4.78		488	90		4.44	0.22	17.25	0.75		327		458		0		122.3			P	Yes	at loading points		Alpha
	T5	T	219.6	89.0	6.39	4.78		528	90		4.81	0.41	17.18	0.75		327		458		0		208.6			P	Yes	Simply supp. ?		Alpha
	T6	T	220.4	169.0	6.38	4.78		610	90		5.54	0.77	17.27	0.75		327		458		0		382.9			U	No			Out

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Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Theta:Thetar (deg.) (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm²)	Static (N/mm²)	(N/mm²)	Dynamic (N/mm²)	Static (N/mm²)	Mre (KN-m)	Pu (KN)	Pfc (KN)	Mu (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
MAKINO (1986)	L - A - C	T	216.5	216.5	4.55	4.55		735	90	6.79	1.00	23.79	1.00		377		522	377	347		392.0			P	Yes	L = L1		
and	L - B - C	T	216.5	165.6	4.55	4.53		735	90	6.79	0.76	23.79	1.00		377		522	341	309		221.0			P	Yes			
Kurobane (1991)	L - C - C	T	216.5	114.3	4.55	4.56		735	90	6.79	0.53	23.79	1.00		377		522	332	300		144.0			P	Yes			
	L - D - C	T	216.5	60.7	4.55	3.96		735	90	6.79	0.28	23.79	0.87		377		522	311	278		79.4			P	Yes			
	M - C - C	T	216.6	114.3	6.28	4.56		735	90	6.79	0.53	17.25	0.73		298		519	332	300		225.0			P	Yes			
	MA - C - C	T	217.9	114.4	6.81	7.03		735	90	6.75	0.53	16.00	1.03		580		650	287	254		393.8			U	No			Fyc, Out
	MH - C - C	T	216.3	114.4	6.65	7.03		735	90	6.80	0.53	16.26	1.06		832		875	287	254		492.7			U	No			Fyc, Out
	H - A - C	T	216.5	216.5	8.06	8.06		735	90	6.79	1.00	13.43	1.00		378		469	378	348		754.6			U	No			
	H - C - C	T	216.5	114.4	8.06	7.03		735	90	6.79	0.53	13.43	0.87		378		469	287	254		366.7			U	No			
	H - D - C	T	216.5	60.3	8.06	10.09		735	90	6.79	0.28	13.43	1.25		378		469	299	266		220.5			U	No			Tau, Out
STOL (1985)	5	T	168.7	59.8	10.55	11.10		870	90	10.31	0.35	8.00	1.05		263		426	376	346		282.0			P	Yes	L = L2		
	69	T	168.4	114.5	10.28	11.31		705	90	8.37	0.68	8.19	1.10		235		385	293	260		440.0			P	Yes	TF = 30		
	6	T	168.1	60.6	5.68	5.72		870	90	10.35	0.36	14.80	1.01		305		397	306	273		87.0			P	Yes			
	9	T	168.1	114.6	5.68	5.95		870	90	10.35	0.68	14.80	1.05		305		397	335	303		170.0			P	Yes			
	60	T	168.1	168.3	5.68	5.78		705	90	8.39	1.00	14.80	1.02		305		397	286	253		275.0			P	Yes			
	12	T	168.5	60.8	3.45	3.81		870	90	10.33	0.36	24.42	1.10		299		370	296	263		42.0			P	Yes			
	15	T	168.5	114.7	3.42	3.90		870	90	10.33	0.68	24.63	1.14		303		383	250	218		79.0			P	Yes	P-d curve is odd		Out
	18	T	168.8	168.3	3.55	3.54		870	90	10.31	1.00	23.77	1.00		305		366	303	270		144.0			P	Yes			
VERITEC (1986)	1	T	495.0	229.0	16.00	12.50		2020	90	8.16	0.46	15.47	0.78		360		520		0		1232.0			P	Yes	L = L1		
STAMENKOVIC	A1	T	114.3	48.3	3.60	4.00		782	90	13.68	0.42	15.88	1.11		350				0		58.0			P	Yes	Fyc is estimated		Out
& SPARROW	B1	T	114.3	48.3	5.00	4.00		782	90	13.68	0.42	11.43	0.80		350				0		100.0			P	Yes	(not measured)		Out
(1983, 1984)	C1	T	114.3	48.3	5.40	4.00		782	90	13.68	0.42	10.58	0.74		350				0		110.0			P	Yes	Dimensions are		Out
and	D1	T	114.3	48.3	6.30	4.00		782	90	13.68	0.42	9.07	0.63		350				0		120.0			P	Yes	nominal		Out
SPARROW (1979)	E1	T	114.3	60.3	3.60	5.00		782	90	13.68	0.53	15.88	1.39		350				0		70.0			P	Yes			Out
	F1	T	114.3	60.3	5.00	5.00		782	90	13.68	0.53	11.43	1.00		350				0		120.0			P	Yes			Out
	G1	T	114.3	60.3	6.30	5.00		782	90	13.68	0.53	9.07	0.79		350				0		168.0			P	Yes			Out
	H1	T	114.3	76.1	3.60	4.50		782	90	13.68	0.67	15.88	1.25		350				0		94.5			P	Yes			Out
	J1	T	114.3	76.1	5.00	4.50		782	90	13.68	0.67	11.43	0.90		350				0		160.0			P	Yes			Out
	K1	T	114.3	76.1	5.40	4.50		782	90	13.68	0.67	10.58	0.83		350				0		177.5			P	Yes			Out
	L1	T	114.3	76.1	6.30	5.00		782	90	13.68	0.67	9.07	0.79		350				0		180.0			P	Yes			Out
	M1	T	114.3	88.9	3.60	5.00		782	90	13.68	0.78	15.88	1.39		350				0		110.0			P	Yes			Out
	N1	T	114.3	88.9	5.40	5.00		782	90	13.68	0.78	10.58	0.93		350				0		227.0			P	Yes			Out
	P1	T	114.3	88.9	6.30	5.00		782	90	13.68	0.78	9.07	0.79		350				0		235.0			P	Yes			Out
	Q1	T	114.3	114.3	3.60	5.00		782	90	13.68	1.00	15.88	1.39		350				0		165.0			P	Yes			Out
	R1	T	114.3	114.3	5.00	5.00		782	90	13.68	1.00	11.43	1.00		350				0		240.0			P	Yes			Out
	S1	T	114.3	114.3	6.30	5.00		782	90	13.68	1.00	9.07	0.79		350				0		270.0			P	Yes			Out
	TCC-8	T	114.9	114.7	5.00	5.10		300	90	5.22	1.00	11.49	1.02		311		462	311	278		220.0					L = L3		
	TCC-9	T	76.6	76.2	4.85	4.90		280	90	7.31	0.99	7.90	1.01		311		462	346	314		153.0							D, Out
DT&X-COMPRESSION																												
JSSC (1972)	I-CS-40-0.2	DT	165.5	42.7	4.70	3.30		826	90	9.98	0.26	17.61	0.70		481		537	343	311		72.6			P	Yes	Ftc is an AV		
and	I-CS-40-0.4	DT	165.2	76.3	4.70	2.90		826	90	10.00	0.46	17.57	0.62		481		537	373	343		102.0			P	Yes			
AKIYAMA (1974)	I-CS-40-0.6	DT	165.2	114.3	4.70	3.80		826	90	10.00	0.69	17.57	0.81		481		537	363	332		137.3			P	Yes			
	I-CS-40-1.0	DT	165.2	165.2	4.70	4.50		826	90	10.00	1.00	17.57	0.96		481		537	471	451		323.7			P	Yes			
	I-CS-70-0.2	DT	318.4	60.5	4.40	3.00		1593	90	10.01	0.19	36.18	0.68		422		534	333	301		49.1			P	Yes			
	I-CS-70-0.4	DT	320.6	139.8	4.40	4.40		1593	90	9.94	0.44	36.43	1.00		422		534	343	311		81.7			P	Yes			
	I-CS-70-0.6	DT	318.3	165.2	4.50	4.50		1593	90	10.01	0.52	35.37	1.00		412		534	-	0		94.2			P	Yes			
	I-CS-70-1.0	DT	318.5	318.5	4.50	4.50		1593	90	10.00	1.00	35.39	1.00		412		534		0		309.0			P	Yes			
	I-CS-100-0.2	DT	456.9	89.1	4.80	3.00		2286	90	10.01	0.20	47.59	0.63		392		549	343	311		54.0			P	Yes			Gamma
	I-CS-100-0.4	DT	457.6	165.2	4.80	4.50		2286	90	9.99	0.36	47.67	0.94		392		549	-	0		80.4			P	Yes			Gamma
AKIYAMA (1974)	I-RS-40-0.6 (1)	DT	165.2	114.3	4.70	3.80		826	90	10.00	0.69	17.57	0.81		461		543		0		131.4			U	No	Ftc from		
	I-RS-40-1.0 (1)	DT	165.2	165.2	4.70	4.50		826	90	10.00	1.00	17.57	0.96		461		543		0		333.4			U	No	Ochl (1984)		
	I-RS-70-0.6 (1)	DT	318.3	165.2	4.40	4.50		1593	90	10.01	0.52	36.17	1.02		451		524		0		90.2			U	No			
	I-RS-70-1.0 (1)	DT	318.5	318.5	4.50	4.50		1593	90	10.00	1.00	35.39	1.00		412		527		0		304.0			U	No			

Database on Simple Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	ThetaC (deg.)	ThetaT (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm2)	Static (N/mm2)	(N/mm2)	Dynamic (N/mm2)	Static (N/mm2)	MPB (KN-m)	Pu (KN)	PPC (KN)	Mu (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
KANATANI (1964, 1966)	C-G-1	DT	139.8	139.8	6.50	6.50		400	90		5.72	1.00	10.75	1.00		324		500	324	291		451.1			U	No	Fyb is LB for CG2 and CG5		
	C-G-2	DT	139.8	114.3	6.50	4.00		400	90		5.72	0.82	10.75	0.62		324		500	382	353		246.2			U	No			
	C-G-3	DT	139.8	101.6	6.50	3.90		400	90		5.72	0.73	10.75	0.60		324		500	392	363		201.5			U	No			
	C-G-4	DT	139.8	76.3	6.50	3.20		400	90		5.72	0.55	10.75	0.49		324		500	402	374		155.0			U	No			
	C-G-5	DT	139.8	48.6	6.50	2.40		400	90		5.72	0.35	10.75	0.37		324		500	422	396		114.7			U	No			
GIBSTEIN (1973)	1	DT	190.1	48.3	4.69	4.50		1000	90		10.52	0.25	20.27	0.96		314			284	251		47.1				No	Fyb is LB		
	2	DT	193.7	48.3	6.50	5.00		1000	90		10.33	0.25	14.90	0.77		334			284	251		96.1				No			
	3	DT	193.7	48.3	9.39	8.00		1000	90		10.33	0.25	10.31	0.85		284			284	251		173.6				No			
	4	DT	188.9	101.6	4.65	4.50		1000	90		10.59	0.54	20.31	0.97		314			284	251		76.5				No			
	5	DT	193.7	101.6	6.50	5.00		1000	90		10.33	0.52	14.90	0.77		334			284	251		152.1				No			
	6	DT	193.7	101.6	9.30	8.00		1000	90		10.33	0.52	10.41	0.86		284			284	251		279.6				No			
	7	DT	190.0	159.0	4.56	4.50		1000	90		10.53	0.84	20.83	0.99		314			284	251		125.6				No			
	8	DT	193.7	159.0	6.50	5.60		1000	90		10.33	0.82	14.90	0.86		334			284	251		225.6				No			
	9	DT	193.7	159.0	9.35	8.00		1000	90		10.33	0.82	10.36	0.86		284			284	251		451.3				No			
SAMMET (1963)	A2-1	DT	159.0	83.0	5.00			878	90		11.04	0.52	15.90	0.00		340				0		94.2					Fyc is uncertain		Out
	A2-2	DT	159.0	83.0	5.00			878	90		11.04	0.52	15.90	0.00		340				0		91.2							Out
BOONE (1982)	A1	DT	407.7	274.3	8.05	6.60		3556	90		17.44	0.67	25.32	0.82		334	321	470	339	331		350.5			P	Yes	L = L3		
and	A21	DT	407.0	407.0	7.98	7.98		3556	90		17.46	1.00	25.53	1.00		348	337	443	348	337		768.2			P	Yes			
SWENSSON (1987	A22	DT	407.4	407.4	7.98	7.98		3556	90		17.46	1.00	25.53	1.00		350	337	444	350	337		673.9			P	Yes			
and	A40	DT	407.4	142.5	7.98	6.65		3556	90		17.46	0.35	25.53	0.83		350	337	444	295	273		186.8			P	Yes			
WEINSTEIN (1985	A41	DT	407.0	142.1	7.98	6.55		3556	90		17.46	0.35	25.53	0.83		348	337	443	301	270		205.6			P	Yes			
	A51	DT	407.4	274.3	7.98	6.60		3556	90		17.46	0.67	25.53	0.83		350	337	444	350	337		315.8			P	Yes			
TOGO (1967)	X-I-3.2-E-40	DT	101.6	48.6	2.97	2.30		400	90		7.87	0.48	17.10	0.77		318		436		0		28.4			P	Yes			
	X-I-3.2-E-50	DT	101.6	48.6	2.97	2.30		500	90		9.84	0.48	17.10	0.77		318		436		0		30.0			P	Yes			
	X-I-3.2-E-60	DT	101.6	48.6	2.97	2.30		600	90		11.81	0.48	17.10	0.77		318		436		0		29.7			P	Yes			
	X-I-3.2-E-80	DT	101.6	48.6	2.97	2.30		800	90		15.75	0.48	17.10	0.77		318		436		0		32.4			P	Yes			
	X-I-3.2-E-100	DT	101.6	48.6	2.97	2.30		1000	90		19.69	0.48	17.10	0.77		318		436		0		31.2			P	Yes			
	X-I-3.2-E-120	DT	101.6	48.6	2.97	2.30		1200	90		23.62	0.48	17.10	0.77		318		436		0		31.9			P	Yes			
	X-I-3.2-A-1	DT	101.6	21.7	3.16	2.30		800	90		15.75	0.21	16.08	0.73		400		462		0		28.0			P	Yes			
	X-I-3.2-A-2	DT	101.6	21.7	3.16	2.30		800	90		15.75	0.21	16.08	0.73		400		462		0		29.4			P	Yes			
	X-I-3.2-A-3	DT	101.6	21.7	3.16	2.30		800	90		15.75	0.21	16.08	0.73		400		462		0		29.4			P	Yes			
	X-I-3.2-B-1	DT	101.6	27.2	3.16	2.30		800	90		15.75	0.27	16.08	0.73		400		462		0		31.6			P	Yes			
	X-I-3.2-B-2	DT	101.6	27.2	3.16	2.30		800	90		15.75	0.27	16.08	0.73		400		462		0		31.4			P	Yes			
	X-I-3.2-B-3	DT	101.6	27.2	3.04	2.30		800	90		15.75	0.27	16.71	0.76		365		448		0		26.5			P	Yes			
	X-I-3.2-C-1	DT	101.6	34.0	3.04	2.30		800	90		15.75	0.33	16.71	0.76		365		448		0		32.7			P	Yes			
	X-I-3.2-E-1	DT	101.6	48.6	3.04	3.50		800	90		15.75	0.48	16.71	1.15		365		448		0		41.2			P	Yes			
	X-I-3.2-E-2	DT	101.6	48.6	3.29	3.50		800	90		15.75	0.48	15.44	1.06		380		452		0		48.9			P	Yes			
	X-I-3.2-E-3	DT	101.6	48.6	3.29	3.50		800	90		15.75	0.48	15.44	1.06		380		452		0		47.1			P	Yes			
	X-I-3.2-E-20	DT	101.6	48.6	2.97	2.30		200	90		3.94	0.48	17.10	0.77		318		436		0		19.1			P	Yes			
	X-I-3.2-E-30	DT	101.6	48.6	2.97	2.30		300	90		5.91	0.48	17.10	0.77		318		436		0		26.6			P	Yes			Alpha, Out
	X-I-3.2-E-60-1	X	101.6	48.6	3.29	3.50		800	60		15.75	0.48	15.44	1.06		380				0		48.5			U	No	* In results table component normal to chord axis ?		Out
	X-I-3.2-E-60-2	X	101.6	48.6	3.29	3.50		800	60		15.75	0.48	15.44	1.06		380				0		52.7			U	No			Out
	X-I-3.2-E-60-3	X	101.6	48.6	3.29	3.50		800	60		15.75	0.48	15.44	1.06		380				0		51.0			U	No			Out
	X-I-3.2-F-1	DT	101.6	60.5	3.04	3.20		800	90		15.75	0.60	16.71	1.05		365		448		0		43.7			P	Yes			
	X-I-3.2-G-1	DT	101.6	76.3	3.04	3.20		800	90		15.75	0.75	16.71	1.05		365		448		0		63.8			P	Yes			
	X-I-3.2-H-1	DT	101.6	89.1	3.04	3.20		800	90		15.75	0.88	16.71	1.05		365		448		0		80.9			P	Yes			
	X-I-3.2-I-1	DT	101.6	101.6	3.04	3.20		800	90		15.75	1.00	16.71	1.05		365		448		0		123.6			P	Yes			
	X-I-4.2-C	DT	101.7	34.0	4.18	2.30		800	90		15.73	0.33	12.17	0.55		400		476		0		63.3			P	Yes			
	X-I-4.2-E-1	DT	101.7	48.6	4.18	3.50		800	90		15.73	0.48	12.17	0.84		400		476		0		79.0			P	Yes			
	X-I-4.2-E-2	DT	102.1	48.6	4.11	3.50		800	90		15.67	0.48	12.42	0.85		438		482		0		81.9			P	Yes			
	X-I-4.2-E-3	DT	102.1	48.6	4.11	3.50		800	90		15.67	0.48	12.42	0.85		438		482		0		82.4			P	Yes			
	X-I-4.2-F	DT	101.7	60.5	4.18	3.20		800	90		15.73	0.59	12.17	0.77		400		476		0		93.7			P	Yes			
	X-I-4.2-G	DT	102.1	76.3	4.11	3.20		800	90		15.67	0.75	12.42	0.78		438		482		0		124.1			P	Yes			
	X-I-4.2-H	DT	102.1	89.1	4.11	3.20		800	90		15.67	0.87	12.42	0.78		438		482		0		157.0			P	Yes			
	X-I-4.2-I	DT	102.1	101.6	4.11	4.20		800	90		15.67	1.00	12.42	1.02		438		482		0		267.8			P	Yes			
	X-I-5.7-C	DT	101.8	34.0	5.70	2.30		800	90		15.72	0.33	8.93	0.40		353		489		0		89.3			P	Yes			
	X-I-5.7-E-1	DT	101.8	48.6	5.70	3.50		800	90		15.72	0.48	8.93	0.61		353		489		0		104.0			P	Yes			
	X-I-5.7-E-2	DT	101.8	48.6	5.70	3.50		800	90		15.72	0.48	8.93	0.61		353		489		0		115.3			P	Yes			
	X-I-5.7-E-3	DT	101.8	48.6	5.70	3.50		800	90		15.72	0.48	8.93	0.61		353		489		0		121.6			P	Yes			
	X-I-5.7-F	DT	101.8	60.5	5.70	3.20		800	90		15.72	0.59	8.93	0.56		353		489		0		137.3			P	Yes			

Database on Simple Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Thetac (deg.)	Thetar (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm^2)	Static (N/mm^2)	(N/mm^2)	Dynamic (N/mm^2)	Static (N/mm^2)	M_{PB} (KN-m)	P_U (KN)	P_{KC} (KN)	M_U (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
TOGO (1967)	X - I - 5.7 - G	DT	101.8	76.3	5.70	3.20		800	90		15.72	0.75	8.93	0.56		353		489		0		198.7			P	Yes			
	X - I - 5.7 - H	DT	101.8	89.1	5.70	3.20		800	90		15.72	0.88	8.93	0.56		353		489		0		261.4			P	Yes			
	X - I - 5.7 - I	DT	101.8	101.6	5.70	5.70		800	90		15.72	1.00	8.93	1.00		353		489		0		416.9			P	Yes			
	IV-1	DT	101.6	48.6	3.18	3.50		1030	90		20.28	0.48	15.97	1.10		308		438		0		43.2			U	No	Not reported by Ochi (1984)		Out
	IV-1	DT	101.6	48.6	3.18	3.50		1030	90		20.28	0.48	15.97	1.10		308		438		0		45.1			U	No			Out
	IV-1	DT	101.6	48.6	3.18	3.50		1030	90		20.28	0.48	15.97	1.10		308		438		0		44.1			U	No			Out
MAKINO (1978)	XTA - 01	DT	140.1	50.9	9.00	9.29			90		0.00	0.36	7.78	1.03		316		488		0		260.9			P	Yes			
	XMA - 01	DT	165.2	60.5	5.65	5.62			90		0.00	0.37	14.62	0.99		506		580		0		132.9			P	Yes			
	XHA - 01	DT	165.4	60.6	5.53	5.57			90		0.00	0.37	14.95	1.01		826		876		0		200.6			P	Yes			Fyc
REF (37) in Ochi (1984)	77	DT	165.2	165.2	4.27	4.50			90		0.00	1.00	19.34	1.05		292		402		0		212.3			U	No			Fyc, Out
DEn (1989) JISSP	2.1	X	508.0	508.0	14.80	14.80		2440	60		9.61	1.00	17.16	1.00		301		463	310	277		3342.0			P	Yes			
	2.2	X	508.0	508.0	8.00	8.00		2440	60		9.61	1.00	31.75	1.00		321		445	297	264		973.0			PL	Yes			
	2.3	X	508.0	508.0	14.80	14.80		2440	75		9.61	1.00	17.16	1.00		299		466	308	275		2933.0			PL	Yes			
VEGTE (1991)	X1	DT	408.0	246.0	10.20	10.35		2440	90		11.96	0.60	20.00	1.01		331		435	284	251		430.0			P	Yes			
SCOLA (1989)	DT1	DT	220.2	89.3	6.30	4.78		530	90		4.81	0.41	17.48	0.76		327		458		0		157.4			P	No	Fillet welded		Alpha, Out
K&YT-COMPRESSION																													
BOUWKAMP (1988)	II-3	YT	168.3	60.3	5.56	11.07	11.30	1349	90	45	16.03	0.36	15.13	1.99	0.07	395		465		0		251.7			U	No			Tau, Out
GRIGORY (1971)	7	K	508.0	219.0	12.70	9.53	198.10	3962	45	45	15.60	0.43	20.00	0.75	0.39	494		636	283	250		1890.5			P	No	T is nominal	BF, Out	
	8	K	508.0	219.0	12.70	9.53	198.10	3962	45	45	15.60	0.43	20.00	0.75	0.39	494		636	283	250		1890.5			P	No		BF, Out	
	9	K	508.0	324.0	12.70	9.53	49.90	3962	45	45	15.60	0.64	20.00	0.75	0.10	494		636	305	272		2935.8			P	No		BF, Out	
	10	K	508.0	324.0	12.70	9.53	49.90	3962	45	45	15.60	0.64	20.00	0.75	0.10	494		636	305	272		3047.0			P	No		BF, Out	
	11	K	508.0	324.0	12.70	9.53	49.90	3962	45	45	15.60	0.64	20.00	0.75	0.10	276		468	305	272		2201.9			P	No			
	12	K	508.0	324.0	12.70	9.53	49.90	3962	45	45	15.60	0.64	20.00	0.75	0.10	276		468	305	272		2112.9			P	No	Failure is odd		Out
JSSC (1972) and AKIYAMA (1974)	II-CK-40-0.2	YT	165.5	42.7	4.65	3.30	31.00	661	90	45	7.99	0.26	17.80	0.71	0.19	486		550	324	291		98.1			U	Yes	CK series are outliers in Ochi		Out
	II-CK-70-0.2	YT	318.4	60.5	4.40	3.00	86.00	1274	90	45	8.00	0.19	36.18	0.68	0.27	412		528	343	311		86.3			U	Yes	Ftc from Ochi (1984)		Out
	II-CK-100-0.2	YT	456.9	89.1	4.90	3.00	121.00	1829	90	45	8.01	0.20	46.62	0.61	0.26	402		534	363	332		88.3			NOT P	Yes			Out, Gamma
	II-CK-100-0.4	YT	457.6	165.2	4.90	4.50	29.00	1829	90	45	7.99	0.36	46.69	0.92	0.06	402		530	490	473		235.4			PL	Yes			Gamma
	II-TK-40-0.2	K	165.5	42.7	4.70	3.30	105.00	661	45	45	7.99	0.26	17.61	0.70	0.63	490		541	324	291		142.2			P	Yes			
	II-TK-40-0.4	K	165.2	76.3	4.70	2.90	57.00	661	45	45	8.00	0.46	17.57	0.62	0.35	490		541	363	332		240.3			P	Yes		BF, Out	
	II-TK-40-0.6	K	165.2	114.3	4.70	4.00	10.00	661	45	45	8.00	0.69	17.57	0.85	0.06	490		541	373	343		475.6			PL	Yes		BF, Out	
	II-TK-70-0.2	K	318.4	60.5	4.50	3.00	233.00	1274	45	45	8.00	0.19	35.38	0.67	0.73	422		509	343	311		107.9			NOT P	Yes		BF, Out	
	II-TK-70-0.4	K	318.5	139.8	4.50	4.50	121.00	1274	45	45	8.00	0.44	35.39	1.00	0.38	422		509	-	0		196.2			NOT P	Yes			Out
	II-TK-70-0.6	K	318.3	165.2	4.50	4.50	85.00	1274	45	45	8.01	0.52	35.37	1.00	0.27	422		509	490	473		255.1			P	Yes			Out
	II-TK-100-0.2	K	456.9	89.1	5.00	3.00	331.00	1829	45	45	8.01	0.20	45.69	0.60	0.72	451		530	363	332		117.7			U	Yes			Out, Gamma
	II-TK-100-0.4	K	457.6	165.2	5.00	4.50	224.00	1829	45	45	7.99	0.36	45.76	0.90	0.49	432		530	490	473		205.0			U	Yes			Out, Gamma
NAKAJIMA (1971)	L-2.3-4	YT	165.2	76.3	2.32	2.40	10.00	1725	45	90	20.88	0.46	35.60	1.03	0.06	294		340		0		78.3			P				
YURA (1976, 1980)	C1-1	YT	507.2	326.4	11.10	7.34	38.10	3591	90	30	14.16	0.64	22.85	0.66	0.08	390	376	469	376	360		1234.3			PL	Yes	L = L1		
	C1-2	YT	507.2	326.4	11.10	7.34	38.10	3591	90	30	14.16	0.64	22.85	0.66	0.08	390	376	469	376	360		1285.6			DL	No	L4 = 3962		Out ?
ZIMMERMAN (1965)	1	K	419.0	168.6	10.00	5.00	47.60	1800	60	60	8.59	0.40	20.95	0.50	0.11	340		452	309	276		602.3			U	No	Rig is unusual		Out
	2	K	419.0	168.3	10.00	5.20	47.60	1800	60	60	8.59	0.40	20.95	0.52	0.11	340		452	309	276		606.3			U	No	Deformations are		Out
	3	K	419.0	168.4	10.00	5.00	47.60	1800	60	60	8.59	0.40	20.95	0.50	0.11	340		452	309	276		590.6			U	No	too small (photos)		Out
	5	K	419.0	168.5	10.00	5.20	47.60	1800	60	60	8.59	0.40	20.95	0.52	0.11	239		373	309	276		477.7			U	No			Out
KONING (1981)	7	K	165.1	51.0	4.83	5.20	90.00		45	45	0.00	0.31	17.09	1.08	0.55	281		405	267	234		122.0			P	Yes	Stiffened bracing		
	8	K	165.1	108.0	4.83	6.38	14.00		45	45	0.00	0.65	17.09	1.32	0.08	281		405	246	214		252.0			P	Yes	for 7, 10 & 11 ?		
	9	K	165.1	165.1	4.82	4.82	14.00		45	45	0.00	1.00	17.13	1.00	0.08	290		400	290	257		425.0			PL	Yes			Tau, Out
	10	K	273.5	88.9	4.79	5.20	145.00		45	45	0.00	0.33	28.55	1.09	0.53	324		462	245	213		140.0			P	Yes			
	11	K	273.5	88.9	4.79	5.20	146.00		45	45	0.00	0.33	28.55	1.09	0.53	324		462	245	213		151.0			P	Yes			

Database on Simple Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Thetac (deg.)	Thetat (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm2)	Static (N/mm2)	(N/mm2)	Dynamic (N/mm2)	Static (N/mm2)	Mre (KN-m)	Pu (KN)	Prc (KN)	Mu (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
WASHIO (1968)	K-I-3.2-F-0-2	K	101.9	60.5	3.10	3.20	0.00	950	60	60	18.65	0.59	16.44	1.03	0.00	358		432		0		126.5							g=0, Out
Chech'd in	K-I-3.2-F-10-3	K	101.6	60.5	3.29	3.20	10.00	950	60	60	18.70	0.60	15.44	0.97	0.10	380		452		0		120.2							
Togo (1967)	K-I-3.2-F-30-1	K	101.9	60.5	3.10	3.20	30.00	950	60	60	18.65	0.59	16.44	1.03	0.29	358		432		0		85.6							
	IV-a-1	K	101.6	48.6	3.16	3.50	20.00	995	60	62	19.59	0.48	16.08	1.11	0.20	400		462		0		85.3			U	No			Out
	IV-a-2	K	101.6	48.6	3.16	3.50	20.00	995	60	62	19.59	0.48	16.08	1.11	0.20	400		462		0		89.3			U	No			Out
	IV-a-3	K	101.6	48.6	3.16	3.50	20.00	995	60	62	19.59	0.48	16.08	1.11	0.20	400		462		0		85.3			U	No			Out
	IV-b-1	K	101.6	48.6	3.16	3.50	20.00	995	60	62	19.59	0.48	16.08	1.11	0.20	400		462		0		85.3			U	No			Out
	IV-b-2	K	101.6	48.6	3.16	3.50	20.00	995	60	62	19.59	0.48	16.08	1.11	0.20	400		462		0		82.4			U	No			Out
	IV-b-3	K	101.6	48.6	3.16	3.50	20.00	995	60	62	19.59	0.48	16.08	1.11	0.20	400		462		0		82.4			U	No			Out
TOGO (1967)	A - C - 1	K	101.5	27.3	3.25	2.60	27.40	950	60	60	18.72	0.27	15.62	0.80	0.27	388		473	417	391		53.9			U	No			
	A - C - 2	K	101.5	27.3	3.25	2.60	27.40	950	60	60	18.72	0.27	15.62	0.80	0.27	388		473	417	391		58.8			U	No			
	A - C - 3	K	101.5	27.3	3.25	2.60	27.40	950	60	60	18.72	0.27	15.62	0.80	0.27	388		473	417	391		55.9			U	No			
	A - C - 4	K	101.5	27.3	3.25	2.60	27.40	950	60	60	18.72	0.27	15.62	0.80	0.27	388		473	417	391		57.9			U	No			
	A - O - 1	K	101.5	27.3	3.25	2.60	56.80	950	60	60	18.72	0.27	15.62	0.80	0.56	388		473	417	391		52.0			U	No			
	A - O - 2	K	101.5	27.3	3.25	2.60	56.80	950	60	60	18.72	0.27	15.62	0.80	0.56	388		473	417	391		66.7			U	No			
	A - O - 3	K	101.5	27.3	3.25	2.60	56.80	950	60	60	18.72	0.27	15.62	0.80	0.56	388		473	417	391		53.9			U	No			
	A - O - 4	K	101.5	27.3	3.25	2.60	56.80	950	60	60	18.72	0.27	15.62	0.80	0.56	388		473	417	391		60.8			U	No			
	B - C - 1	K	101.5	42.8	3.25	2.50	9.40	950	60	60	18.72	0.42	15.62	0.77	0.09	388		473	400	372		102.0			U	No			
	B - C - 2	K	101.5	42.8	3.25	2.50	9.40	950	60	60	18.72	0.42	15.62	0.77	0.09	388		473	400	372		98.1			U	No			
	B - C - 3	K	101.5	42.8	3.25	2.50	9.40	950	60	60	18.72	0.42	15.62	0.77	0.09	388		473	400	372		104.0			U	No			
	B - O - 1	K	101.5	42.8	3.25	2.50	38.90	950	60	60	18.72	0.42	15.62	0.77	0.38	388		473	400	372		77.5			U	No			
	B - O - 2	K	101.6	42.8	3.88	2.50	38.90	950	60	60	18.70	0.42	13.09	0.64	0.38	393		491	400	372		97.1			U	No			
	B - O - 3	K	101.5	42.8	3.25	2.50	38.90	950	60	60	18.72	0.42	15.62	0.77	0.38	388		473	400	372		80.4			U	No			
	C - O - 1	K	101.6	60.2	3.88	2.90	28.50	950	60	60	18.70	0.59	13.09	0.75	0.28	393		491	422	396		125.5			U	No			
	C - O - 2	K	101.5	60.2	3.25	2.90	28.50	950	60	60	18.72	0.59	15.62	0.89	0.28	388		473	422	396		109.8			U	No			
	C - O - 3	K	101.5	60.2	3.25	2.90	28.50	950	60	60	18.72	0.59	15.62	0.89	0.28	388		473	422	396		109.8			U	No			
	D - C - 1	K	101.5	48.7	3.25	3.60	2.60	950	60	60	18.72	0.48	15.62	1.11	0.03	388		473	351	320		131.4			U	No			g < t, , Out
	D - C - 2	K	101.5	48.7	3.25	3.60	2.60	950	60	60	18.72	0.48	15.62	1.11	0.03	388		473	351	320		142.2			U	No			g < t, , Out
	D - C - 3	K	101.5	48.7	3.25	3.60	2.60	950	60	60	18.72	0.48	15.62	1.11	0.03	388		473	351	320		127.5			U	No			g < t, , Out
	D - O - 1	K	101.5	48.7	3.25	3.60	32.00	950	60	60	18.72	0.48	15.62	1.11	0.32	388		473	351	320		91.2			U	No			
	D - O - 2	K	101.5	48.7	3.25	3.60	32.00	950	60	60	18.72	0.48	15.62	1.11	0.32	388		473	351	320		84.3			U	No			
	D - O - 3	K	101.5	48.7	3.25	3.60	32.00	950	60	60	18.72	0.48	15.62	1.11	0.32	388		473	351	320		78.5			U	No			
	E - O - 1	K	101.5	60.2	3.25	2.90	18.20	950	60	60	18.72	0.59	15.62	0.89	0.18	388		473	422	396		107.9			U	No			
	E - O - 2	K	101.5	60.2	3.25	2.90	18.20	950	60	60	18.72	0.59	15.62	0.89	0.18	388		473	422	396		110.8			U	No			
	E - O - 3	K	101.5	60.2	3.25	2.90	18.20	950	60	60	18.72	0.59	15.62	0.89	0.18	388		473	422	396		115.7			U	No			
	E - O' - 1	K	101.6	60.2	3.88	2.90	47.50	950	60	60	18.70	0.59	13.09	0.75	0.47	393		491	422	396		130.4			U	No			
	E - O' - 2	K	101.6	60.2	3.88	2.90	47.50	950	60	60	18.70	0.59	13.09	0.75	0.47	393		491	422	396		130.4			U	No			
	E - O' - 3	K	101.5	60.2	3.25	2.90	47.50	950	60	60	18.72	0.59	15.62	0.89	0.47	388		473	422	396		97.1			U	No			
	F - O - 1	K	101.5	60.3	3.25	3.00	18.20	950	60	60	18.72	0.59	15.62	0.92	0.18	388		473	432	407		121.6			U	No			
	F - O - 2	K	101.5	60.3	3.25	3.00	18.20	950	60	60	18.72	0.59	15.62	0.92	0.18	388		473	432	407		118.7			U	No			
	F - O - 3	K	101.5	60.3	3.25	3.00	18.20	950	60	60	18.72	0.59	15.62	0.92	0.18	388		473	432	407		101.0			U	No			
	H - O - 1	K	101.8	60.2	4.11	2.90	18.20	950	60	60	18.66	0.59	12.38	0.71	0.18	489		550	422	396		175.5			U	No			
	H - O - 2	K	101.8	60.2	4.11	2.90	18.20	950	60	60	18.66	0.59	12.38	0.71	0.18	489		550	422	396		182.4			U	No			
	H - O - 3	K	101.8	60.2	4.11	2.90	18.20	950	60	60	18.66	0.59	12.38	0.71	0.18	489		550	422	396		173.6			U	No			
KUROBANE	261	K	101.6	42.7	3.25	3.20	21.00		60	60	0.00	0.42	15.63	0.98	0.21	407		492		0		80.5							
(1965)	262	K	101.6	42.7	3.43	3.20	22.00		60	60	0.00	0.42	14.81	0.93	0.22	407		492		0		83.8							
Checked in	263	K	101.6	42.7	3.44	3.20	19.70		60	60	0.00	0.42	14.77	0.93	0.19	407		492		0		92.9							
OCHI (1984)	292	K	101.6	42.7	3.26	3.20	20.00		60	60	0.00	0.42	15.58	0.98	0.20	396		480		0		78.4							
TOPRAC (1970)	1	YT	219.1	88.9	4.67	5.30	53.00	1219	45	90	11.13	0.41	23.46	1.13	0.24	366		504	219	187		226.5	227.0			No	Not in Yura (80's)		Out ?
	2	YT	219.1	88.9	4.67	5.30	2.30		45	90	0.00	0.41	23.46	1.13	0.01	366		504	219	187		340.3	338.0			No	Not in DEn (84's)	BF, Out	g < 1, Out
	3	YT	219.1	95.3	4.80	4.80	45.30		90	45	0.00	0.43	22.82	1.00	0.21	365		502	500	485		173.6	174.0			No			Out ?
WARDENIER	W-CC-109	K	114.5	114.5	5.30	5.30	5.70	686	45	45	11.98	1.00	10.80	1.00	0.05	274		431	280	247		357.0			NOT P	Yes	L is estimated		Out
(1977)	W-CC-113	K	114.5	70.1	5.30	5.50	5.70	686	45	45	11.98	0.61	10.80	1.04	0.05	274		431	278	245		288.0			NOT P	Yes	Type 1	BF, Out	Out
	W-CC-117	K	114.5	47.6	5.30	5.30	5.70	686	45	45	11.98	0.42	10.80	1.00	0.05	274		431	330	298		207.0			NOT P	Yes	Large fillet welds		Out
	W-CC-118	K	114.5	114.5	5.30	5.30	45.80	686	45	45	11.98	1.00	10.80	1.00	0.40	274		431	280	247		275.0			NOT P	Yes	at inner crown		Out
	W-CC-120	K	114.5	70.1	5.30	5.50	45.80	686	45	45	11.98	0.61	10.80	1.04	0.40	274		431	278	245		214.0			PL	Yes	(between braces)		Out
	W-CC-123	K	114.5	47.6	5.30	5.30	45.80	686	45	45	11.98	0.42	10.80	1.00	0.40	274		431	330	298		184.0			NOT P	Yes			Out
	W-CC-195	K	114.1	114.1	5.60	5.60	22.80	686	45	45	12.02	1.00	10.19	1.00	0.20	251		403	270	237		316.0			PL	Yes			Out
	W-CC-196	K	114.1	70.0	5.60	5.30	22.80	686	45	45	12.02	0.61	10.19	0.95	0.20	251		403	290	257		245.0			NOT P	Yes			Out
	W-CC-197	K	114.1	47.6	5.60	5.30	22.80	686	45	45	12.02	0.42	10.19	0.95	0.20	251		403	330	298		199.0			NOT P	Yes			Out

Database on Simple Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Thetac (deg.)	Thetat (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm²)	Static (N/mm²)	(N/mm²)	Dynamic (N/mm²)	Static (N/mm²)	M_{rs} (KN-m)	P_u (KN)	P_{rc} (KN)	M_u (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
WARDENIER (1977)	W-CC-198	K	114.8	114.8	5.10	5.10	23.00	686	45	45	11.95	1.00	11.25	1.00	0.20	255		398	262	229		306.0			NOT P	Yes			Out
	W-CC-199	K	114.8	70.0	5.10	5.30	23.00	686	45	45	11.95	0.61	11.25	1.04	0.20	255		398	290	257		239.0			NOT P	Yes			Out
	W-CC-200	K	114.8	47.5	5.10	4.90	23.00	686	45	45	11.95	0.41	11.25	0.96	0.20	255		398	347	315		174.0			PL ?	Yes			Out
	W-CC-201	K	114.1	114.1	3.90	3.90	22.80	686	45	45	12.02	1.00	14.63	1.00	0.20	258		384	265	232		231.0			NOT P	Yes			Out
	W-CC-202	K	114.1	70.1	3.90	4.00	22.80	686	45	45	12.02	0.61	14.63	1.03	0.20	258		384	290	257		149.0			NOT P	Yes			Out
	W-CC-203	K	114.1	48.6	3.90	4.40	22.80	686	45	45	12.02	0.43	14.63	1.13	0.20	258		384	258	225		118.0			NOT P	Yes			Out
KUROBANE (1980)	K1A - 2	K	140.0	50.9	8.56	9.12	24.00	1077	60	60	15.39	0.36	8.18	1.07	0.17	316		488	310	277		408.1			NOT P	Yes	Type 1	BF, Out	Out
	K1A - 1	K	140.2	50.7	8.48	9.23	48.00	1077	60	60	15.36	0.36	8.27	1.09	0.34	316		488	310	277		377.7			NOT P	Yes	Compression	BF, Out	Out
	K1B - 2	K	140.3	50.9	8.94	9.45	24.00	1077	60	60	15.35	0.36	7.85	1.06	0.17	324		510	310	277		475.8			NOT P	Yes	brace is reinforced	BF, Out	Out
	K1B - 1	K	139.9	50.9	9.00	9.32	54.00	1077	60	60	15.40	0.36	7.77	1.04	0.39	324		510	310	277		430.7			NOT P	Yes	in K1As & K1Bs	BF, Out	Out
	K1C - 3	K	165.8	60.7	5.37	5.80	0.00	1077	60	60	12.99	0.37	15.44	1.08	0.00	381		515	386	357		335.5			P	Yes			g=0, Out
	K1C - 2	K	165.7	60.7	5.35	5.90	27.50	1077	60	60	13.00	0.37	15.49	1.10	0.17	381		515	386	357		243.3			P	Yes			
	K1C - 1	K	165.5	60.7	5.32	5.51	55.00	1077	60	60	13.02	0.37	15.55	1.04	0.33	381		515	386	357		195.2			P	Yes			
	K1D - 3	K	165.2	60.6	5.45	5.72	0.00	1077	60	60	13.04	0.37	15.16	1.05	0.00	506		579	386	357		391.4			P	Yes		BF, Out	g=0, Out
	K1D - 2	K	165.0	60.8	5.44	5.55	27.50	1077	60	60	13.05	0.37	15.17	1.02	0.17	506		579	386	357		257.0			P	Yes			
	K1D - 1	K	165.2	60.5	5.42	5.59	55.00	1077	60	60	13.04	0.37	15.24	1.03	0.33	506		579	386	357		249.2			P	Yes			
	K1E - 3	K	166.0	60.6	5.56	5.61	0.00	1077	60	60	12.98	0.37	14.93	1.01	0.00	826		876	386	357		473.8			P	Yes		BF, Out	g=0, Out
	K1E - 2	K	165.6	60.5	5.51	5.52	27.50	1077	60	60	13.01	0.37	15.03	1.00	0.17	826		876	386	357		387.5			P	Yes		BF, Out	
	K1E - 1	K	165.7	60.5	5.59	5.63	55.00	1077	60	60	13.00	0.37	14.82	1.01	0.33	826		876	386	357		348.3			P	Yes		BF, Out	
	K2A - 1	K	215.4	102.0	4.27	4.01	70.00	1342	60	60	12.46	0.47	25.22	0.94	0.32	353		450	415	388		128.3			P	Yes			
	K2A - 2	K	216.3	102.4	4.27	4.14	30.00	1342	60	60	12.41	0.47	25.33	0.97	0.14	353		450	415	388		134.9			P	Yes			
	K2A - 3	K	216.4	102.3	4.34	4.05	0.00	1342	60	60	12.40	0.47	24.93	0.93	0.00	353		450	415	388		257.9			P	Yes			g=0, Out
	K2B - 1	K	215.4	140.0	4.28	3.77	30.00	1342	60	60	12.46	0.65	25.16	0.88	0.14	353		450	376	346		192.0			P	Yes			
	K2B - 2	K	216.2	140.3	4.26	3.79	0.00	1342	60	60	12.41	0.65	25.38	0.89	0.00	353		450	376	346		331.0			P	Yes			g=0, Out
	K3A - 1	K	216.0	102.0	2.17	3.09	70.00	1342	60	60	12.43	0.47	49.77	1.42	0.32	236		379	362	331		31.4			P	Yes			Tau, Out
	K3A - 2	K	215.9	102.0	2.17	3.09	30.00	1342	60	60	12.43	0.47	49.75	1.42	0.14	236		379	362	331		34.6			P	Yes			Tau, Out
	K3B - 1	K	215.9	101.8	3.02	3.09	70.00	1342	60	60	12.43	0.47	35.75	1.02	0.32	306		373	362	331		65.2			P	Yes			
	K3B - 2	K	215.5	102.0	3.02	3.09	30.00	1342	60	60	12.45	0.47	35.68	1.02	0.14	306		373	362	331		68.2			P	Yes			
	K3C - 1	K	215.1	101.9	3.79	3.09	70.00	1342	60	60	12.48	0.47	28.38	0.82	0.33	360		498	362	331		118.1			P	Yes			
	K3C - 2	K	214.6	101.5	3.79	3.09	30.00	1342	60	60	12.51	0.47	28.31	0.82	0.14	360		498	362	331		120.1			P	Yes			
	K3D - 1	K	216.0	101.4	4.33	3.00	70.00	1342	60	60	12.43	0.47	24.94	0.69	0.32	399		518	411	384		147.6			P	Yes			
	K3D - 2	K	215.6	101.7	4.28	3.09	30.00	1342	60	60	12.45	0.47	25.19	0.72	0.14	412		536	411	384		175.5			P	Yes			
	K3E - 1	K	215.8	101.7	4.28	7.46	70.00	1342	60	60	12.44	0.47	25.21	1.74	0.32	412		536	383	353		156.9			P	Yes			Tau, Out
	K3E - 2	K	216.3	101.7	4.33	7.46	30.00	1342	60	60	12.41	0.47	24.98	1.72	0.14	399		518	383	353		168.8			P	Yes			Tau, Out
	K3F - 1	K	215.9	101.8	5.58	3.09	70.00	1342	60	60	12.43	0.47	19.35	0.55	0.32	281		359	362	331		167.2			P	Yes			
	K3F - 2	K	215.5	101.9	5.49	3.09	30.00	1342	60	60	12.45	0.47	19.63	0.56	0.14	361		466	362	331		225.1			P	Yes			
	K3G - 1	K	215.4	101.5	5.49	7.46	70.00	1342	60	60	12.46	0.47	19.62	1.36	0.32	361		466	383	353		211.3			P	Yes			Tau, Out
	K3G - 2	K	216.0	101.6	5.58	7.46	30.00	1342	60	60	12.43	0.47	19.35	1.34	0.14	281		359	383	353		178.0			P	Yes			Tau, Out
REF (35) in Ochi (1984)	418	K	165.2	76.3	4.96	3.90	57.30		45	45	0.00	0.46	16.65	0.79	0.35	327		442		0		221.6				No			
	421	YT	165.2	76.3	5.00	4.20	57.30		90	45	0.00	0.46	16.52	0.84	0.35	399		516		0		142.2				No			
	423	YT	165.2	101.6	5.00	4.20	42.50		90	45	0.00	0.62	16.52	0.84	0.26	399		516		0		198.1				No			
NISHIDA (1978)	1	YT	318.5	114.3	6.10	11.00	63.00	1911	90	45	12.00	0.36	26.11	1.80	0.20	749		798		0		406.1			P	Yes			Tau, Fyc, Out
	2	YT	318.5	114.3	8.80	11.00	63.00	1911	90	45	12.00	0.36	18.10	1.25	0.20	748		796		0		814.2			P	Yes			Tau, Fyc, Out
OHTAKE (1978)	A	YT	762.0	324.0	10.50	18.90	40.00	2130	90	45	5.59	0.43	36.29	1.80	0.05	740		816	742	791		1637.1			P	Yes	Rejected by Ochi		Out, Tau, Fyc
	C	YT	762.0	324.0	22.50	18.90	40.00	2130	90	45	5.59	0.43	16.93	0.84	0.05	833		896	742	791		6333.2			P	Yes	Rig ?		Out, Fyc
	D	YT	660.0	273.0	20.60	16.70	50.00	2130	90	45	6.45	0.41	16.02	0.81	0.08	814		866	720	762		5008.3			P	Yes			Out, Fyc
HLAVACEK (1970)	2a	K	159.0	89.0	5.70	4.30	146.00		45	45	0.00	0.56	13.95	0.75	0.92	353		508		0		298.3					???		Out
OCHI (1981)	K - 6	K	217.4	140.3	4.38	3.29	30.00	1502	60	60	13.82	0.65	24.82	0.75	0.14	354		458	401	373		224.6			P	Yes			
	K - 7	K	216.7	140.1	4.35	3.29	60.00	1502	60	60	13.86	0.65	24.91	0.76	0.28	355		476	401	373		209.9			P	Yes	Compression		
	K - 8	K	216.6	48.8	4.36	3.03	30.00	1502	60	60	13.87	0.23	24.84	0.69	0.14	355		458	401	373		90.3			P	Yes	brace filled with		Out
	K - 9	K	217.8	48.7	4.35	3.05	130.00	1502	60	60	13.79	0.22	25.03	0.70	0.60	355		458	401	373		82.4			P	Yes	concrete: K8, K9		Out
	K - 12	K	165.7	140.3	4.34	3.30	30.00	1090	60	60	13.16	0.85	19.09	0.76	0.18	348		470	401	373		270.8			P	Yes			
VERITEC (1993)		K	498.6	356.5	10.25	9.30	50.00	3900	45	45	15.64	0.72	24.32	0.91	0.10	360	322	502	379	353		1523.0			P	Yes			
MAKINO (1988)	KA-4	K	165.4	101.8	3.57	3.20	25.00	1222	60	60	14.78	0.62	23.17	0.90	0.15	323		435	412	385		133.2			P	Yes			

Database on Simple Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	ThetaC (deg.)	ThetaT (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm^2)	Static (N/mm^2)	(N/mm^2)	Dynamic (N/mm^2)	Static (N/mm^2)	M_{PB} (KN-m)	P_U (KN)	P_{YC} (KN)	M_U (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
T&Y-TENSION																													
WIMPEY (1977) and TEBBETT (1979)	A11	T	508.0	168.3	7.94	7.94		1473		90	5.80	0.33	31.99	1.00		335		463	312	279		470.3	368.7		PL	Yes	L = L1		
	W1	T	508.0	193.7	12.70	6.35		1473		90	5.80	0.38	20.00	0.50		338		462	256	224		1151.8	1006.4		PL	Yes	L4 = 2032	BF, Out	
KANATANI (1964, 1966)	T-B-D	T	139.8	76.3	6.50	4.00		400		90	5.72	0.55	10.75	0.62		284		431	412	385		299.1				Yes	Fyb is LB for TBE		
	T-B-E	T	139.8	60.5	6.50	3.80		400		90	5.72	0.43	10.75	0.58		284		431	284	251		259.9				No		BF, Out	
	T-A-D	T	165.2	76.3	7.20	4.00		400		90	4.84	0.46	11.47	0.56		324		412	412	385		323.6				No	Fyb is LB for		
	T-A-E	T	165.2	60.5	7.20	3.80		400		90	4.84	0.37	11.47	0.53		324		412	284	251		294.2				No	TAE & TCE	BF, Out	
	T-C-D	T	114.3	76.3	4.70	4.00		400		90	7.00	0.67	12.16	0.85		431		471	412	385		255.0				No			
	T-C-E	T	114.3	60.5	4.70	3.80		400		90	7.00	0.53	12.16	0.81		431		471	284	251		228.5				No		BF, Out	
JSSC (1972) and AKIYAMA (1974)	I-T-40-0.2	T	165.5	42.7	4.70	3.30		826		90	9.98	0.26	17.61	0.70		441		532	324	291		193.2			PL	Yes	Fyc for T-70 series	BF, Out	
	I-T-40-0.4	T	165.2	76.3	4.70	2.90		826		90	10.00	0.46	17.57	0.62		441		532	363	332		250.1			P	Yes	from JSSC	BF, Out	
	I-T-70-0.2	T	318.4	60.5	4.50	3.00		1593		90	10.01	0.19	35.38	0.67		415		533	333	301		220.7			PL	Yes		BF, Out	
	I-T-70-0.4	T	318.5	139.8	4.50	4.40		1593		90	10.00	0.44	35.39	0.98		415		533	343	311		350.1			P	Yes	Ftc from		
	I-T-100-0.4	T	457.6	165.2	4.90	4.70		2286		90	9.99	0.36	46.69	0.96		392		534	441	417		307.9			P	Yes	Ochi (1984)		Gamma
	I-T-100-0.2	T	456.9	89.1	4.90	3.00		2286		90	10.01	0.20	46.62	0.61		392		534	363	332		298.1			P	Yes		BF, Out	Gamma
TOPRAC (1966, 1969)	T-1	T	323.9	73.0	12.70	5.16		1219		90	7.53	0.23	12.75	0.41		274		451		0		453.7	311.4		JACK CAP	Yes	Fyc is nominal ?		Out
	T-2	T	323.9	73.0	6.35	5.16		1219		90	7.53	0.23	25.50	0.81		274		451		0		249.1	200.2		P	Yes	Fyc, Ftc from Ochi		Out
	T-3	T	406.4	88.9	6.35	5.45		1829		90	9.00	0.22	32.00	0.86		274		451		0		240.2	177.9		P	Yes			Out
	T-4	T	323.9	141.3	6.35	6.55		1219		90	7.53	0.44	25.50	1.03		274		451		0		364.8	169.0		P	Yes			Out
	T-5	T	219.1	141.3	6.35	4.78		610		90	5.57	0.64	17.25	0.75		274		451		0		467.1	275.8		JACK CAP	Yes			Out
	T-6	T	323.9	141.3	6.35	6.55		2438		90	15.05	0.44	25.50	1.03		274		451		0		311.4	191.3		P	Yes			Out
	T-7	T	323.9	141.3	6.35	6.55		1829		90	11.29	0.44	25.50	1.03		274		451		0		364.8	173.5		P	Yes			Out
BEALE (1967)	Y-1 (5)	Y	323.9	60.3	6.35	5.54		2438		45	15.06	0.19	25.50	0.87		290		445		79		289.1	97.9		NOT P	Yes	L = L2	BF, Out	
	Y-2 (6)	Y	323.9	101.6	6.35	5.74		2438		45	15.06	0.31	25.50	0.90		290		445		110		355.9	133.4		NOT P	Yes		BF, Out	
	T-8 (1)	T	323.9	60.3	6.35	5.54		2438		90	15.05	0.19	25.50	0.87		290		445		0		195.7	66.7		NOT P	Yes	8 & 9 are outliers		
	T-9 (2)	T	323.9	101.6	6.35	5.74		2438		90	15.05	0.31	25.50	0.90		290		445		0		249.1	106.8		NOT P	Yes	in Ochi		
	T-10 (3)	T	323.9	273.1	6.35	6.35		2438		90	15.05	0.84	25.50	1.00		290		445		0		422.6	222.4		NOT P	Yes			Ti, Out
	T-11 (4)	T	323.9	323.9	6.35	6.35		2438		90	15.05	1.00	25.50	1.00		290		445		0		489.3	444.8		NOT P	Yes			Ti, Out
	Y-3 (7)	Y	323.9	273.1	6.35	6.35		2438		45	15.05	0.84	25.50	1.00		290		445		0		533.8	266.9		NOT P	Yes			Ti, Out
MAKINO (1981)	1	T	216.4	164.8	2.19	4.50		1330		90	12.29	0.76	49.41	2.05		219		350		0		95.9	53.5		PL	Yes			Tau, Out
	2	T	216.4	164.8	3.03	4.50		1330		90	12.29	0.76	35.71	1.49		293		347		0		149.9	86.9		PL	Yes			Tau, Out
	3	T	216.1	164.8	4.28	4.50		1330		90	12.31	0.76	25.25	1.05		393		510		0		314.1	201.4		PL	Yes			
	4	T	215.7	164.9	5.47	4.50		1330		90	12.33	0.76	19.72	0.82		341		441		0		396.4	256.6		NOT P	Yes			
	5	T	215.7	59.9	4.30	3.20		1330		90	12.33	0.28	25.08	0.74		391		489		0		151.1	127.2		NOT P	Yes			
	6	T	216.7	102.1	4.30	3.20		1330		90	12.28	0.47	25.20	0.74		389		498		0		217.7	133.6		NOT P	Yes			
MAKINO (1986) and Kurobane (1991)	L - A - T	T	216.5	216.5	4.55	4.55		735		90	6.79	1.00	23.79	1.00		377		522	377	347		519.0							PF, Out
	L - B - T	T	216.5	165.6	4.55	4.53		735		90	6.79	0.76	23.79	1.00		377		522	341	309		486.0							PF, Out
	L - C - T	T	216.5	114.3	4.55	4.56		735		90	6.79	0.53	23.79	1.00		377		522	332	300		336.0			U	Yes			
	L - D - T	T	216.5	60.7	4.55	3.96		735		90	6.79	0.28	23.79	0.87		377		522	311	278		210.0			U	Yes		BF, Out	
	M - C - T	T	216.6	114.3	6.28	4.56		735		90	6.79	0.53	17.25	0.73		298		519	332	300		551.0			P	Yes		BF, Out	Out
	MA - C - T	T	217.9	114.4	6.81	7.03		735		90	6.75	0.53	16.00	1.03		580		650	287	254		709.0				No		BF, Out	Out
	H - C - T	T	216.5	114.4	8.06	7.03		735		90	6.79	0.53	13.43	0.87		378		469	287	254		710.0				No		BF, Out	Out
	H - D - T	T	216.5	60.3	8.06	10.09		735		90	6.79	0.28	13.43	1.25		378		469	299	266		404.0				No			Tau, Out
VERITEC (1986)	2	T	495.0	229.0	16.00	12.50		2020		90	8.16	0.46	15.47	0.78		360		520		0		2340.0	2050.0		P	Yes	L = L1		
DT&X-TENSION																													
SAMMET (1963)	A2-3	DT	159.0	83.0	5.00	3.50		1037		90	13.04	0.52	15.90	0.70		343				0		158.9			NOT P	Yes	Outliers in Ochi		Out
	A2-4	DT	159.0	83.0	5.00	3.50		1037		90	13.04	0.52	15.90	0.70		343				0		178.5			NOT P	Yes	Fyc is uncertain		Out
GIBSTEIN (1973)	10	DT	193.7	48.3	6.67	4.50		1000		90	10.33	0.25	14.52	0.67		334			310	0		165.8	137.3		NOT P	Yes	Outliers in Ochi		
	11	DT	193.7	101.6	6.59	5.60		1000		90	10.33	0.52	14.70	0.85		334			310	0		243.3	196.2		NOT P	Yes	Fyb is AV		PF, Out
	12	DT	193.7	159.0	6.65	8.00		1000		90	10.33	0.82	14.56	1.20		334			310	0		412.0	294.3		NOT P	Yes			

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Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Thetac (deg.)	Thetat (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm2)	Static (N/mm2)	(N/mm2)	Dynamic (N/mm2)	Static (N/mm2)	Mpb (KN-m)	Pu (KN)	Pfc (KN)	Mu (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
JSSC (1972)	I-TS-40-0.2	DT	165.5	42.7	4.70	3.30		826		90	9.98	0.26	17.61	0.70		471		537	343	311		153.0			PL	Yes	Ftc is an average	BF, Out	
and	I-TS-40-0.4	DT	165.2	76.3	4.60	2.90		826		90	10.00	0.46	17.96	0.63		471		537	373	343		215.8			NOT P	Yes			
AKIYAMA (1974)	I-TS-40-0.6	DT	165.2	114.3	4.60	3.80		826		90	10.00	0.69	17.96	0.83		471		537	373	343		311.0			P	Yes			
	I-TS-40-1.0	DT	165.2	165.2	4.60	4.60		826		90	10.00	1.00	17.96	1.00		471		537	471	451		765.9			NOT P	Yes			
	I-TS-70-0.2	DT	318.4	60.5	4.40	3.00		1593		90	10.01	0.19	36.18	0.68		441		534	333	301		143.2			P	Yes			
	I-TS-70-0.4	DT	320.6	139.8	4.40	4.40		1593		90	9.94	0.44	36.43	1.00		441		534	343	311		179.5			P	Yes			
	I-TS-70-0.6	DT	318.3	165.2	4.40	4.50		1593		90	10.01	0.52	36.17	1.02		422		534	-	0		189.3			P	Yes			
	I-TS-100-0.2	DT	456.9	89.1	4.90	3.00		2286		90	10.01	0.20	46.62	0.61		402		549	343	311		158.9			P	Yes			Gamma
	I-TS-100-0.4	DT	457.6	165.2	4.90	4.50		2286		90	9.99	0.36	46.69	0.92		402		549	-	0		197.2			P	Yes			Gamma
	I-TS-70-1.0	DT	318.5	318.5	4.40	4.40		1593		90	10.00	1.00	36.19	1.00		422		534	422	396		941.5			U	Yes	P-d is incomplete		Out ?
YAMASAKI	DT-M	DT	1400.0	800.0	36.00	12.00		3000		90	4.29	0.57	19.44	0.33		254		454	300	267		7612.6			U	No			Alpha
(1979, 1980)	DT-H	DT	1400.0	800.0	36.00	12.00		3000		90	4.29	0.57	19.44	0.33		336		518	344	312		8083.4			U	No			Alpha
MAKINO (1981)	1	DT	216.1	165.2	2.20	4.50		1330		90	12.31	0.76	49.11	2.05		215		345		0		35.3	40.6		PL	Yes			Tau, FL, Out
	2	DT	216.5	165.2	3.01	4.50		1330		90	12.29	0.76	35.96	1.50		287		345		0		77.5	79.0		PCF	Yes			Tau, FL, Out
	3	DT	215.8	165.1	3.82	4.50		1330		90	12.33	0.77	28.25	1.18		351		477		0		135.3	109.8		PCF	Yes			FL, Out
	4	DT	215.3	60.7	3.77	3.20		1330		90	12.35	0.28	28.55	0.85		345		476		0		83.6	69.7		NOT P	Yes			
	5	DT	216.6	101.8	3.84	3.20		1330		90	12.28	0.47	28.20	0.83		340		474		0		98.4	77.9		P	Yes			
TOGO (1967)	X - I - 5.7 - C *	DT	101.8	34.0	5.70	2.30		800		90	15.72	0.33	8.93	0.40		353		489		0		96.6			NOT P	Yes			Out, PF
	X - I - 5.7 - E *	DT	101.8	48.6	5.70	3.50		800		90	15.72	0.48	8.93	0.61		353		489		0		139.1			NOT P	Yes			Out, PF
	X - I - 5.7 - F	DT	101.8	60.5	5.70	3.20		800		90	15.72	0.59	8.93	0.56		353		489		0		239.9			NOT P	Yes			
	X - I - 4.2 - C *	DT	101.7	34.0	4.18	2.30		800		90	15.73	0.33	12.17	0.55		400		476		0		90.0			NOT P	Yes			Out, PF
	X - I - 4.2 - E	DT	101.7	48.6	4.18	3.50		800		90	15.73	0.48	12.17	0.84		400		476		0		144.2			NOT P	Yes			
	X - I - 4.2 - F	DT	101.7	60.5	4.18	3.20		800		90	15.73	0.59	12.17	0.77		400		476		0		160.9			NOT P	Yes			
	X - I - 3.2 - C	DT	101.9	34.0	3.10	2.30		800		90	15.70	0.33	16.44	0.74		358		432		0		65.7			NOT P	Yes			
	X - I - 3.2 - E	DT	101.9	48.6	3.10	3.50		800		90	15.70	0.48	16.44	1.13		358		432		0		86.4			NOT P	Yes			
	X - I - 3.2 - F	DT	101.9	60.5	3.10	3.20		800		90	15.70	0.59	16.44	1.03		358		432		0		95.2			NOT P	Yes			
MAKINO (1978)	XTB-01	DT	140.0	50.9	8.95	9.30		840		90	12.00	0.36	7.82	1.04		316		485		0		325.6			P	Yes			
	XMB-01	DT	165.3	60.7	5.51	5.66		990		90	11.98	0.37	15.00	1.03		506		582		0		212.3			P	Yes			FYC
	XHB-01	DT	165.2	60.6	5.50	5.72		990		90	11.99	0.37	15.02	1.04		826		879		0		392.3			PL	Yes			FYC, Out
	XHB-02	DT	165.2	60.5	5.53	5.60		990		90	11.99	0.37	14.94	1.01		826		879		0		323.6			P	Yes			FYC, Out
MAKINO (1982) Checked in OCHI (1984)	34	DT	165.1	164.6	4.24	4.50		1400		90	16.96	1.00	19.47	1.06		286		398		0		612.9					From Ochi		
	35	DT	114.2	114.3	4.26	4.50		920		90	16.11	1.00	13.40	1.06		360		443		0		488.2							
RODRIGUEZ	1	DT	410.0	220.0	9.50	7.80		800		90	3.90	0.54	21.58	0.82		321				0		451.0					Ref. unavailable		Out
(1985)	2	DT	410.0	220.0	9.50	7.80		1991		90	9.71	0.54	21.58	0.82		355				0		568.0							Out
SANDERS	T1	DT	407.4	407.4	7.98	7.98		3556		90	17.46	1.00	25.53	1.00		350	337	444	350	337		1836.1	1317.6		M	Yes			
(1987)	T2	DT	407.4	407.4	7.98	7.98		3556		90	17.46	1.00	25.53	1.00		350	337	444	350	337		2186.4	1313.2		M	Yes			
	T3	DT	407.4	407.4	7.98	7.98		3556		90	17.46	1.00	25.53	1.00		350	337	444	350	337		2310.5	1308.3		M	Yes			
	T4	DT	407.4	407.4	7.98	7.98		610		90	2.99	1.00	25.53	1.00		350	337	444	350	337		2113.9	1521.8		M	Yes			Alpha, Out
	T8	DT	407.4	142.5	6.65	6.65		914		90	4.49	0.35	30.63	1.00		350	337	444	295	273		425.7	214.4		M	Yes			Alpha
	T9	DT	407.4	142.5	6.65	6.65		914		90	4.49	0.35	30.63	1.00		350	337	444	295	273		380.3	215.7		M	Yes			Alpha
	T10	DT	407.4	135.1	8.18	8.18		914		90	4.49	0.33	24.90	1.00		350	337	444		470		377.7	212.6		M	Yes			Alpha
	T11	DT	407.4	135.1	8.18	8.18		914		90	4.49	0.33	24.90	1.00		350	337	444		470		372.8	209.5		M	Yes			Alpha
	T12	DT	407.4	135.1	8.18	8.18		914		90	4.49	0.33	24.90	1.00		350	337	444		470		367.9	237.1		M	Yes			Alpha
T&Y-IPB																													
GIBSTEIN	4	T	219.1	71.6	6.30	18.50			90		0.00	0.33	17.39	2.94		314		439	335	303	16.44			8.24	U	No			Tau, Out
(1976)	5	T	219.1	71.6	8.90	18.50			90		0.00	0.33	12.31	2.08		422		579	335	303	16.44			17.75	U	No		BF, Out	Tau, Out
	6	T	298.5	101.6	7.20	16.00			90		0.00	0.34	20.73	2.22		294		422	417	391	46.33			14.32	U	No			Tau, Out
	7	T	219.1	101.6	5.50	16.00			90		0.00	0.46	19.92	2.91		305		439	417	391	46.33			11.67	U	No			Tau, Out
	8	T	219.1	101.6	8.40	16.00			90		0.00	0.46	13.04	1.90		367		549	417	391	46.33			25.79	U	No			Tau, Out
	9	T	219.1	101.6	10.00	16.00			90		0.00	0.46	10.96	1.60		368		579	417	391	46.33			34.91	U	No			Tau, Out
	10	T	219.1	101.6	12.30	16.00			90		0.00	0.46	8.91	1.30		404		596	417	391	46.33			53.94	U	No		BF, Out	Tau, Out
	11	T	219.1	139.7	6.00	17.50			90		0.00	0.64	18.26	2.92		314		439	415	388	102.20			25.79	U	No			Tau, Out

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Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Theta: (deg.)	Thetar (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]
GIBSTEIN	12	T	219.1	139.7	8.80	17.50			90		0.00	0.64	12.45	1.99	
(1976)	13	T	219.1	139.7	12.30	17.50			90		0.00	0.64	8.91	1.42	
	14	T	298.5	193.7	7.30	7.10			90		0.00	0.65	20.45	0.97	
	15	T	298.5	193.7	10.00	7.10			90		0.00	0.65	14.93	0.71	
	16	T	298.5	193.7	10.00	7.10			90		0.00	0.65	14.93	0.71	
	17	T	219.1	177.8	5.90	16.00			90		0.00	0.81	18.57	2.71	
	18	T	219.1	177.8	8.60	16.00			90		0.00	0.81	12.74	1.86	
	19	T	219.1	177.8	12.50	16.00			90		0.00	0.81	8.76	1.28	
JSSC (1972)	I-B-40-0.2	T	165.5	42.7	4.70	3.30		661	90		7.99	0.26	17.61	0.70	
and	I-B-40-0.4	T	165.5	76.3	4.50	2.90		661	90		7.99	0.46	18.39	0.64	
AKIYAMA (1974)	I-B-70-0.2	T	318.4	60.5	4.40	3.00		1274	90		8.00	0.19	36.18	0.68	
	I-B-70-0.4	T	318.5	139.8	4.40	4.40		1274	90		8.00	0.44	36.19	1.00	
	I-B-100-0.2	T	456.9	89.1	4.80	3.00		1829	90		8.01	0.20	47.59	0.63	
	I-B-100-0.4	T	457.6	165.2	4.80	4.70		1829	90		7.99	0.36	47.67	0.98	
WIMPEY (1977)	W7	T	508.0	193.7	12.70	6.35		1473	90		5.80	0.38	20.00	0.50	
and	W9	T	508.0	193.7	12.70	6.35		1473	90		5.80	0.38	20.00	0.50	
TEBBETT (1979)	A 17	T	508.0	168.3	7.94	7.94		1473	90		5.80	0.33	31.99	1.00	
	A 19	T	508.0	168.3	7.94	7.94		1473	90		5.80	0.33	31.99	1.00	
TOPRAC (1966)	8C1-90	T	220.0	220.0	7.10	7.10			90		0.00	1.00	15.49	1.00	
	8C2-90	T	219.7	219.7	8.20	8.20			90		0.00	1.00	13.40	1.00	
	4C1-90	T	114.6	114.6	5.87	5.87			90		0.00	1.00	9.76	1.00	
	8T1-90	T	220.0	220.0	7.10	7.10			90		0.00	1.00	15.49	1.00	
	8T2-90	T	219.7	219.7	7.60	7.60			90		0.00	1.00	14.45	1.00	
STAMENKOVIC	A2	T	114.2	48.3	3.44	3.99		794	90		13.91	0.42	16.60	1.16	
& SPARROW	B2	T	114.1	48.4	4.95	3.72		794	90		13.92	0.42	11.53	0.75	
(1983, 1984)	C2	T	114.3	48.4	5.41	4.14		794	90		13.89	0.42	10.56	0.77	
and	D2	T	113.9	48.4	6.01	4.03		794	90		13.94	0.42	9.48	0.67	
SPARROW (1979)	E2	T	114.1	60.7	3.45	4.95		794	90		13.92	0.53	16.54	1.43	
	F2	T	114.1	60.3	4.92	5.00		794	90		13.92	0.53	11.60	1.02	
	G2	T	114.0	60.6	6.05	4.71		794	90		13.93	0.53	9.42	0.78	
	H2	T	114.2	76.1	3.45	4.33		794	90		13.91	0.67	16.55	1.26	
	J2	T	114.1	76.0	4.92	4.50		794	90		13.92	0.67	11.60	0.91	
	K2	T	114.3	76.1	5.41	4.50		794	90		13.89	0.67	10.56	0.83	
	L2	T	114.1	76.0	6.03	5.00		794	90		13.92	0.67	9.46	0.83	
	M2	T	114.2	89.0	3.42	4.85		794	90		13.91	0.78	16.70	1.42	
	N2	T	114.3	89.3	5.41	4.77		794	90		13.89	0.78	10.56	0.88	
	P2	T	114.0	89.1	5.96	4.95		794	90		13.93	0.78	9.56	0.83	
	Q2	T	114.2	114.1	3.42	5.02		794	90		13.91	1.00	16.70	1.47	
	R2	T	114.1	114.2	4.95	5.01		794	90		13.92	1.00	11.53	1.01	
	S2	T	114.1	114.3	5.93	4.87		794	90		13.92	1.00	9.62	0.82	
DEn (1989)	1.9	Y	508.0	203.0	12.40	12.40		1575	45		6.20	0.40	20.48	1.00	
JISSP	1.10	Y	508.0	406.0	12.40	12.40		1575	45		6.20	0.80	20.48	1.00	
	1.11	Y	508.0	406.0	7.90	7.90		1575	45		6.20	0.80	32.15	1.00	
	1.12	Y	508.0	508.0	8.00	8.00		1575	45		6.20	1.00	31.75	1.00	
STOL (1985)	3	T	168.7	59.8	10.55	11.10		870	90		10.31	0.35	8.00	1.05	
	70	T	168.4	114.5	10.28	11.31		705	90		8.37	0.68	8.19	1.10	
	1	T	168.3	60.6	5.78	5.63		870	90		10.34	0.36	14.56	0.97	
STOL (1985)	10	T	168.3	114.6	5.90	5.95		870	90		10.34	0.68	14.26	1.01	
	61	T	168.1	168.3	5.68	5.78		705	90		8.39	1.00	14.80	1.02	
	13	T	168.5	60.8	3.45	3.81		870	90		10.33	0.36	24.42	1.10	
	16	T	168.5	114.7	3.42	3.90		870	90		10.33	0.68	24.63	1.14	
	19	T	168.8	168.8	3.55	3.55		870	90		10.31	1.00	23.77	1.00	
VERITEC (1987)	4	T	495.0	230.0	16.00	12.50		2614	90		10.56	0.46	15.47	0.78	
STAMENKOVIC	TCC-1	T	273.4	219.5	12.65	12.40		2134	90		15.61	0.80	10.81	0.98	
& SPARROW	TCC-2	T	272.6	218.8	8.00	8.16		2134	90		15.66	0.80	17.04	1.02	
(1983, 1984)	TCC-3	T	273.0	219.0	5.95	6.27		2134	90		15.63	0.80	22.94	1.05	

Specimen	Dynamic (N/mm^2)	Static (N/mm^2)	(N/mm^2)	Dynamic (N/mm^2)	Static (N/mm^2)	M_{FB} (KN-m)	P_u (KN)	P_{FC} (KN)	M_u (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
12	422		579	415	388	102.20			58.84	U	No			Tau, Out
13	392		549	415	388	102.20			88.26	U	No			Tau, Out
14	296		439	340	308	76.19			53.45	U	No			
15	294		422	340	308	76.19			78.46	U	No		BF, Out	
16	294		422	340	308	76.19			85.62	U	No		BF, Out	
17	314		439	399	371	155.87			40.50	U	No			Tau, Out
18	422		579	399	371	155.87			98.07	U	No			Tau, Out
19	392		549	399	371	155.87			160.83	U	No		BF, Out	Tau, Out
I-B-40-0.2	471		537	343	311	1.60			2.11	PL	Yes	Ftc is an AV	BF, Out	
I-B-40-0.4	471		537	373	343	5.36			6.28	PL	Yes		BF, Out	
I-B-70-0.2	441		534	333	301	2.99			3.33	PL	Yes		BF, Out	
I-B-70-0.4	441		534	343	311	25.11			14.91	P	Yes			
I-B-100-0.2	402		549	363	332	7.39			6.08	PL	Yes			Gamma
I-B-100-0.4	402		549	471	451	54.67			18.04	P	Yes			Gamma
W7	338		462	256	224	49.88			77.44	U	(Yes)	L-d curves are	BF, Out	Out
W9	338		462	256	224	49.88			78.96	U	(Yes)	incomplete	BF, Out	Out
A 17	335		463	312	279	57.05			36.95	U	(Yes)			
A 19	335		463	312	279	57.05			35.94	U	(Yes)			
8C1-90	276				0	0.00			95.80			Not found in Ref.		Out
8C2-90	172				0	0.00			65.70					Out
4C1-90	224				0	0.00			16.00					Out
8T1-90	276				0	0.00			83.60					Out
8T2-90	328				0	0.00			113.40					Out
A2	347		497	320	287	2.26			2.24	NOT P	Yes	Fyb is a LB		Out
B2	329		480	320	287	2.14			2.06	P	Yes	L = L1		Out
C2	333		489	320	287	2.34			2.35	P	Yes		BF, Out	
D2	352		512	320	287	2.29			2.98	NOT P	Yes		BF, Out	Out
E2	388		507	320	287	4.43			3.87	NOT P	Yes			Tau, Out
F2	320		471	320	287	4.41			5.66	NOT P	Yes		BF, Out	Out
G2	349		515	320	287	4.24			5.22	NOT P	Yes		BF, Out	Out
H2	356		492	320	287	6.42			4.47	P	Yes			Tau, Out
J2	330		453	320	287	6.62			7.45	P	Yes		BF, Out	
K2	342		499	320	287	6.64			9.70	P	Yes		BF, Out	
L2	362		498	320	287	7.25			9.09	P	Yes		BF, Out	
M2	347		489	320	287	9.88			7.02	NOT P	Yes			Tau, Out
N2	345		498	320	287	9.80			12.81	P	Yes		BF, Out	
P2	361		504	320	287	10.08			12.74	NOT P	Yes		BF, Out	Out
Q2	341		497	320	287	17.18			12.50	PL ?	Yes			Tau, Out
R2	335		478	320	287	17.18			18.98	P	Yes		BF, Out	
S2	359		506	320	287	16.77			19.80	NOT P	Yes		BF, Out	Out
1.9	322		483	475	456	205.70			206.00	P	Yes	L4 = 2032	BF, Out	
1.10	317		448	387	358	687.76			762.00	P	Yes		BF, Out	
1.11	278		424	378	348	436.03			376.00	PL	Yes			
1.12	300		428	405	377	754.98			712.00	PL	Yes			
3	263		426	376	346	9.27			13.20	DL2	Yes		BF, Out	
70	235		385	293	260	31.43			38.80	DL2	Yes		BF, Out	
1	286		398	316	283	4.84			4.80	DL2	Yes			
10	332		410	335	303	21.29			15.80	DL2	Yes			
61	305		397	286	253	38.63			37.20	DL2	Yes			
13	299		370	296	263	3.26			2.70	DL2	Yes			Out, FL
16	303		383	250	218	10.42			7.45	P	Yes			
19	305		366	305	272	26.38			19.60	P	Yes			
4	352		511	734	781	462.15			185.70	P	Yes	L= L1		
TCC-1	290		482	316	283	150.83			153.80	P	Yes	L= L4	BF, Out	
TCC-2	284		430	276	243	88.02			70.80	PL	Yes			
TCC-3	304		457	290	257	72.93			54.40	NOT P	Yes			Out

Database on Simple Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Thetac (deg.)	Thetar (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm^2)	Static (N/mm^2)	(N/mm^2)	Dynamic (N/mm^2)	Static (N/mm^2)	M_{PB} (KN-m)	P_U (KN)	P_{FC} (KN)	M_U (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
STAMENKOVIC	TCC-4	T	273.0	114.3	12.48	6.00		2134	90		15.63	0.42	10.94	0.48		233		485	367	336	23.70			32.00	PL ?	Yes		BF, Out	PF, Out
& SPARROW	TCC-5	T	273.0	114.3	7.70	6.00		2134	90		15.63	0.42	17.73	0.78		284		430	367	336	23.70			18.80	PL	Yes			
(1983, 1984)	TCC-6	T	273.0	114.3	5.98	6.00		2134	90		15.63	0.42	22.83	1.00		304		457	367	336	23.70			15.50	PL ?	Yes			
	TCC-7	T	168.3	76.1	6.64	4.85		2134	90		25.36	0.45	12.67	0.73		353		439	346	314	7.75			6.64	NOT P	Yes			Out
DT&X-IPB																													
BOONE (1982)	I7	DT	407.7	274.3	8.05	6.60		3556	90		17.44	0.67	25.32	0.82		334	321	470	339	331	156.59			119.32	P	Yes			
WEINSTEIN (1985	I24	DT	407.4	407.4	7.98	7.98		3556	90		17.46	1.00	25.53	1.00		348	337	443	348	337	429.09			255.92	P	Yes			
SWENSSON (1987	I43	DT	407.4	142.5	7.98	6.65		3556	90		17.46	0.35	25.53	0.83		350	337	444	295	273	33.53			30.17	DL	Yes			
VEGTE (1991)	X5	DT	408.0	246.0	10.00	10.35		2440	90		11.96	0.60	20.40	1.04		318		425	284	251	144.32			113.05	PL	Yes			
STAMENKOVIC	XCC-1	DT	114.3	114.7	3.70	5.00		795	90		13.91	1.00	15.45	1.35		292		449	311	278	16.75			10.85	PL	Yes	L = L1		Tau, Out
& SPARROW	XCC-2	DT	113.9	88.9	3.62	5.04		795	90		13.96	0.78	15.73	1.39		292		449	357	326	11.56			6.76	NOT P	Yes	TF = 12.5		Tau, Out
(1983, 1984)	XCC-3	DT	114.9	60.9	3.66	4.85		795	90		13.84	0.53	15.70	1.33		292		449	363	332	5.07			3.47	PL ?	Yes			Tau, Out
	XCC-4	DT	114.8	48.4	3.59	4.95		795	90		13.85	0.42	15.99	1.38		292		449	365	334	3.14			2.36	NOT P	Yes			Tau, Out
	XCC-5	DT	114.7	114.3	4.85	4.90		795	90		13.86	1.00	11.82	1.01		311		462	311	278	16.31			15.92	PL	Yes			
	XCC-6	DT	114.0	89.0	4.95	5.00		795	90		13.95	0.78	11.52	1.01		311		462	357	326	11.51			10.10	PL	Yes			Out
	XCC-7	DT	115.0	60.7	4.71	5.00		795	90		13.83	0.53	12.21	1.06		311		462	363	332	5.17			5.09	NOT P	Yes			Out
	XCC-8	DT	115.1	48.3	4.75	4.95		795	90		13.81	0.42	12.12	1.04		311		462	365	334	3.12			3.22	PL ?	Yes		BF, Out	
	XCC-9	DT	114.3	114.7	6.10	4.90		795	90		13.91	1.00	9.37	0.80		349		478	311	278	16.44			21.43	PL	Yes		BF, Out	Out
	XCC-10	DT	114.4	89.0	6.01	5.01		795	90		13.90	0.78	9.52	0.83		349		478	357	326	11.53			12.69	PL	Yes		BF, Out	Out
	XCC-11	DT	114.4	60.6	6.16	5.00		795	90		13.90	0.53	9.29	0.81		349		478	363	332	5.15			6.70	PL ?	Yes		BF, Out	Out
	XCC-12	DT	114.6	48.3	6.05	4.95		795	90		13.87	0.42	9.47	0.82		349		478	365	334	3.12			3.70	PL ?	Yes		BF, Out	Out
	XCC-13	DT	272.1	218.6	6.15	6.30		2300	90		16.91	0.80	22.12	1.02		304		457	290	257	72.98			49.70	PL	Yes			
	XCC-14	DT	272.4	114.4	6.25	6.20		2300	90		16.89	0.42	21.79	0.99		304		457	367	336	24.43			14.11	PL	Yes			
K&YT-IPB																													
DEn (1989)	3.1	K	508.0	254.0	12.40	12.40	50.80	3200	45	45	12.60	0.50	20.48	1.00	0.10	280		436	377	347	251.48			219.00	PL	Yes	L4 = 3988		
JISSP	3.2	K	508.0	508.0	12.60	12.60	50.80	3200	45	45	12.60	1.00	20.16	1.00	0.10	349		504	390	361	1117.00			857.00	PL	Yes			
	3.3	K	508.0	254.0	12.20	12.20	76.20	3200	45	45	12.60	0.50	20.82	1.00	0.15	274		426	373	343	244.77			208.00	PL	Yes	3.1 - 3.3: IPB in		
	3.4	K	508.0	254.0	12.30	12.30	50.80	3200	45	45	12.60	0.50	20.65	1.00	0.10	310		445	378	348	250.43			198.00	PL	Yes	same direction.		
	3.5	K	508.0	508.0	12.50	12.50	50.80	3200	45	45	12.60	1.00	20.32	1.00	0.10	356		494	377	347	1065.60			1030.00	PL	Yes	3.4 - 3.6: IPB		
	3.6	K	508.0	254.0	12.10	12.10	76.20	3200	45	45	12.60	0.50	20.99	1.00	0.15	294		449	369	339	239.94			191.00	PL	Yes	inwards.		
T&Y-OPB																													
JSSC (1972)	I-BL-40-0.2	T	165.5	42.7	4.70	3.30		661	90		7.99	0.26	17.61	0.70		471		537	343	311	1.60			1.81	PL	Yes	Ftc is an average	BF, Out	
and	I-BL-40-0.4	T	165.5	76.3	4.50	2.90		661	90		7.99	0.46	18.39	0.64		471		537	373	343	5.36			3.97	PL	Yes			
AKIYAMA (1974)	I-BL-70-0.2	T	318.4	60.5	4.40	3.00		1274	90		8.00	0.19	36.18	0.68		441		534	333	301	2.99			2.21	PL	Yes			
	I-BL-70-0.4	T	318.5	139.8	4.40	4.40		1274	90		8.00	0.44	36.19	1.00		441		534	343	311	25.11			6.62	NOT P	Yes			
	I-BL-100-0.2	T	456.9	89.1	4.80	3.00		1829	90		8.01	0.20	47.59	0.63		402		549	363	332	7.39			3.53	PL ?	Yes			Gamma
	I-BL-100-0.4	T	457.6	165.2	4.80	4.70		1829	90		7.99	0.36	47.67	0.98		402		549	471	451	54.67			6.67	P	Yes			Gamma
YURA	G1	T	507.2	170.9	11.10	7.16		3591	90		14.16	0.34	22.85	0.65		378	351	465	300	281	53.98			33.40	PL	Yes			
(1978, 1980)	G2	T	507.2	170.9	11.10	7.16		3591	90		14.16	0.34	22.85	0.65		378	351	465	300	281	53.98			35.80	DL	Yes			Out, FL
	H1	T	507.2	326.4	11.10	7.34		3591	90		14.16	0.64	22.85	0.66		382	354	470	393	373	278.76			103.05	DL	Yes			Out, FL
YURA	H2	T	507.2	326.4	11.10	7.34		3591	90		14.16	0.64	22.85	0.66		382	354	470	393	373	278.76			116.19	PL	Yes			
(1978, 1980)	I1	T	507.2	455.9	11.10	9.50		3591	90		14.16	0.90	22.85	0.86		378	351	465	364	337	638.07			264.40	DL	Yes			Out, FL
	I2	T	507.2	455.9	11.10	9.50		3591	90		14.16	0.90	22.85	0.86		378	351	465	364	337	638.07			265.75	DL	Yes			Out, FL
	E1	Y	507.2	455.9	11.10	9.50		3591	30		14.16	0.90	22.85	0.86		367	338	458	364	337	638.07			591.16	DL	Yes			Out, FL
	E2	Y	507.2	455.9	11.10	9.50		3591	30		14.16	0.90	22.85	0.86		367	338	458	364	337	638.07			588.45	DL	Yes			Out, FL
DEn (1989)	1.2	Y	508.0	508.0	8.00	8.00		1575	45		6.20	1.00	31.75	1.00		276		435	300	267	534.05			535.00	RIG CAP	Yes	L4 = 2032	BF, Out	
JISSP	1.13	T	508.0	406.0	12.40	12.40		1575	90		6.20	0.80	20.48	1.00		300		456	385	356	683.61			239.00	P	Yes			
	1.14	Y	508.0	406.0	12.60	12.60		1575	45		6.20	0.80	20.16	1.00		296		451	387	358	698.15			433.00	P	Yes			

Database on Simple Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	ThetaC (deg.)	ThetaT (deg.)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Dynamic (N/mm^2)	Static (N/mm^2)	(N/mm^2)	Dynamic (N/mm^2)	Static (N/mm^2)	M_{PB} (KN-m)	P_U (KN)	P_{FC} (KN)	M_U (KN-m)	Failure criterion	Load-def curve	Notes	Brace check	Disposition code
MAKINO (1986)	L - A - M	T	216.5	216.5	4.55	4.55		735	90		6.79	1.00	23.79	1.00		377		522	377	347	70.97			35.90	NOT P	Yes			Out
and	L - B - M	T	216.5	165.6	4.55	4.53		735	90		6.79	0.76	23.79	1.00		377		522	341	309	36.33			14.40	P	Yes			
Kurobane (1991)	L - C - M	T	216.5	114.3	4.55	4.56		735	90		6.79	0.53	23.79	1.00		377		522	332	300	16.47			6.10	PL	Yes			
	L - D - M	T	216.5	60.7	4.55	3.96		735	90		6.79	0.28	23.79	0.87		377		522	311	278	3.55			2.46	PL	Yes			
	M - C - M	T	216.6	114.3	6.28	4.56		735	90		6.79	0.53	17.25	0.73		298		519	332	300	16.47			10.10	PL	Yes			
	MA - C - M	T	217.9	114.4	6.81	7.03		735	90		6.75	0.53	16.00	1.03		580		650	287	254	20.61			16.80	U	No			FYC, Out
	MH - C - M	T	216.3	114.4	6.65	7.03		735	90		6.80	0.53	16.26	1.06		832		875	287	254	20.61			19.70	U	No			FYC, Out
	H - A - M	T	216.5	216.5	8.06	8.06		735	90		6.79	1.00	13.43	1.00		378		469	378	348	122.00			71.00	U	No			
	H - C - M	T	216.5	114.4	8.06	7.03		735	90		6.79	0.53	13.43	0.87		378		469	287	254	20.61			17.10	U	No			
	H - D - M	T	216.5	60.3	8.06	10.09		735	90		6.79	0.28	13.43	1.25		378		469	299	266	6.86			6.80	U	No			Tau, Out
STOL (1985)	4	T	168.7	59.8	10.55	11.10		870	90		10.31	0.35	8.00	1.05		263		426	376	346	9.27			10.60	DL2	Yes		BF, Out	
	71	T	168.4	114.5	10.28	11.31		705	90		8.37	0.68	8.19	1.10		235		385	293	260	31.43			29.50	DL2	Yes			
	2	T	168.3	60.6	5.78	5.63		870	90		10.34	0.36	14.56	0.97		286		398	316	283	4.84			3.20	DL2	No			Out
	11	T	168.3	114.6	5.90	5.95		870	90		10.34	0.68	14.26	1.01		332		410	335	303	21.29			8.40	DL2	Yes			
	62	T	168.6	168.3	5.79	5.78		705	90		8.36	1.00	14.56	1.00		291		392	286	253	38.63			25.50	DL2	Yes			
	14	T	168.5	60.8	3.45	3.81		870	90		10.33	0.36	24.42	1.10		299		370	296	263	3.26			2.05	DL2	Yes			Out, FL
	17	T	168.5	114.7	3.42	3.90		870	90		10.33	0.68	24.63	1.14		303		383	250	218	10.42			3.70	DL2	Yes			Out, FL
	20	T	168.8	168.3	3.55	3.54		870	90		10.31	1.00	23.77	1.00		305		366	303	270	25.95			13.90	DL2	Yes			
VERITEC (1987)	3	T	495.0	230.0	16.00	12.50		2614	90		10.56	0.46	15.47	0.78		352		511	734	781	462.15			98.50	P	Yes	L = L1		
DT&X-OPB																													
BOONE (1982)	O8	DT	407.7	274.3	8.05	6.60		3556	90		17.44	0.67	25.32	0.82		334	321	470	339	331	156.59			45.20	P	Yes			
WEINSTEIN (1985	O23	DT	407.4	407.4	7.98	7.98		3556	90		17.46	1.00	25.53	1.00		348	337	443	348	337	429.09			147.11	DL2	Yes			
SWENSSON (1987	O28	DT	407.4	407.4	7.98	7.98		3556	90		17.46	1.00	25.53	1.00		350	337	444	350	337	429.09			166.77	P	Yes			
	O42	DT	407.4	142.5	7.98	6.65		3556	90		17.46	0.35	25.53	0.83		350	337	444	295	273	33.53			13.33	P	Yes			
VEGTE(1991)	X9	DT	408.0	246.0	10.20	10.35		2440	90		11.96	0.60	20.00	1.01		331		435	284	251	144.32			53.55	PL	Yes			
K&YT-OPB																													
DEn (1989)	3.7	K	508.0	406.0	12.30	12.30	50.80	3150	45	45	12.40	0.80	20.65	1.00	0.10	335		470	380	350	668.18			244.00	NOT P	Yes			
JISSP	3.8	K	508.0	254.0	12.10	12.10	50.80	3150	45	45	12.40	0.50	20.99	1.00	0.10	306		429	385	356	252.09			108.00	PL ?	Yes			
	3.9	K	508.0	508.0	12.20	12.20	50.80	3150	45	45	12.40	1.00	20.82	1.00	0.10	277		431	420	394	1181.71			435.00	PL	Yes			
	3.10	K	508.0	254.0	12.10	12.10	76.20	3150	45	45	12.40	0.50	20.99	1.00	0.15	296		432	350	319	225.70			105.00	PL ?	Yes			
	3.11 - 1	YT	508.0	254.0	12.30	12.30	50.80	3150	45	90	12.40	0.50	20.65	1.00	0.10	277		421	389	360	258.94			83.00	PL ?	Yes			
	3.11 - 2	YT	508.0	254.0	12.30	12.30	50.80	3150	90	45	12.40	0.50	20.65	1.00	0.10	277		421	389	360	258.94			60.00	PL ?	Yes			
YURA	C2-1-90	YT	507.2	326.4	11.10	7.30	50.80	3591	90	30	14.16	0.64	22.85	0.66	0.10	378	351	465	393	373	277.31			88.60	PL	Yes			
(1978, 1980)	C2-1-30	YT	507.2	455.9	11.10	9.50	50.80	3591	30	90	14.16	0.90	22.85	0.86	0.10	378	351	465	364	337	638.07			489.35	DL	Yes			Out, FL
	C2-2-90	YT	507.2	326.4	11.10	7.30	50.80	3591	90	30	14.16	0.64	22.85	0.66	0.10	378	351	465	393	373	277.31			118.60	PL	Yes			
	C2-2-30	YT	507.2	455.9	11.10	9.50	50.80	3591	30	90	14.16	0.90	22.85	0.86	0.10	378	351	465	364	337	638.07			580.10	DL	Yes	L-d is odd		Out

Notes:

1. In all cases measured dimensions are used.
   Where these are not reported, nominal dimensions are used.

BOMEL ENGINEERING CONSULTANTS

APPENDIX A3.2 DATABASE ON CHORD LOAD EFFECTS

Database on Chord Load Effects

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Thetac (deg)	Thetat (deg)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	F_{YC} (N/mm2)	F_{TC} (N/mm2)	P_U (KN)	Mu (kN.m)	Brace load	Chord load	Test Qf (reported)	Test Qf (estimated)	---- Additional chord stresses / Fy --- f(a)/Fy	f(b)/Fy	[f(a)+f(b)]/Fy	(A) due to add. stress
MAKINO (1988)	KA-1	K	165.3	101.6	3.61	3.2	25	1222	60	60	14.79	0.61	22.89	0.89	0.15	323	435	119.2		Bal. Axial	IPB		0.875		-0.600	-0.600	0.600
	KA-2	K	165.5	101.6	3.58	3.2	25	1222	60	60	14.77	0.61	23.11	0.89	0.15	323	435	106.6		Bal. Axial	IPB		0.796		-0.900	-0.900	0.900
	KA-3	K	165.4	101.6	3.55	3.2	25	1222	60	60	14.78	0.61	23.30	0.90	0.15	323	435	116.8		Bal. Axial	Comp.		0.887	-0.370		-0.370	0.370
	KA-5	K	165.4	101.7	3.59	3.2	25	1222	60	60	14.78	0.61	23.04	0.89	0.15	323	435	141.2		Bal. Axial	IPB		1.048		0.600	0.600	0.600
	KA-6	K	165.4	101.8	3.59	3.2	25	1222	60	60	14.78	0.62	23.04	0.89	0.15	323	435	142.2		Bal. Axial	IPB		1.056		0.900	0.900	0.900
	KA-7	K	165.4	101.8	3.58	3.2	25	1222	60	60	14.78	0.62	23.10	0.89	0.15	323	435	88.3		Bal. Axial	IPB		0.659		-1.160	-1.160	1.160
	KB-1	K	165.3	101.6	3.55	3.2	-30	1222	60	60	14.79	0.61	23.28	0.90	-0.18	323	435	218.2		Bal. Axial	IPB		0.934		-0.600	-0.600	0.600
	KB-2	K	165.3	101.6	3.61	3.2	-30	1222	60	60	14.79	0.61	22.89	0.89	-0.18	323	435	193.2		Bal. Axial	IPB		0.800		-0.900	-0.900	0.900
	KB-6	K	165.3	101.6	3.57	3.2	-30	1222	60	60	14.79	0.61	23.15	0.90	-0.18	323	435	229.5		Bal. Axial	IPB		0.971		0.900	0.900	0.900
	KB-7	K	165.4	101.8	3.59	3.2	-30	1222	60	60	14.78	0.62	23.04	0.89	-0.18	323	435	152		Bal. Axial	IPB		0.636		-1.100	-1.100	1.100
	KC-1	K	165.5	101.7	4.53	5.0	25	1222	60	60	14.77	0.61	18.27	1.10	0.15	326	440	185.8		Bal. Axial	IPB		0.888		-0.600	-0.600	0.600
	KC-2	K	165.5	101.7	4.53	5.3	25	1222	60	60	14.77	0.61	18.27	1.17	0.15	326	440	180.4		Bal. Axial	IPB		0.863		-0.900	-0.900	0.900
	KC-6	K	165.5	101.7	4.54	5.1	25	1222	60	60	14.77	0.61	18.23	1.12	0.15	326	440	208.4		Bal. Axial	IPB		0.992		0.900	0.900	0.900
	KD-1	K	165.1	101.7	7.09	4.9	25	1222	60	60	14.80	0.62	11.64	0.69	0.15	390	469	453.6		Bal. Axial	IPB		0.777		-0.600	-0.600	0.600
	KD-2	K	165.2	101.6	7.05	5.3	25	1222	60	60	14.79	0.62	11.72	0.75	0.15	390	469	416.8		Bal. Axial	IPB		0.722		-0.900	-0.900	0.900
	KD-7	K	165.4	101.6	7.13	5.2	25	1222	60	60	14.78	0.61	11.60	0.73	0.15	390	469	365.3		Bal. Axial	IPB		0.619		-1.200	-1.200	1.200
	KE-1	K	165.5	101.6	7.00	5.1	25	1222	60	60	14.77	0.61	11.82	0.73	0.15	231	424	371.7		Bal. Axial	IPB		1.101		-0.600	-0.600	0.600
	KE-2	K	165.5	101.7	7.11	5.0	25	1222	60	60	14.77	0.61	11.64	0.70	0.15	231	424	348.6		Bal. Axial	IPB		1.002		-0.900	-0.900	0.900
	KE-7	K	165.6	101.6	6.99	5.1	25	1222	60	60	14.76	0.61	11.85	0.73	0.15	231	424	275.1		Bal. Axial	IPB		0.817		-1.200	-1.200	1.200
NAKAJIMA (1971)	L-1.6-1	YT	165.2	76.3	1.62	1.6	10.00	1765	45	90	21.37	0.46	50.99	0.99	0.06	348	436	48.2		Bal. axial	Comp.		0.978	-0.169		-0.169	0.169
	L-1.6-2	YT	165.2	76.3	1.64	1.6	10.00	1765	45	90	21.37	0.46	50.37	0.98	0.06	331	437	40.8		Bal. axial	Comp.		0.854	-0.356		-0.356	0.356
	L-2.3-1	YT	165.2	76.3	2.35	2.4	10.00	1765	45	90	21.37	0.46	35.15	1.02	0.06	288	333	60.5		Bal. axial	Comp.		0.771	-0.204		-0.204	0.204
	L-2.3-2	YT	165.2	60.5	2.26	2.4	10.00	1765	45	90	21.37	0.37	36.55	1.06	0.06	338	422	59.5		Bal. axial	Comp.		0.835	-0.174		-0.174	0.174
	L-2.3-3	YT	165.2	48.6	2.24	2.4	10.00	1765	45	90	21.37	0.29	36.88	1.07	0.06	340	422	58.6		Bal. axial	Comp.		0.982	-0.173		-0.173	0.173
	L-2.3-5	YT	165.2	76.3	2.30	2.4	10.00	1765	45	90	21.37	0.46	35.91	1.04	0.06	283	339	51.4		Bal. axial	Comp.		0.695	-0.417		-0.417	0.417
	L-3.2-1	YT	165.2	76.3	3.19	3.2	10.00	1765	45	90	21.37	0.46	25.89	1.00	0.06	314	415	136.6		Bal. axial	Comp.		0.917	-0.188		-0.188	0.188
	L-3.2-2	YT	165.2	76.3	3.18	3.2	10.00	1765	45	90	21.37	0.46	25.97	1.01	0.06	283	414	114.2		Bal. axial	Comp.		0.857	-0.417		-0.417	0.417
	L-4.5	YT	165.2	76.3	5.14	4.5	10.00	1765	45	90	21.37	0.46	16.07	0.88	0.06	329	442	282.5		Bal. axial	Comp.		0.744	-0.179		-0.179	0.179
	L-6.0-1	YT	165.2	76.3	6.29	6.0	10.00	1765	45	90	21.37	0.46	13.13	0.95	0.06	278	431	350.3		Bal. axial	Comp.		0.743	-0.212		-0.212	0.212
	L-6.0-2	YT	165.2	76.3	6.09	6.0	10.00	1765	45	90	21.37	0.46	13.56	0.99	0.06	282	381	317.8		Bal. axial	Comp.		0.707	-0.209		-0.209	0.209
	U-1.6-1	YT	165.2	76.3	1.63	1.6	10.00	1765	90	45	21.37	0.46	50.67	0.98	0.06	358	434	39.3		Bal. axial	Comp.		1.084	-0.164		-0.164	0.164
	U-1.6-2	YT	165.2	76.3	1.62	1.6	10.00	1765	90	45	21.37	0.46	50.99	0.99	0.06	326	406	27.9		Bal. axial	Comp.		0.855	-0.361		-0.361	0.361
	U-2.3-1	YT	165.2	76.3	2.20	2.4	10.00	1765	90	45	21.37	0.46	37.55	1.09	0.06	339	420	75.0		Bal. axial	Comp.		1.290	-0.173		-0.173	0.173
	U-2.3-2	YT	165.2	60.5	2.37	2.4	10.00	1765	90	45	21.37	0.37	34.85	1.01	0.06	342	421	56.7		Bal. axial	Comp.		1.020	-0.172		-0.172	0.172
	U-2.3-3	YT	165.2	48.6	2.32	2.4	10.00	1765	90	45	21.37	0.29	35.60	1.03	0.06	270	332	46.7		Bal. axial	Comp.		1.310	-0.218		-0.218	0.218
	U-2.3-5	YT	165.2	76.3	2.30	2.4	10.00	1765	90	45	21.37	0.46	35.91	1.04	0.06	284	342	47.7		Bal. axial	Comp.		0.907	-0.415		-0.415	0.415
	U-3.2-1	YT	165.2	76.3	3.18	3.2	10.00	1765	90	45	21.37	0.46	25.97	1.01	0.06	263	294	107.6		Bal. axial	Comp.		1.226	-0.224		-0.224	0.224
	U-3.2-2	YT	165.2	76.3	3.16	3.2	10.00	1765	90	45	21.37	0.46	26.14	1.01	0.06	331	425	101.3		Bal. axial	Comp.		0.928	-0.356		-0.356	0.356
	U-4.5	YT	165.2	76.3	5.43	4.5	10.00	1765	90	45	21.37	0.46	15.21	0.83	0.06	339	432	263.9		Bal. axial	Comp.		0.856	-0.173		-0.173	0.173
	U-6.0-1	YT	165.2	76.3	6.14	6.0	10.00	1765	90	45	21.37	0.46	13.45	0.98	0.06	360	453	269.8		Bal. axial	Comp.		0.653	-0.164		-0.164	0.164
	U-6.0-2	YT	165.2	76.3	6.18	6.0	10.00	1765	90	45	21.37	0.46	13.37	0.97	0.06	292	435	237.4		Bal. axial	Comp.		0.699	-0.201		-0.201	0.201

Database on Chord Load Effects

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Theta (deg)	Theta (deg)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	F_{yc} (N/mm²)	F_{tc} (N/mm²)	P_u (KN)	Mu (kN.m)	Brace load	Chord load	Test Qf (reported)	Test Qf (estimated)	---- Additional chord stresses / Fy --- f(a)/Fy	f(b)/Fy	[f(a)+f(b)]/Fy	(A) due to add. stress
KUROBANE (1965) Checked in OCHI (1984)	264	K	101.6	42.7	3.27	3.2	21.5		60	60	0	0.42	15.54	0.98	0.21	407	492	80.9		Bal. axial	Comp.		1.009	-0.097		-0.097	0.097
	265	K	101.6	42.7	3.45	3.2	20.0		60	60	0	0.42	14.72	0.93	0.20	407	492	87.1		Bal. axial	Comp.		0.965	-0.201		-0.201	0.201
	266	K	101.6	42.7	3.19	3.2	23.0		60	60	0	0.42	15.92	1.00	0.23	407	492	65.2		Bal. axial	Comp.		0.864	-0.162		-0.162	0.162
	267	K	101.6	42.7	3.48	3.2	20.0		60	60	0	0.42	14.60	0.92	0.20	407	492	91.7		Bal. axial	Comp.		0.999	-0.419		-0.419	0.419
	268	K	101.6	42.7	3.41	3.2	21.0		60	60	0	0.42	14.90	0.94	0.21	407	492	79		Bal. axial	Comp.		0.903	-0.369		-0.369	0.369
	269	K	101.6	42.7	3.35	3.2	21.0		60	60	0	0.42	15.16	0.96	0.21	407	492	78.4		Bal. axial	Comp.		0.929	-0.373		-0.373	0.373
	270	K	101.6	42.7	3.22	3.2	15.5		60	60	0	0.42	15.78	0.99	0.15	407	492	65.9		Bal. axial	Comp.		0.809	-0.489		-0.489	0.489
	271	K	101.6	42.7	3.36	3.2	19.5		60	60	0	0.42	15.12	0.95	0.19	407	492	76.8		Bal. axial	Comp.		0.894	-0.545		-0.545	0.545
	272	K	101.6	42.7	3.49	3.2	21.0		60	60	0	0.42	14.56	0.92	0.21	407	492	71		Bal. axial	Comp.		0.775	-0.487		-0.487	0.487
	273	K	101.6	42.7	3.37	3.2	19.5		60	60	0	0.42	15.07	0.95	0.19	407	492	77.7		Bal. axial	Comp.		0.899	-0.550		-0.550	0.550
	274	K	101.6	42.7	3.26	3.2	19.3		60	60	0	0.42	15.58	0.98	0.19	407	492	58.6		Bal. axial	Comp.		0.723	-0.571		-0.571	0.571
	275	K	101.6	42.7	3.38	3.2	22.0		60	60	0	0.42	15.03	0.95	0.22	407	492	64.7		Bal. axial	Comp.		0.758	-0.610		-0.610	0.610
	276	K	101.6	42.7	3.5	3.2	20.5		60	60	0	0.42	14.51	0.91	0.20	407	492	67.3		Bal. axial	Comp.		0.727	-0.670		-0.670	0.670
	277	K	101.6	42.7	3.21	3.2	23.4		60	60	0	0.42	15.83	1.00	0.23	407	492	50.8		Bal. axial	Comp.		0.667	-0.629		-0.629	0.629
	278	K	101.6	42.7	3.39	3.2	21.0		60	60	0	0.42	14.99	0.94	0.21	407	492	63.6		Bal. axial	Comp.		0.736	-0.691		-0.691	0.691
	279	K	101.6	42.7	3.2	3.2	23.6		60	60	0	0.42	15.88	1.00	0.23	407	492	85		Bal. axial	Tension		1.125	0.070		0.070	0.070
	280	K	101.6	42.7	3.2	3.2	23.8		60	60	0	0.42	15.88	1.00	0.23	407	492	85.3		Bal. axial	Tension		1.130	0.104		0.104	0.104
	281	K	101.6	42.7	3.2	3.2	22.0		60	60	0	0.42	15.88	1.00	0.22	407	492	86.3		Bal. axial	Tension		1.129	0.214		0.214	0.214
	282	K	101.6	42.7	3.2	3.2	21.2		60	60	0	0.42	15.88	1.00	0.21	407	492	93.7		Bal. axial	Tension		1.218	0.231		0.231	0.231
	283	K	101.6	42.7	3.2	3.2	21.0		60	60	0	0.42	15.88	1.00	0.21	407	492	97.9		Bal. axial	Tension		1.271	0.243		0.243	0.243
	284	K	101.6	42.7	3.2	3.2	22.0		60	60	0	0.42	15.88	1.00	0.22	407	492	98.1		Bal. axial	Tension		1.283	0.487		0.487	0.487
	285	K	101.6	42.7	3.2	3.2	22.0		60	60	0	0.42	15.88	1.00	0.22	407	492	84.8		Bal. axial	Tension		1.109	0.422		0.422	0.422
	286	K	101.6	42.7	3.2	3.2	22.0		60	60	0	0.42	15.88	1.00	0.22	407	492	80.4		Bal. axial	Tension		1.051	0.599		0.599	0.599
	287	K	101.6	42.7	3.2	3.2	20.0		60	60	0	0.42	15.88	1.00	0.20	407	492	90.2		Bal. axial	Tension		1.162	0.673		0.673	0.673
	288	K	101.6	42.7	3.2	3.2	22.0		60	60	0	0.42	15.88	1.00	0.22	407	492	100		Bal. axial	Tension		1.308	0.730		0.730	0.730
	289	K	101.6	42.7	3.2	3.2	22.5		60	60	0	0.42	15.88	1.00	0.22	407	492	87.4		Bal. axial	Tension		1.147	0.730		0.730	0.730
	290	K	101.6	42.7	3.2	3.2	19.0		60	60	0	0.42	15.88	1.00	0.19	407	492	95.2		Bal. axial	Tension		1.217	0.730		0.730	0.730
	291	K	101.6	42.7	3.2	3.2	20.9		60	60	0	0.42	15.88	1.00	0.21	407	492	100		Bal. axial	Tension		1.297	0.730		0.730	0.730
TOGO (1967)	I-1	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	85.3		Bal. axial	Tension		0.985	0.654		0.654	0.654
	I-2	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	89.2		Bal. axial	Tension		1.030	0.684		0.684	0.684
	I-3	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	84.3		Bal. axial	Tension		0.973	0.647		0.647	0.647
	II-1	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	85.3		Bal. axial	Tension		0.985	0.436		0.436	0.436
	II-2	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	87.3		Bal. axial	Tension		1.008	0.446		0.446	0.446
	II-3	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	85.3		Bal. axial	Tension		0.985	0.436		0.436	0.436
	III-1	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	87.3		Bal. axial	Tension		1.008	0.223		0.223	0.223
	III-2	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	87.3		Bal. axial	Tension		1.008	0.223		0.223	0.223
	III-3	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	89.2		Bal. axial	Tension		1.030	0.228		0.228	0.228
	V-1	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	76.5		Bal. axial	Comp.		0.883	-0.195		-0.195	0.195
	V-2	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	85.3		Bal. axial	Comp.		0.985	-0.218		-0.218	0.218
	V-3	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	80.4		Bal. axial	Comp.		0.928	-0.206		-0.206	0.206
	VI-1	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	73.5		Bal. axial	Comp.		0.849	-0.376		-0.376	0.376
	VI-2	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	73.5		Bal. axial	Comp.		0.849	-0.376		-0.376	0.376
	VI-3	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	75.5		Bal. axial	Comp.		0.872	-0.386		-0.386	0.386
	VII-1	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	69.6		Bal. axial	Comp.		0.804	-0.534		-0.534	0.534
	VII-2	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	71.6		Bal. axial	Comp.		0.827	-0.549		-0.549	0.549
	VII-3	K	101.6	48.6	3.16	3.5	20	1030	60	60	20.3	0.48	16.08	1.11	0.20	400.1	461.9	64.7		Bal. axial	Comp.		0.747	-0.496		-0.496	0.496

Database on Chord Load Effects

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	L (mm)	Theta_c (deg)	Theta_t (deg)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	Fyc (N/mm²)	Frc (N/mm²)	Pu (KN)	Mu (kN.m)	Brace load	Chord load	Test Qf (reported)	Test Qf (estimated)	---- Additional chord stresses / Fy --- f(a)/Fy	f(b)/Fy	[f(a)+f(b)]/Fy	(A) due to add. stress
KONING and	32	K	165.1	51	4.83	5.2	93.0		45	45	0.0	0.31	17.09	1.08	0.56	281	405	95		Bal. axial	Comp.		0.787	-0.659		-0.659	0.659
WARDENIER	33	K	165.1	108	4.83	6.38	16.0		45	45	0.0	0.65	17.09	1.32	0.10	281	405	214		Bal. axial	Comp.		0.860	-0.483		-0.483	0.483
(1981)	35	K	273.5	88.9	4.79	5.2	147.0		45	45	0.0	0.33	28.55	1.09	0.54	324	462	129		Bal. axial	Comp.		0.925	-0.408		-0.408	0.408
	36	K	273.2	88.9	4.85	5.2	148.0		45	45	0.0	0.33	28.16	1.07	0.54	332	454	120		Bal. axial	Comp.		0.790	-0.442		-0.442	0.442
	37	K	273.5	178	4.87	5.2	19.0		45	45	0.0	0.65	28.08	1.07	0.07	331	467	271		Bal. axial	Comp.		0.868	-0.478		-0.478	0.478
	39	K	273	273.5	4.98	4.87	24.0		45	45	0.0	1.00	27.41	0.98	0.09	373	475	548		Bal. axial	Comp.		0.860	-0.288		-0.288	0.288
	40	K	273	273.5	4.98	4.87	22.0		45	45	0.0	1.00	27.41	0.98	0.08	373	475	536		Bal. axial	Comp.		0.835	-0.288		-0.288	0.288
	44	K	273.5	89	4.79	5.1	-62.8		45	45	0.0	0.33	28.55	1.06	-0.23	324	462	275		Bal. axial	Comp.		0.977	-0.458		-0.458	0.458
	45	K	273.5	89	4.79	5.1	-62.8		45	45	0.0	0.33	28.55	1.06	-0.23	324	462	271		Bal. axial	Comp.		0.963	-0.496		-0.496	0.496
BOONE	AP2	DT	407.7	274.3	8.05	6.60	-	3556	90		17.44	0.67	25.32	0.82		334	470	183.3	-	Comp.	Comp.	0.52	0.523	-0.790	-0.040	-0.830	0.791
(19820	AP5	DT	407.7	274.3	8.05	6.60	-	3556	90		17.44	0.67	25.32	0.82		334	470	257.6	-	Comp.	Comp.	0.73	0.735	-0.600	-0.040	-0.640	0.601
	AM6	DT	407.7	274.3	8.05	6.60	-	3556	90		17.44	0.67	25.32	0.82		334	470	305.2	-	Comp.	Comp.+IPB	0.87	0.871	-0.300	-0.340	-0.640	0.453
	IP12	DT	407.7	274.3	8.05	6.60	-	3556	90		17.44	0.67	25.32	0.82		334	470	-	72.77	IPB	Comp.	0.61	0.610	-0.600	-0.040	-0.640	0.601
	IM11	DT	407.7	274.3	8.05	6.60	-	3556	90		17.44	0.67	25.32	0.82		334	470	-	87.57	IPB	Comp.+IPB	0.73	0.734	-0.300	-0.340	-0.640	0.453
	OP9	DT	407.7	274.3	8.05	6.60	-	3556	90		17.44	0.67	25.32	0.82		334	470	-	36.50	OPB	Comp.	0.81	0.808	-0.600	-0.040	-0.640	0.601
	OM10	DT	407.7	274.3	8.05	6.60	-	3556	90		17.44	0.67	25.32	0.82		334	470	-	41.92	OPB	Comp.+IPB	0.93	0.927	-0.300	-0.340	-0.640	0.453
WEINSTEIN	AP25	DT	407.0	407.0	7.98	7.98	-	3556	90		17.47	1.00	25.50	1.00		348	443	778.5	-	Comp.	Comp.	1.08	1.080	-0.670	-0.060	-0.730	0.673
and	AP46	DT	407.0	142.1	7.98	6.55	-	3556	90		17.47	0.35	25.50	0.82		348	443	129.0	-	Comp.	Comp.	0.66	0.657	-0.610	-0.060	-0.670	0.613
YURA (1986)	AM47	DT	407.0	142.1	7.98	6.55	-	3556	90		17.47	0.35	25.50	0.82		348	443	154.8	-	Comp.	Comp.+IPB	0.79	0.789	-0.310	-0.350	-0.660	0.468
	IP29	DT	407.4	407.4	7.98	7.98	-	3556	90		17.46	1.00	25.53	1.00		348	443	-	159.09	IPB	Comp.	0.62	0.622	-0.610	-0.060	-0.670	0.613
	IM30	DT	407.4	407.4	7.98	7.98	-	3556	90		17.46	1.00	25.53	1.00		348	443	-	173.78	IPB	Comp.+IPB	0.68	0.679	-0.310	-0.350	-0.660	0.468
	OP27	DT	407.4	407.4	7.98	7.98	-	3556	90		17.46	1.00	25.53	1.00		348	443	-	142.59	OPB	Comp.	0.91	0.909	-0.610	-0.360	-0.970	0.708
SANDERS (1987)	TP4	DT	407.4	407.4	7.98	8.0		3556		90	17.46	1.00	25.53	1.00	0.00	350	444	2052.0		Tension	Comp.	0.97	0.972	-0.600		-0.600	0.600
DEn (1989)	4.1	T	508.0	406.0	12.30	12.3		1575	90		6.20	0.80	20.65	1.00		286	444	956		Comp.	Comp.	0.74	0.740	-0.520	0.000	-0.520	0.520
JISSP	4.2	T	508.0	406.0	12.10	12.1		1575	90		6.20	0.80	20.99	1.00		280	434	1126		Comp.	Comp.+IPB	0.92	0.920	-0.270	-0.270	-0.540	0.382
	4.3	T	508.0	406.0	12.40	12.4		1575	90		6.20	0.80	20.48	1.00		303	439		315	IPB	Comp.	0.77	0.857	-0.500	0.000	-0.500	0.500
	4.4	T	508.0	406.0	12.30	12.3		1575	90		6.20	0.80	20.65	1.00		273	432		330	IPB	Comp.+IPB	0.9	1.008	-0.290	-0.290	-0.580	0.410
	4.5	T	508.0	406.0	12.00	12.0		1575	90		6.20	0.80	21.17	1.00		283	440		226	OPB	Comp.	1.07	1.070	-0.520	0.000	-0.520	0.520
	4.6	T	508.0	406.0	12.20	12.2		1575	90		6.20	0.80	20.82	1.00		272	429		258	OPB	Comp.+IPB	1.23	1.230	-0.270	-0.270	-0.540	0.382
	4.7	DT	508.0	406.0	12.10	12.1		1575	90		6.20	0.80	20.99	1.00		280	425	850		Comp.	Comp.	1.09	1.180	-0.540	0.000	-0.540	0.540

BOMEL ENGINEERING CONSULTANTS

APPENDIX A3.3 DATABASE ON BRACE LOAD INTERACTION

Database on Brace Load Interaction

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	L (mm)	Theta (degrees)	F_{YC} (N/mm^2)	F_{TC} (N/mm^2)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	P_U (KN)	M_U ipb (KN-m)	M_U opb (KN-m)	Pref	Mip,ref	Mop,ref	P / Pref	Mip/Mip,ref	Mop/Mop,ref	X
MAKINO	L - A - CM	T	216.5	216.5	4.55	4.55	735	90	377	522	6.79	1.00	23.79	1.00	196.0		20.30	392.0		35.90	0.50		0.57	1.07
(1986)	L - B - CM	T	216.5	165.6	4.55	4.53	735	90	377	522	6.79	0.76	23.79	1.00	39.4		11.50	221.0		14.40	0.18		0.80	0.98
and	L - C - CM	T	216.5	114.3	4.55	4.56	735	90	377	522	6.79	0.53	23.79	1.00	72.7		3.15	144.0		6.10	0.50		0.52	1.02
KUROBANE	L - D - CM	T	216.5	60.7	4.55	3.96	735	90	377	522	6.79	0.28	23.79	0.87	39.6		1.27	79.4		2.46	0.50		0.52	1.02
(1991)	M - C - CM	T	216.6	114.3	6.28	4.56	735	90	298	519	6.79	0.53	17.25	0.73	114.0		5.94	225.0		10.10	0.51		0.59	1.09
	MA - C - CM	T	217.9	114.4	6.81	7.03	735	90	580	650	6.75	0.53	16.00	1.03	276.0		8.57	393.8		16.80	0.70		0.51	1.21
	H - A - CM	T	216.5	216.5	8.06	8.06	735	90	378	469	6.79	1.00	13.43	1.00	438.0		40.40	754.6		71.00	0.58		0.57	1.15
	H - C - CM	T	216.5	114.4	8.06	7.03	735	90	378	469	6.79	0.53	13.43	0.87	98.6		15.06	366.7		17.10	0.27		0.88	1.15
	L - B - TM	T	216.5	165.6	4.55	4.53	735	90	377	522	6.79	0.76	23.79	1.00	413.0		8.63	486.0		14.40	0.85		0.60	1.45
	L - C - TM	T	216.5	114.3	4.55	4.56	735	90	377	522	6.79	0.53	23.79	1.00	258.0		8.15	336.0		6.10	0.77		1.34	2.10
	L - D - TM	T	216.5	60.7	4.55	3.96	735	90	377	522	6.79	0.28	23.79	0.87	74.9		2.87	210.0		2.46	0.36		1.17	1.52
	L - D - TM2	T	216.5	60.7	4.55	3.96	735	90	377	522	6.79	0.28	23.79	0.87	156.9		1.51	210.0		2.46	0.75		0.61	1.36
	H - D - TM	T	216.5	60.3	8.06	10.09	735	90	378	469	6.79	0.28	13.43	1.25	162.0		6.12	404.0		6.80	0.40		0.90	1.30
	----- M - C - TM2 & MA - C - TM are lower bound data -----																							
	M - C - TM2	T	216.6	114.3	6.28	4.56	735	90	298	519	6.79	0.53	17.25	0.73	422.0		7.32	551.0		10.10	0.77		0.72	1.49
	MA - C - TM	T	217.9	114.4	6.81	7.03	735	90	580	650	6.75	0.53	16.00	1.03	511.0		18.00	709.0		16.80	0.72		1.07	1.79
HOADLEY	AO-4	DT	407.7	274.3	8.05	6.6	3556	90	334	470	17.44	0.67	25.32	0.82	87.6		36.04	328.6	119.32	45.20	0.27	0.00	0.80	1.06
and	AO-13	DT	407.7	274.3	8.05	6.6	3556	90	334	470	17.44	0.67	25.32	0.82	234.0		20.00	328.6	119.32	45.20	0.71	0.00	0.44	1.15
YURA	AI-20	DT	407.7	274.3	8.05	6.6	3556	90	334	470	17.44	0.67	25.32	0.82	112.1	100.00		328.6	119.32	45.20	0.34	0.84	0.00	1.03
(1985)	AI-17	DT	407.7	274.3	8.05	6.6	3556	90	334	470	17.44	0.67	25.32	0.82	234.4	77.62		328.6	119.32	45.20	0.71	0.65	0.00	1.10
	IO-15	DT	407.7	274.3	8.05	6.6	3556	90	334	470	17.44	0.67	25.32	0.82	24.5	39.21	42.60	328.6	119.32	45.20	0.07	0.33	0.94	1.11
	IO-14	DT	407.7	274.3	8.05	6.6	3556	90	334	470	17.44	0.67	25.32	0.82	22.2	76.61	30.28	328.6	119.32	45.20	0.07	0.64	0.67	1.11
	AIO-16	DT	407.7	274.3	8.05	6.6	3556	90	334	470	17.44	0.67	25.32	0.82	88.1	37.06	37.85	328.6	119.32	45.20	0.27	0.31	0.84	1.19
	AIO-18	DT	407.7	274.3	8.05	6.6	3556	90	334	470	17.44	0.67	25.32	0.82	220.6	46.33	17.29	328.6	119.32	45.20	0.67	0.39	0.38	1.18
	AIO-19	DT	407.7	274.3	8.05	6.6	3556	90	334	470	17.44	0.67	25.32	0.82	219.3	39.77	15.82	328.6	119.32	45.20	0.67	0.33	0.35	1.12
SWENSSON	AO44	DT	407.4	142.5	7.98	6.65	3556	90	350	444	17.46	0.35	25.53	0.83	55.6	0.00	14.69	196.2	30.17	13.33	0.28	0.00	1.10	1.39
and	AO45	DT	407.4	142.5	7.98	6.65	3556	90	350	444	17.46	0.35	25.53	0.83	138.8	0.00	8.25	196.2	30.17	13.33	0.71	0.00	0.62	1.33
YURA	AI46	DT	407.4	142.5	7.98	6.65	3556	90	350	444	17.46	0.35	25.53	0.83	58.7	26.33	0.00	196.2	30.17	13.33	0.30	0.87	0.00	1.04
(1987)	AI47	DT	407.4	142.5	7.98	6.65	3556	90	350	444	17.46	0.35	25.53	0.83	134.3	22.60	0.00	196.2	30.17	13.33	0.68	0.75	0.00	1.17
	IO48	DT	407.4	142.5	7.98	6.65	3556	90	350	444	17.46	0.35	25.53	0.83	18.2	9.83	16.04	196.2	30.17	13.33	0.09	0.33	1.20	1.37
	IO49	DT	407.4	142.5	7.98	6.65	3556	90	350	444	17.46	0.35	25.53	0.83	15.6	20.23	14.12	196.2	30.17	13.33	0.08	0.67	1.06	1.45
	AO31	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	197.5		129.26	721.1	255.92	156.94	0.27	0.00	0.82	1.10
	AO32	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	391.0		89.83	721.1	255.92	156.94	0.54	0.00	0.57	1.11
	AO33	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	526.7		42.82	721.1	255.92	156.94	0.73	0.00	0.27	1.00
	AI34	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	194.8	239.88		721.1	255.92	156.94	0.27	0.94	0.00	1.08
	AI35	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	385.2	241.80		721.1	255.92	156.94	0.53	0.94	0.00	1.25
	AI36	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	751.8	136.49		721.1	255.92	156.94	1.04	0.53	0.00	1.27
	AI50	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	573.8	180.78		721.1	255.92	156.94	0.80	0.71	0.00	1.21
	IO37	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	67.6	65.76	160.33	721.1	255.92	156.94	0.09	0.26	1.02	1.17
	IO38	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	76.5	131.07	143.16	721.1	255.92	156.94	0.11	0.51	0.91	1.23
	IO39	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	72.1	245.53	65.99	721.1	255.92	156.94	0.10	0.96	0.42	1.25
	IO26	DT	407.4	407.4	7.98	7.98	3556	90	350	444	17.46	1.00	25.53	1.00	64.9	179.65	95.02	721.1	255.92	156.94	0.09	0.70	0.61	1.13

Database on Brace Load Interaction

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	L (mm)	Theta (degrees)	F_{YC} (N/mm²)	F_{TC} (N/mm²)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	P_U (KN)	M_U ipb (KN-m)	M_U opb (KN-m)	Pref	Mip,ref	Mop,ref	P / Pref	Mip/Mip,ref	Mop/Mop,ref	X
STOL (1985)	24	T	168.4	59.8	10.28	11.1	870	90	235	385	10.33	0.36	8.19	1.08	108.0	10.20	0.00	239.2	11.20	8.99	0.45	0.91	0.00	1.16
	27	T	168.4	59.8	10.28	11.1	870	90	235	385	10.33	0.36	8.19	1.08	0.0	9.08	6.60	239.2	11.20	8.99	0.00	0.81	0.73	1.26
	54	T	168.4	59.8	10.28	11.1	870	90	235	385	10.33	0.36	8.19	1.08	140.0	7.10	5.25	239.2	11.20	8.99	0.59	0.63	0.58	1.45
	72	T	168.4	114.5	10.28	11.31	705	90	235	385	8.37	0.68	8.19	1.10	355.0	15.80	0.00	440.0	38.80	29.50	0.81	0.41	0.00	0.98
	73	T	168.4	114.5	10.28	11.31	705	90	235	385	8.37	0.68	8.19	1.10	189.0	32.00	0.00	440.0	38.80	29.50	0.43	0.82	0.00	1.07
	74	T	168.4	114.5	10.28	11.31	705	90	235	385	8.37	0.68	8.19	1.10	169.0	0.00	21.20	440.0	38.80	29.50	0.38	0.00	0.72	1.10
	75	T	168.4	114.5	10.28	11.31	705	90	235	385	8.37	0.68	8.19	1.10	314.5	0.00	10.00	440.0	38.80	29.50	0.71	0.00	0.34	1.05
	76	T	168.4	114.5	10.28	11.31	705	90	235	385	8.37	0.68	8.19	1.10	0.0	25.50	18.80	440.0	38.80	29.50	0.00	0.66	0.64	1.05
	77	T	168.4	114.5	10.28	11.31	705	90	235	385	8.37	0.68	8.19	1.10	196.0	17.00	12.60	440.0	38.80	29.50	0.45	0.44	0.43	1.05
	7	T	168.1	60.6	5.68	5.72	870	90	305	397	10.35	0.36	14.80	1.01	62.0	2.58	0.00	87.0	4.94	3.00	0.71	0.52	0.00	0.99
	50	T	168.1	60.6	5.68	5.72	870	90	305	397	10.35	0.36	14.80	1.01	39.5	2.08	1.40	87.0	4.94	3.00	0.45	0.42	0.47	1.08
	51	T	168.1	60.6	5.68	5.72	870	90	305	397	10.35	0.36	14.80	1.01	54.0	2.14	1.36	87.0	4.94	3.00	0.62	0.43	0.45	1.23
	52	T	168.1	60.6	5.68	5.63	870	90	305	397	10.35	0.36	14.80	0.99	41.0	3.25	1.36	87.0	4.94	3.00	0.47	0.66	0.45	1.27
	28	T	168.3	114.6	5.9	5.95	870	90	332	410	10.34	0.68	14.26	1.01	126.0	5.80	0.00	199.7	15.80	8.40	0.63	0.37	0.00	0.80
	30	T	168.3	114.6	5.9	5.95	870	90	332	410	10.34	0.68	14.26	1.01	126.0	0.00	3.28	199.7	15.80	8.40	0.63	0.00	0.39	1.02
	31	T	168.3	114.6	5.9	5.95	870	90	332	410	10.34	0.68	14.26	1.01	61.0	0.00	6.18	199.7	15.80	8.40	0.31	0.00	0.74	1.04
	32	T	168.3	114.6	5.9	5.95	870	90	332	410	10.34	0.68	14.26	1.01	0.0	14.30	3.80	199.7	15.80	8.40	0.00	0.91	0.45	1.16
	33	T	168.3	114.6	5.9	5.95	870	90	332	410	10.34	0.68	14.26	1.01	0.0	7.60	7.95	199.7	15.80	8.40	0.00	0.48	0.95	1.15
	57	T	168.3	114.6	5.9	5.95	870	90	332	410	10.34	0.68	14.26	1.01	80.0	7.40	4.05	199.7	15.80	8.40	0.40	0.47	0.48	1.08
	58	T	168.3	114.6	5.9	5.95	870	90	332	410	10.34	0.68	14.26	1.01	113.0	5.25	3.10	199.7	15.80	8.40	0.57	0.33	0.37	1.04
	63	T	168.6	168.3	5.79	5.78	705	90	291	392	8.36	1.00	14.56	1.00	229.0	16.00	0.00	272.6	36.88	25.50	0.84	0.43	0.00	1.02
	64	T	168.6	168.3	5.79	5.78	705	90	291	392	8.36	1.00	14.56	1.00	117.5	31.00	0.00	272.6	36.88	25.50	0.43	0.84	0.00	1.08
	65	T	168.6	168.3	5.79	5.78	705	90	291	392	8.36	1.00	14.56	1.00	235.0	0.00	11.00	272.6	36.88	25.50	0.86	0.00	0.43	1.29
	66	T	168.6	168.3	5.79	5.78	705	90	291	392	8.36	1.00	14.56	1.00	114.5	0.00	21.00	272.6	36.88	25.50	0.42	0.00	0.82	1.24
	67	T	168.3	168.3	5.9	5.78	705	90	332	410	8.38	1.00	14.26	0.98	0.0	27.50	18.80	323.0	43.69	30.21	0.00	0.63	0.62	1.01
	68	T	168.3	168.3	5.9	5.78	705	90	332	410	8.38	1.00	14.26	0.98	145.0	19.60	13.60	323.0	43.69	30.21	0.45	0.45	0.45	1.08
	36	T	168.5	60.8	3.45	3.81	870	90	299	370	10.33	0.36	24.42	1.10	39.0	0.00	0.78	42.0	2.33	1.42	0.93	0.00	0.55	1.48
	37	T	168.5	60.8	3.3	3.81	870	90	337	387	10.33	0.36	25.53	1.15	14.8	0.00	1.19	43.3	2.40	1.46	0.34	0.00	0.81	1.15
	38	T	168.5	60.8	3.3	3.81	870	90	337	387	10.33	0.36	25.53	1.15	0.0	1.08	1.54	43.3	2.40	1.46	0.00	0.45	1.05	1.22
	53	T	168.5	60.8	3.3	3.67	870	90	337	387	10.33	0.36	25.53	1.11	17.7	1.16	0.89	43.3	2.40	1.46	0.41	0.48	0.61	1.21
	39	T	168.5	114.7	3.42	3.9	870	90	303	383	10.33	0.68	24.63	1.14	32.5	5.84	0.00	89.8	7.45	3.70	0.36	0.78	0.00	0.99
	40	T	168.5	114.7	3.42	3.9	870	90	303	383	10.33	0.68	24.63	1.14	66.0	3.10	0.00	89.8	7.45	3.70	0.73	0.42	0.00	0.92
	41	T	168.5	114.7	3.42	3.9	870	90	303	383	10.33	0.68	24.63	1.14	24.0	0.00	3.04	89.8	7.45	3.70	0.27	0.00	0.82	1.09
	42	T	168.5	114.7	3.3	3.9	870	90	337	387	10.33	0.68	25.53	1.18	54.0	0.00	1.74	93.0	7.71	3.83	0.58	0.00	0.45	1.03
	43	T	168.5	114.7	3.3	3.9	870	90	337	387	10.33	0.68	25.53	1.18	0.0	3.20	4.38	93.0	7.71	3.83	0.00	0.41	1.14	1.28
	44	T	168.3	114.7	3.54	3.9	870	90	303	371	10.34	0.68	23.77	1.10	0.0	6.00	2.04	96.2	7.98	3.96	0.00	0.75	0.51	1.05
	55	T	168.3	114.7	3.54	3.9	870	90	303	371	10.34	0.68	23.77	1.10	32.5	2.90	2.14	96.2	7.98	3.96	0.34	0.36	0.54	1.01
	45	T	168.8	168.8	3.45	3.55	870	90	336	367	10.31	1.00	24.46	1.03	116.0	7.95	0.00	149.8	20.39	14.46	0.77	0.39	0.00	0.94
	46	T	168.8	168.3	3.45	3.54	870	90	336	367	10.31	1.00	24.46	1.03	54.5	14.85	0.00	149.8	20.39	14.46	0.36	0.73	0.00	0.93
	47	T	168.8	168.8	3.45	3.55	870	90	336	367	10.31	1.00	24.46	1.03	48.0	0.00	9.24	149.8	20.39	14.46	0.32	0.00	0.64	0.96
	49	T	168.8	168.5	3.45	3.3	870	90	336	367	10.31	1.00	24.46	0.96	0.0	12.40	8.70	149.8	20.39	14.46	0.00	0.61	0.60	0.98
	59	T	168.8	168.3	3.45	3.54	870	90	336	367	10.31	1.00	24.46	1.03	64.0	8.70	6.40	149.8	20.39	14.46	0.43	0.43	0.44	1.04

BOMEL ENGINEERING CONSULTANTS

APPENDIX A3.4 DATABASE ON OVERLAPPING JOINTS

Database on Overlapping Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	L (mm)	g (mm)	$Theta_c$ (degrees)	$Theta_t$ (degrees)	F_{YC} (N/mm^2)	F_{TC} (N/mm^2)	F_{YB} dyn. (N/mm^2)	F_{YB} sta. (N/mm^2)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	P_u (KN)
Bouwkamp (1968)	II-2	K	168.3	114.3	7.90	8.6	1349	-53.8	90	45	384	465	382	353	16.03	0.68	10.65	1.09	-0.32	864.9
	II-4	K	168.3	88.9	5.60	7.6	1349	-23.2	90	45	395	465	387	358	16.03	0.53	15.03	1.36	-0.14	597.6
	II-8	K	219.1	141.3	5.60	6.5	1349	-61.0	90	45	395	465	378	348	12.31	0.64	19.56	1.16	-0.28	723.4
	II-7	K	219.1	114.3	5.60	8.6	1349	-28.4	90	45	395	465	382	353	12.31	0.52	19.56	1.54	-0.13	581.9
	II-10	K	273.1	114.3	4.80	8.6	1349	-1.4	90	45	426	483	382	353	9.88	0.42	28.45	1.79	-0.01	220.2
	II-11	K	273.1	141.3	4.80	6.5	1349	-34.0	90	45	426	483	378	348	9.88	0.52	28.45	1.35	-0.12	534.8
	II-12	K	273.1	168.3	4.80	5.6	1349	-66.6	90	45	426	483	394	365	9.88	0.62	28.45	1.17	-0.24	676.3
	II-14	K	219.1	88.9	5.60	7.6	1349	-52.5	90	45	395	465	387	358	12.31	0.41	19.56	1.36	-0.24	550.4
	II-15	K	273.1	88.9	4.80	7.6	1349	-39.0	90	45	426	483		0	9.88	0.33	28.45	1.58	-0.14	566.1
	II-16	K	273.1	114.3	4.80	6.3	1349	-69.7	90	45	426	483		0	9.88	0.42	28.45	1.31	-0.26	550.4
	II-17	K	273.1	141.3	4.80	6.5	1349	-102.3	90	45	426	483	378	348	9.88	0.52	28.45	1.35	-0.37	723.4
	II-5	K	168.3	114.3	5.50	6.0	1349	-53.8	90	45	394		392	363	16.03	0.68	15.30	1.09	-0.32	676.2
	II-13	K	168.3	60.3	5.50	5.5	1349	-30.8	90	45	394		396	368	16.03	0.36	15.30	1.00	-0.18	323.9
Toprac (1970)		K	219.1	95.3	4.70	4.8		-5.0	90	45	365	502				0.43	23.31	1.02	-0.02	347.2
		K	219.1	95.3	4.70	4.8		-56.0	90	45	365	502				0.43	23.31	1.02	-0.26	417.8
Akiyama (1974)	I-CK-40-0.4	K	165.2	76.3	4.70	3.0	661	-10.0	90	45	485	550	363	332	8.00	0.46	17.57	0.64	-0.06	194.2
	I-CK-40-0.6	K	165.2	114.3	4.70	3.8	661	-55.0	90	45	485	550	353	322	8.00	0.69	17.57	0.81	-0.33	374.6
	I-CK-70-0.4	K	318.2	139.8	4.40	4.4	1273	-10.0	90	45	413	528	343	311	8.00	0.44	36.16	1.00	-0.03	284.4
	I-CK-70-0.6	K	318.2	165.2	4.40	4.5	1273	-40.0	90	45	413	528	491	475	8.00	0.52	36.16	1.02	-0.13	431.5
Pan (1976)	2	K	323.9	168.3	6.40	-	-	-41.1	90	45	290					0.52	25.30	0.00	-0.13	929.6
	3	K	323.9	168.3	6.40	-	-	-122.1	90	45	290					0.52	25.30	0.00	-0.38	1232.1
Iskikawajima (1978)		K	165.2	76.3	5.00	3.9	-	-25.3	45	45	327	442				0.46	16.52	0.78	-0.15	339.3
		K	165.2	76.3	5.00	3.9	-	-2.2	45	45	327	442				0.46	16.52	0.78	-0.01	274.6
		K	165.2	76.3	5.00	3.9	-	-25.3	90	45	399	516				0.46	16.52	0.84	-0.15	264.8
		K	165.2	101.6	5.00	4.2	-	-40.0	90	45	399	516				0.62	16.52	0.84	-0.24	353.0
Kurobane (1980)	K1A-3	K	140.0	50.9	8.20	9.5	1092	-12.0	60	60	316	488	310	277	15.60	0.36	8.54	1.16	-0.09	509.0
	K1B-3	K	140.0	50.9	9.10	9.3	1092	-12.0	60	60	325	510	310	277	15.60	0.36	7.69	1.02	-0.09	512.9
	K2A-4	K	215.1	102.4	4.30	4.0	1355	-25.0	60	60	353	449	414	387	12.60	0.48	25.01	0.93	-0.12	309.4
	K2A-5	K	216.3	102.1	4.30	3.9	1355	-50.0	60	60	353	449	414	387	12.53	0.47	25.15	0.91	-0.23	329.5
	K2B-3	K	215.9	140.0	4.30	3.9	1355	-50.0	60	60	353	449	376	346	12.55	0.65	25.10	0.91	-0.23	365.8
Koning (1981)	19	K	165.1	51.0	4.80	5.2	-	-36.1	45	45	281	405	267	234		0.31	17.20	1.08	-0.22	200.0
	20	K	165.1	165.1	4.80	4.8	-	-67.7	45	45	281	405	281	248		1.00	17.20	1.00	-0.41	505.0
	21	K	273.5	89.0	4.80	5.1	-	-62.9	45	45	324	462	253	220		0.33	28.49	1.06	-0.23	280.0
	22	K	273.5	89.0	4.80	5.1	-	-62.9	45	45	324	462	253	220		0.33	28.49	1.06	-0.23	283.0
	23	K	273.2	178.0	4.90	5.2	-	-125.9	45	45	332	454	267	234		0.65	27.88	1.06	-0.46	549.0
	24	K	273.2	178.0	4.90	5.2	-	-125.9	45	45	332	454	267	234		0.65	27.88	1.06	-0.46	517.0
	25	K	273.2	273.5	4.90	4.9	-	-112.2	45	45	332	454	331	299		1.00	27.88	1.00	-0.41	630.0
	43	K	165.1	51.0	4.80	5.2	-	-36.1	45	45	281	405	267	234		0.31	17.20	1.08	-0.22	200.0
	44	K	273.5	89.0	4.80	5.1	-	-62.9	45	45	324	462	253	220		0.33	28.49	1.06	-0.23	275.0
	45	K	273.5	89.0	4.80	5.1	-	-62.9	45	45	324	462	253	220		0.33	28.49	1.06	-0.23	271.0
	46	K	273.2	178.0	4.90	5.2	-	-125.9	45	45	332	454	267	234		0.65	27.88	1.06	-0.46	486.0
	47	K	273.2	178.0	4.90	5.2	-	-125.9	45	45	332	454	267	234		0.65	27.88	1.06	-0.46	490.0
	48	K	273.2	273.5	4.90	4.8	-	-112.2	45	45	332	454	331	299		1.00	27.88	0.98	-0.41	580.0

Database on Overlapping Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	L (mm)	g (mm)	$Theta_c$ (degrees)	$Theta_t$ (degrees)	F_{YC} (N/mm²)	F_{TC} (N/mm²)	F_{YB} dyn. (N/mm²)	F_{YB} sta. (N/mm²)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	P_u (KN)
Ochi (1981)	K-1	K	217.1	216.9	4.40	4.4		-130.0	60	60	369	470	382	353		1.00	24.67	1.00	-0.60	653.1
	K-2	K	216.7	216.8	4.40	4.4		-60.0	60	60	369	470	382	353		1.00	24.63	1.00	-0.28	662.4
	K-3	K	216.9	216.9	4.40	4.4		-40.0	60	60	369	470	382	353		1.00	24.65	1.00	-0.18	666.9
	K-4	K	216.5	165.1	4.40	4.3		-40.0	60	60	354	458	348	316		0.76	24.60	0.98	-0.18	509.5
	K-5	K	217.4	139.8	4.40	3.3		-40.0	60	60	354	458	401	373		0.64	24.70	0.75	-0.18	357.9
	K-10	K	165.4	165.4	4.40	4.2		-60.0	60	60	348	470	344	312		1.00	18.80	0.95	-0.36	535.4
	K-11	K	165.6	139.8	4.40	3.3		-40.0	60	60	348	470	401	373		0.84	18.82	0.75	-0.24	380.5
Fumagalli (1985)	20	K	194.3	140.2	3.00	3.1		-104.8	45	45	295	390	380	350		0.72	32.38	1.03	-0.54	225.0
	70	K	193.6	140.0	3.00	3.0		-55.0	45	45	373	390	380	350		0.72	32.27	1.00	-0.28	294.0
Kurobane (1986)	L1A	K	216.1	165.7	4.40	3.5		-90.0	60	60	472	521	431	406		0.77	24.56	0.80	-0.42	519.0
	L3A	K	216.1	165.6	7.90	3.5		-90.0	60	60	478	518	431	406		0.77	13.68	0.44	-0.42	710.0
	L3B	K	216.1	165.0	7.90	4.3		-90.0	60	60	478	518	409	382		0.76	13.68	0.54	-0.42	774.0
	L3C	K	216.1	165.0	7.90	5.3		-90.0	60	60	478	518	363	332		0.76	13.68	0.67	-0.42	885.0
	L3D	K	216.1	165.2	7.90	5.5		-90.0	60	60	478	518	313	280		0.76	13.68	0.70	-0.42	836.0
	I1A	K	216.1	165.7	4.40	3.5		-30.0	60	60	472	521	431	406		0.77	24.56	0.80	-0.14	490.0
	I3A	K	216.1	165.7	7.90	3.5		-30.0	60	60	478	518	431	406		0.77	13.68	0.44	-0.14	693.0
	I3C	K	216.1	165.0	7.90	5.3		-30.0	60	60	478	518	363	332		0.76	13.68	0.67	-0.14	922.0
Veritec (1993)	L-1	K	498.6	356.5	10.25	9.3	3900	-180.0	45	45	350			485	15.64	0.72	24.32	0.91	-0.36	3200.0
	L-2	YT	495.0	254.0	7.10	6.7	3900	-62.0	90	45	338		379	349	15.76	0.51	34.86	0.94	-0.13	900.0
Makino (1988)	KB-4	K	165.3	101.7	3.58	3.2	1222	-30.0	60	60	323	435	412	385	14.79	0.62	23.09	0.89	-0.18	237.6
Togo (1967)	A-I-1	K	101.6	27.3	3.88	2.6	950	-2.1	60	60	393	492	417	391	18.70	0.27	13.09	0.68	-0.02	98.1
	A-I-2	K	101.5	27.3	3.25	2.6	950	-2.1	60	60	388	473	417	391	18.73	0.27	15.61	0.81	-0.02	82.4
	A-I-3	K	101.5	27.3	3.25	2.6	950	-2.1	60	60	388	473	417	391	18.73	0.27	15.61	0.81	-0.02	85.3
	B-I-1	K	101.5	42.8	3.25	2.5	950	-20.1	60	60	388	473	400	372	18.73	0.42	15.61	0.77	-0.20	129.5
	B-I-2	K	101.5	42.8	3.25	2.5	950	-20.1	60	60	388	473	400	372	18.73	0.42	15.61	0.77	-0.20	128.5
	B-I-3	K	101.5	42.8	3.25	2.5	950	-20.1	60	60	388	473	400	372	18.73	0.42	15.61	0.77	-0.20	125.6
	C-I-1	K	101.5	60.2	3.25	2.9	950	-30.4	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.30	118.7
	C-I-2	K	101.5	60.2	3.25	2.9	950	-30.4	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.30	154.0
	C-I-3	K	101.5	60.2	3.25	2.9	950	-30.4	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.30	156.0
	C-C-1	K	101.5	60.2	3.25	2.9	950	-0.9	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.01	147.2
	C-C-2	K	101.6	60.2	3.88	2.9	950	-0.9	60	60	393	492	422	396	18.70	0.59	13.09	0.74	-0.01	145.2
	C-C-3	K	101.5	60.2	3.25	2.9	950	-0.9	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.01	139.3
	D-I-1	K	101.5	48.7	3.25	3.6	950	-26.9	60	60	388	473	351	320	18.73	0.48	15.61	1.11	-0.27	171.7
	D-I-2	K	101.5	48.7	3.25	3.6	950	-26.9	60	60	388	473	351	320	18.73	0.48	15.61	1.11	-0.27	166.8
	D-I-3	K	101.6	48.7	3.88	3.6	950	-26.9	60	60	393	492	351	320	18.70	0.48	13.09	0.93	-0.26	170.7

Database on Overlapping Joints

Reference	Specimen	Joint Type	D (mm)	d (mm)	T (mm)	t (mm)	L (mm)	g (mm)	$Theta_c$ (degrees)	$Theta_t$ (degrees)	F_{YC} (N/mm^2)	F_{TC} (N/mm^2)	F_{YB} dyn. (N/mm^2)	F_{YB} sta. (N/mm^2)	Alpha [2L/D]	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Eta [g/D]	P_u (KN)
Togo (1967)	E-I-1	K	101.6	60.2	3.88	2.9	950	-40.7	60	60	393	492	422	396	18.70	0.59	13.09	0.74	-0.40	194.2
	E-I-2	K	101.5	60.2	3.25	2.9	950	-40.7	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.40	185.4
	E-I-3	K	101.5	60.2	3.25	2.9	950	-40.7	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.40	184.4
	E-C-1	K	101.5	60.2	3.25	2.9	950	-11.3	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.11	166.8
	E-C-2	K	101.5	60.2	3.25	2.9	950	-11.3	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.11	161.9
	E-C-3	K	101.5	60.2	3.25	2.9	950	-11.3	60	60	388	473	422	396	18.73	0.59	15.61	0.88	-0.11	159.9
	F-I-1	K	101.6	60.3	3.88	3.0	950	-40.7	60	60	393	492	432	407	18.70	0.59	13.09	0.78	-0.40	206.0
	F-I-2	K	101.5	60.3	3.25	3.0	950	-40.7	60	60	388	473	432	407	18.73	0.59	15.61	0.93	-0.40	182.5
	F-I-3	K	101.5	60.3	3.25	3.0	950	-40.7	60	60	388	473	432	407	18.73	0.59	15.61	0.93	-0.40	186.4
	F-C-1	K	101.5	60.3	3.25	3.0	950	-11.3	60	60	388	473	432	407	18.73	0.59	15.61	0.93	-0.11	182.5
	F-C-2	K	101.6	60.3	3.88	3.0	950	-11.3	60	60	393	492	432	407	18.70	0.59	13.09	0.78	-0.11	204.0
	F-C-3	K	101.6	60.3	3.88	3.0	950	-11.3	60	60	393	492	432	407	18.70	0.59	13.09	0.78	-0.11	205.0
	G-I-1	K	101.6	76.4	3.88	3.5	950	-59.0	60	60	393	492	412	385	18.70	0.75	13.09	0.91	-0.58	274.7
	G-I-2	K	101.5	76.4	3.25	3.5	950	-59.0	60	60	388	473	412	385	18.73	0.75	15.61	1.09	-0.58	251.1
	G-I-3	K	101.5	76.4	3.25	3.5	950	-59.0	60	60	388	473	412	385	18.73	0.75	15.61	1.09	-0.58	247.2
	G-C-1	K	101.6	76.4	3.88	3.5	950	-29.6	60	60	393	492	412	385	18.70	0.75	13.09	0.91	-0.29	264.9
	G-C-2	K	101.5	76.4	3.25	3.5	950	-29.6	60	60	388	473	412	385	18.73	0.75	15.61	1.09	-0.29	232.5
	G-C-3	K	101.5	76.4	3.25	3.5	950	-29.6	60	60	388	473	412	385	18.73	0.75	15.61	1.09	-0.29	235.4
	G-O-1	K	101.5	76.4	3.25	3.5	950	-0.1	60	60	388	473	412	385	18.73	0.75	15.61	1.09	-0.00	206.0
	G-O-2	K	101.5	76.4	3.25	3.5	950	-0.1	60	60	388	473	412	385	18.73	0.75	15.61	1.09	-0.00	205.0
	G-O-3	K	101.5	76.4	3.25	3.5	950	-0.1	60	60	388	473	412	385	18.73	0.75	15.61	1.09	-0.00	203.1
	H-I-1	K	101.8	60.2	4.11	2.9	950	-40.7	60	60	489	550	432	407	18.66	0.59	12.38	0.70	-0.40	207.0
	H-I-2	K	101.8	60.2	4.11	2.9	950	-40.7	60	60	489	550	432	407	18.66	0.59	12.38	0.70	-0.40	206.0
	H-I-3	K	101.8	60.2	4.11	2.9	950	-40.7	60	60	489	550	432	407	18.66	0.59	12.38	0.70	-0.40	195.2
	H-C-1	K	101.8	60.2	4.11	2.9	950	-11.3	60	60	489	550	432	407	18.66	0.59	12.38	0.70	-0.11	205.0
	H-C-2	K	101.8	60.2	4.11	2.9	950	-11.3	60	60	489	550	432	407	18.66	0.59	12.38	0.70	-0.11	218.8
	H-C-3	K	101.8	60.2	4.11	2.9	950	-11.3	60	60	489	550	432	407	18.66	0.59	12.38	0.70	-0.11	209.9

APPENDIX A3.5 DATABASE ON MULTIPLANAR JOINTS

Database on multiplanar Joints

Reference	Specimen	Joint Type	D (mm)	T (mm)	d (mm)	t (mm)	L (mm)	PHI (deg)	Theta$_c$ (degrees)	Theta$_t$ (degrees)	gi (mm) (NOM)	go (mm) (NOM)	go (mm) Round (Formula)	go (mm) (Straight) (Formula)	Fyc (N/mm^2)	Ftc (N/mm^2)	Fyb / Ftb (N/mm^2)	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Fo / Fi	P$_u$ (kN)	M$_u$ (kNm)	Load-Displacement Curves
MAKINO (1984)	DK-1	K-K	217.1	4.41	48.9	3.2	1514	60	60	60	54.0	63.3	64.4	63.4	352	472	No	0.23	24.6	0.7	1	82.9		YES
	DK-2	K-K	217.2	4.41	60.7	4.0	1514	60	60	60	40.9	51.6	52.2	51.7	352	472	No	0.28	24.6	0.9	1	107.9		YES
	DK-3	K-K	217.1	4.41	76.6	4.0	1514	60	60	60	23.0	35.1	35.4	35.2	352	472	No	0.35	24.6	0.9	1	149.1		YES
	DK-4	K-K	217.2	4.42	48.5	3.2	1514	60	60	60	3.6	6.3	64.8	63.9	432	556	No	0.22	24.6	0.7	1	149.1		YES
	DK-5	K-K	217.0	4.45	60.1	4.0	1514	60	60	60	70.6	86.5	52.7	52.2	432	556	No	0.28	24.4	0.9	1	113.8		YES
	DK-6	K-K	165.3	4.39	48.9	3.2	1156	60	60	60	28.4	36.9	36.9	36.6	385	491	No	0.30	18.8	0.7	1	136.3		YES
	DK-7	K-K	165.0	4.29	48.3	3.2	1156	60	60	60	3.3	7.4	37.4	37.1	277	402	No	0.29	19.2	0.7	1	126.5		YES
	DK-8	K-K	165.0	4.21	48.5	3.2	1156	60	60	60	61.6	76.2	37.2	36.9	277	402	No	0.29	19.6	0.8	1	71.0		YES
	DK-9	K-K	165.2	4.21	60.2	4.0	1156	60	60	60	38.0	52.6	24.9	24.8	277	402	No	0.36	19.6	1.0	1	97.0		YES
	DK-10	K-K	139.8	4.37	48.4	3.2	1156	60	60	60	15.7	23.5	23.8	23.7	387	475	No	0.35	16.0	0.7	1	136.3		YES
	DK-11	K-K	216.2	4.48	60.7	3.8	1514	60	90	41	78.5	102.8	51.7	51.2	472	521	No	0.28	24.1	0.8	1	105.9		YES
	DK-12	K-K	216.2	4.54	76.5	4.0	1514	60	90	41	45.8	71.4	35.0	34.9	472	521	No	0.35	23.8	0.9	1	139.3		YES
	DK-13	K-K	216.0	4.49	76.6	4.0	1514	60	90	41	59.4	88.3	34.8	34.6	472	521	No	0.35	24.1	0.9	1	131.4		YES
	DK-14	K-K	165.4	4.32	60.7	3.8	1156	60	90	45	20.9	52.4	24.5	24.4	409	483	No	0.37	19.1	0.9	1	139.3		YES
	DK-15	K-K	165.4	4.42	60.6	3.8	1156	60	90	45	30.0	65.4	24.6	24.5	409	483	No	0.37	18.7	0.9	1	125.5		YES
	DK-16	K-K	165.4	4.32	76.4	4.0	1156	60	90	45	10.8	49.1	7.2	7.2	409	483	No	0.46	19.1	0.9	1	198.1		YES
	DK-17	K-K	165.3	4.41	76.3	4.0	1156	60	90	45	11.6	50.4	7.2	7.2	409	483	No	0.46	18.7	0.9	1	179.5		YES
	DK-18	K-K	139.9	4.12	60.7	3.8	1156	60	90	45	6.9	35.2	10.5	10.5	370	468	No	0.43	17.0	0.9	1	164.8		YES
	DK-19	K-K	140.5	4.08	60.6	3.8	1156	60	90	45	11.4	41.8	10.9	10.9	370	468	No	0.43	17.2	0.9	1	162.8		YES
	DK-20	K-K	140.1	4.05	60.6	3.8	1156	60	90	45	14.6	46.6	10.7	10.7	370	468	No	0.43	17.3	0.9	1	152.0		YES
AKIYAMA (1974)	II-KK-40-0.2	K-K	165.2	4.70	42.7	3.3	661	180	45	45	105	159.6	216.3	159.6	441	-	343/536	-	-	-	-1	127.5		YES
	II-KK-40-0.4	K-K	165.2	4.70	60.5	3.0	661	180	45	45	80	153.7	197.6	153.7	471	-	334/540	-	-	-	-1	201.1		YES
	II-KK-70-0.2	K-K	318.5	4.40	60.5	3.0	1274	180	45	45	233	312.7	439.4	312.7	412	-	334/528	0.19	36.2	0.7	-1	107.9		YES
	II-KK-70-0.4	K-K	318.5	4.40	139.8	4.4	1274	180	45	45	121	286.2	355.6	286.2	412	-	343/528	0.44	36.2	1.0	-1	235.4		YES
Makino (1993)	DK-S-NP	K-K	215.9	4.4	101.7	5.2	1700	60	45	45	52.8	7.9	7.1	7.1	388	470		0.47	24.5	1.2	1	179.5		
	DK-S-N	K-K	215.9	4.4	101.7	5.2	1700	60	45	45	52.8	7.9	7.1	7.1	388	470		0.47	24.5	1.2	1	189.3		
	DK-U-NP	K-K	215.9	4.4	101.7	5.2	1700	60	45	45	52.7	7.9	7.1	7.1	388	470		0.47	24.5	1.2	-1	161.4		
	DK-U-N	K-K	215.9	4.4	101.7	5.2	1700	60	45	45	52.7	7.9	7.1	7.1	388	470		0.47	24.5	1.2	-1	243.3		
Paul (1992)	KK-1	K-K	190.8	5.21	89	5.66	1678	60	49.1	49.1	72.8	8	7.3	7.3	384	444		0.47	18.3	1.1	1	223.0		Yes
	KK-2	K-K	190.8	5.21	89	5.66	1678	60	49.1	49.1	51.3	9	7.3	7.3	384	444		0.47	18.3	1.1	1	230.1		Yes
	KK-3	K-K	190.8	5.21	89	5.66	1678	60	49.1	49.1	31	8	7.3	7.3	384	444		0.47	18.3	1.1	1	240.0		Yes
	KK-4	K-K	190.8	5.21	89	5.66	1678	60	49.1	49.1	9.5	9	7.3	7.3	384	444		0.47	18.3	1.1	1	285.5		Yes
	KK-5	K-K	190.8	5.21	60.5	5.66	1678	60	49.1	49.1	52	37	38.3	38.1	384	444		0.32	18.3	1.1	1	188.1		Yes
	KK-6	K-K	190.8	5.21	60.5	5.66	1678	60	49.1	49.1	31	40	38.3	38.1	384	444		0.32	18.3	1.1	1	203.3		Yes
	KK-7	K-K	190.8	5.21	60.5	5.66	1678	60	49.1	49.1	11	38.5	38.3	38.1	384	444		0.32	18.3	1.1	1	227.9		Yes
	KK-8	K-K	190.8	5.21	42.8	5.46	1678	60	49.1	49.1	30	55	56.7	55.9	384	444		0.22	18.3	1.0	1	155.8		Yes
	KK-9	K-K	190.8	5.21	42.8	5.46	1678	60	49.1	49.1	11.5	55	56.7	55.9	384	444		0.22	18.3	1.0	1	174.5		Yes
	KK-10	K-K	190.8	5.21	89	5.66	1678	90	54.7	54.7	73	56	57.3	56.4	384	444		0.47	18.3	1.1	1	241.5		Yes
	KK-11	K-K	190.8	5.21	89	5.66	1678	90	54.7	54.7	52	56	57.3	56.4	384	444		0.47	18.3	1.1	1	251.8		Yes
	KK-12	K-K	190.8	5.21	89	5.66	1678	90	54.7	54.7	31	56	57.3	56.4	384	444		0.47	18.3	1.1	1	263.3		Yes
	KK-13	K-K	190.8	5.21	89	5.66	1678	90	54.7	54.7	11.3	55.8	57.3	56.4	384	444		0.47	18.3	1.1	1	291.7		Yes
	KK-14	K-K	190.8	5.21	60.5	5.66	1678	90	54.7	54.7	53	83.3	88.3	85.2	384	444		0.32	18.3	1.1	1	154.5		Yes
	KK-15	K-K	190.8	5.21	60.5	5.66	1678	90	54.7	54.7	31	83	88.3	85.2	384	444		0.32	18.3	1.1	1	161.7		Yes
	KK-16	K-K	190.8	5.21	60.5	5.66	1678	90	54.7	54.7	10.5	83	88.3	85.2	384	444		0.32	18.3	1.1	1	181.8		Yes
	KK-17	K-K	190.8	5.21	42.8	5.46	1678	90	54.7	54.7	31	100	106.7	101.2	384	444		0.22	18.3	1.0	1	122.2		Yes
	KK-18	K-K	190.8	5.21	42.8	5.46	1678	90	54.7	54.7	11.5	99.8	106.7	101.2	384	444		0.22	18.3	1.0	1	161.4		Yes

BOMEL CONSULTING ENGINEERS

Database on multiplanar Joints

Reference	Specimen	Joint Type	D (mm)	T (mm)	d (mm)	t (mm)	L (mm)	PHI (deg)	$Theta_c$ (degrees)	$Theta_i$ (degrees)	gi (mm) (NOM)	go (mm) (NOM)	go (mm) Round (Formula)	go (mm) (Straight) (Formula)	Fyc (N/mm^2)	Ftc (N/mm^2)	Fyb / Ftb (N/mm^2)	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Fo / Fi	P_u (kN)	M_u (kNm)	Load-Displacement Curves
MITRI (1987)	T1	T	219.8	4.94	89.0	4.78	528.6	-	90	-	-	-	-	-	335	465	Not Given	0.40	22.2	1.0	-	115.2		YES
	T2	T	219.7	8.21	89.3	4.78	528.7	-	90	-	-	-	-	-	400	482	Not Given	0.41	13.4	0.6	-	330.5		YES
	T3	T	219.7	6.40	141.8	6.55	581.2	-	90	-	-	-	-	-	327	458	Not Given	0.65	17.2	1.0	-	328.7		YES
	T4	T	219.8	6.37	48.7	4.78	488.3	-	90	-	-	-	-	-	327	458	Not Given	0.22	17.3	0.8	-	122.3		YES
	T5	T	219.6	6.39	89.0	4.78	528.2	-	90	-	-	-	-	-	327	458	Not Given	0.41	17.2	0.7	-	208.6		YES
	V1	T-T	219.95	4.92	89.1	4.78	529.0	90	90	90	-	79.2	81.0	79.2	335	465	Not Given	0.41	22.4	1.0	1	131.5		YES
	V2	T-T	219.75	8.24	89.3	4.78	528.8	90	90	90	-	78.8	80.6	78.8	400	482	Not Given	0.41	13.3	0.6	1	383.7		YES
	V3	T-T	220.20	6.315	142.3	6.55	582.7	90	90	90	-	18.2	18.2	18.2	327	458	Not Given	0.65	17.4	1.0	1	452.9		YES
	V4	T-T	220.35	6.34	49.0	4.78	489.7	90	90	90	-	117.3	123.6	117.3	327	458	Not Given	0.22	17.4	0.8	1	122.0		YES
	V5	T-T	220.40	6.39	89.6	4.78	530.4	60	90	90	-	23.1	23.1	23.1	327	458	Not Given	0.41	17.2	0.7	1	238.8		YES
	V6	T-T	219.90	6.39	89.3	4.78	528.9	120	90	90	-	129.3	138.3	129.4	327	458	Not Given	0.41	17.2	0.7	1	177.4		YES
	V7	T-T	220.50	6.32	89.8	4.78	530.8	90	90	90	-	78.9	80.7	78.9	327	458	Not Given	0.41	17.4	0.8	1	206.3		YES
	V8	T-T	220.25	6.30	169.3	4.78	609.8	120	90	90	-	37.4	37.5	37.4	327	458	Not Given	0.77	17.5	0.8	-	458.1		YES
PAUL (1988)	TT-1	T-T	190.8	5.23	42.8	3.45	850	60.6	90	90	-	55.9	57.7	56.9	384	444	236/356	0.22	18.2	0.7	1	87.7		/ NO ?
	TT-2	T-T	190.8	5.23	60.6	3.93	850	60.3	90	90	-	38.0	38.7	38.5	384	444	400/437	0.32	18.2	0.8	1	112.8		/ NO ?
	TT-3	T-T	190.8	5.23	89.1	4.03	850	60.3	90	90	-	7.1	7.6	7.6	384	444	219/352	0.47	18.2	0.8	1	143.5		/ NO ?
	TT-4	T-T	190.8	5.23	42.8	3.45	850	90.2	90	90	-	101.2	107.0	101.5	384	444	236/356	0.22	18.2	0.7	1	82.1		/ NO ?
	TT-5	T-T	190.8	5.23	60.6	3.93	850	90.1	90	90	-	85.1	88.3	85.2	384	444	400/437	0.32	18.2	0.8	1	111.2		/ NO ?
	TT-6	T-T	190.8	5.23	89.1	4.03	850	90.0	90	90	-	56.2	57.1	56.2	384	444	219/352	0.47	18.2	0.8	1	174.2		/ NO ?
	TT-7	T-T	190.8	5.23	114.3	4.24	850	89.9	90	90	-	27.2	27.1	27.0	384	444	377/452	0.60	18.2	0.8	1	255.8		/ NO ?
	TT-8	T-T	190.8	5.23	42.8	3.45	850	120.2	90	90	-	139.6	157.0	139.8	384	444	236/356	0.22	18.2	0.7	1	78.5		/ NO ?
	TT-9	T-T	190.8	5.23	60.6	3.93	850	120.0	90	90	-	126.5	138.1	126.4	384	444	400/437	0.32	18.2	0.8	1	96.9		/ NO ?
	TT-10	T-T	190.8	5.23	89.1	4.03	850	120.1	90	90	-	101.5	107.2	101.6	384	444	219/352	0.47	18.2	0.8	1	133.4		/ NO ?
	TT-11	T-T	190.8	5.23	114.3	4.24	850	120.4	90	90	-	75.1	77.9	75.7	384	444	377/452	0.60	18.2	0.8	1	169.8		/ NO ?
	TT-12	T-T	190.8	5.23	139.7	4.31	850	120.2	90	90	-	42.5	43.4	43.0	384	444	321/376	0.73	18.2	0.8	1	252.3		/ NO ?
PAUL (1989)	T1	DT	1006.3	25.00	399.4	10.0	6038	0	90	0	-	0.0	-	0.0	265	430	265	0.40	20.1	0.4	0	1737.4		YES
	T2	DT	1006.3	25.00	599.4	10.0	6038	0	90	0	-	0.0	-	0.0	265	430	265	0.60	20.1	0.4	0	2274.0		YES
	DT3	DT-DT	1006.3	25.00	399.4	10.0	6038	90	90	90	-	379.8	379.6	370.7	265	430	265	0.40	20.1	0.4	0	1740.7		YES
	DT4	DT-DT	1006.3	25.00	599.4	10.0	6038	90	90	90	-	148.3	148.3	147.7	265	430	265	0.60	20.1	0.4	0	2572.2		YES
	DT5	DT-DT	1006.3	25.00	399.4	10.0	6038	90	90	90	-	379.8	379.6	370.7	265	430	265	0.40	20.1	0.4	1	2303.8		YES
	DT6	DT-DT	1006.3	25.00	599.4	10.0	6038	90	90	90	-	148.3	148.3	147.7	265	430	265	0.60	20.1	0.4	1	6641.6		YES
	DT7	DT-DT	1006.3	25.00	601.9	15.0	6038	90	90	90	-	145.1	145.1	144.6	265	430	265	0.60	20.1	0.6	0.75	5101.3		YES
	DT8	DT-DT	1006.3	25.00	399.4	10.0	6038	90	90	90	-	379.8	379.6	370.7	265	430	265	0.40	20.1	0.4	-1	1131.2		YES
	DT9	DT-DT	1006.3	25.00	601.9	15.0	6038	90	90	90	-	145.1	145.1	144.6	265	430	265	0.60	20.1	0.6	-1	1669.5		YES
SAKHAROV (1989)	T1	DT	1002.0	10.00	528.0	8.0	-	-	90	-	-	-	-	0.0	324	N/A	Not Given	0.53	50.1	0.8	0	394.0		/
	DT2	DT-DT	1002.0	10.00	528.0	8.0	-	90	90	90	-	231	230.9	228.8	324	N/A	Not Given	0.53	50.1	0.8	1	1121.0		/
	DT3	DT-DT	1002.0	10.00	528.0	8.0	-	90	90	90	-	231		0.0	324	N/A	Not Given	0.53	50.1	0.8	-1	418.0		/
VEGTE (1991) (Axial load)	X1	DT	408.0	10.20	246.00	10.350	2440	0	90	-	-	0.0	-	0.0	331	435	284/414	0.60	20.0	1.0	0	430.0		YES
	XX2	DT-DT	408.0	10.20	246.25	10.285	2440	90	90	90	-	56.8	56.1	55.9	331	435	244/398	0.60	20.0	1.0	0	532.0		YES
	XX3	DT-DT	408.5	10.00	246.00	10.350	2440	90	90	90	-	56.8	56.8	56.7	318	425	289/415	0.60	20.4	1.0	0.31	683.0		YES
	XX4	DT-DT	408.5	10.00	246.25	10.315	2440	90	90	90	-	56.8	56.5	56.3	318	425	264/395	0.60	20.4	1.0	-0.55	422.0		YES
VEGTE (1991) (In-plane IPB)	X5	DT	408.5	10.00	246.00	10.350	2440	-	90	-	-	376.0	-	0.0	318	425	284/414	0.60	20.4	1.0	-	-		YES
	XX6	DT-DT	408.0	10.20	246.50	10.275	2440	90	90	90	-	56.8	55.8	55.6	331	435	244/398	0.60	20.0	1.0	0	-		YES
	XX7	DT-DT	408.5	10.00	246.50	10.275	2440	90	90	90	-	56.8	56.2	56.0	318	425	244/398	0.60	20.4	1.0	1	-		YES
	XX8	DT-DT	408.5	10.12	247.00	10.260	2440	90	90	90	-	56.8	55.6	55.4	268	395	279/413	0.60	20.2	1.0	-1	-		YES

Database on multiplanar Joints

Reference	Specimen	Joint Type	D (mm)	T (mm)	d (mm)	t (mm)	L (mm)	PHI (deg)	$Theta_c$ (degrees)	$Theta_t$ (degrees)	gi (mm) (NOM)	go (mm) (NOM)	go (mm) Round (Formula)	go (mm) (Straight) (Formula)	Fyc (N/mm^2)	Ftc (N/mm^2)	Fyb / Ftb (N/mm^2)	Beta [d/D]	Gamma [D/2T]	Tau [t/T]	Fo / Fi	P_u (kN)	M_u (kNm)	Load-Displacement Curves
VEGTE	X9	DT	408.0	10.20	246.00	10.350	2440	-	90	-	-	376.0	-	0.0	331	435	284/414	0.60	20.0	1.0	-	-		YES
(1991)	XX10	DT-DT	408.5	10.12	246.50	10.305	2440	90	90	90	-	56.8	56.2	56.0	268	395	279/413	0.60	20.2	1.0	0	-		YES
(In-plane OPB)	XX11	DT-DT	408.5	10.12	246.50	10.305	2440	90	90	90	-	56.8	56.2	56.0	268	395	279/413	0.60	20.2	1.0	1	-		YES
	XX12	DT-DT	408.0	10.20	246.50	10.305	2440	90	90	90	-	56.8	55.8	55.6	331	435	279/413	0.60	20.0	1.0	-1	-		YES
Mouty	1-1	K-K	139.7	6.3	48.3	3.2	840	60	45	45	-	-	23.8	23.7	322	451	279	0.35	11.1	0.5	1	151.3		
and	2-1	K-K	139.7	6.3	48.3	3.2	840	90	45	45	-	-	60.4	58.5	367	514	329	0.35	11.1	0.5	1	146.3		
Rondal	3-1	K-K	139.7	6.3	48.3	3.2	840	60	30	30	-	-	23.8	23.7	328	459	260	0.35	11.1	0.5	1	115.2		
(1990)	4-1	K-K	139.7	6.3	48.3	3.2	840	90	30	30	-	-	60.4	58.5	353	494	295	0.35	11.1	0.5	1	-		
	5-1	K-K	139.7	6.3	48.3	3.2	840	60	60	60	-	-	23.8	23.7	328	459	310	0.35	11.1	0.5	1	125.5		
	6-1	K-K	139.7	6.3	48.3	3.2	840	90	60	60	-	-	60.4	58.5	353	494	328	0.35	11.1	0.5	1	131.3		
	7-1	K-K	139.7	6.3	33.7	2.6	840	60	45	45	-	-	39.1	38.6	349	489	290	0.24	11.1	0.4	1	70.0		
	8-1	K-K	139.7	6.3	33.7	2.6	840	90	45	45	-	-	75.7	72.0	328	459	290	0.24	11.1	0.4	1	68.5		
	9-1	K-K	139.7	6.3	33.7	2.6	840	60	30	30	-	-	39.1	38.6	327	458	290	0.24	11.1	0.4	1	70.8		
	10-1	K-K	139.7	6.3	33.7	2.6	840	90	30	30	-	-	75.7	72.0	357	500	290	0.24	11.1	0.4	1	69.2		
	11-1	K-K	139.7	6.3	33.7	2.6	840	60	60	60	-	-	39.1	38.6	335	469	301	0.24	11.1	0.4	1	70.2		
	12-1	K-K	139.7	6.3	33.7	2.6	840	90	60	60	-	-	75.7	72.0	335	469	301	0.24	11.1	0.4	1	70.5		
	13-1	K-K	139.7	6.3	76.1	4.0	840	60	45	45	-	-	-7.3	-7.3	342	479	303	0.54	11.1	0.6	1	279.1		
	14-1	K-K	139.7	6.3	76.1	4.0	840	90	45	45	-	-	29.2	29.0	323	452	285	0.54	11.1	0.6	1	215.2		
	15-1	K-K	139.7	6.3	76.1	4.0	840	60	30	30	-	-	-7.3	-7.3	323	452	295	0.54	11.1	0.6	1	255.2		
	16-1	K-K	139.7	6.3	76.1	4.0	840	90	30	30	-	-	29.2	29.0	342	479	275	0.54	11.1	0.6	1	235.2		
	17-1	K-K	139.7	6.3	76.1	4.0	840	60	60	60	-	-	-7.3	-7.3	341	477	310	0.54	11.1	0.6	1	285.3		
	18-1	K-K	139.7	6.3	76.1	4.0	840	90	60	60	-	-	29.2	29.0	341	477	299	0.54	11.1	0.6	1	258.2		
	19-1	K-K	139.7	4.0	48.3	3.2	840	60	45	45	-	-	23.8	23.7	322	451	287	0.35	17.5	0.8	1	80.3		
	20-1	K-K	139.7	4.0	33.7	2.6	840	60	45	45	-	-	39.1	38.6	322	451	271	0.24	17.5	0.7	1	50.2		
	21-1	K-K	139.7	4.0	76.1	4.0	840	60	45	45	-	-	-7.3	-7.3	320	448	297	0.54	17.5	1.0	1	110.3		
	22-1	K-K	139.7	10.0	48.3	3.2	840	60	45	45	-	-	23.8	23.7	345	483	330	0.35	7.0	0.3	1	110.0		
	23-1	K-K	139.7	10.0	33.7	2.6	840	60	45	45	-	-	39.1	38.6	345	483	301	0.24	7.0	0.3	1	73.4		
	24-1	K-K	139.7	10.0	76.1	4.0	840	60	45	45	-	-	-7.3	-7.3	337	472	305	0.54	7.0	0.4	1	252.5		
	25-1	K-K	88.9	4.0	33.7	2.6	840	60	45	45	-	-	12.0	11.9	320	448	301	0.38	11.1	0.7	1	68.3		
	26-1	K-K	219.1	6.3	76.1	4.0	533	60	45	45	-	-	37.0	36.8	331	463	310	0.35	17.4	0.6	1	170.1		
	27-1	K-K	139.7	6.3	48.3	3.2	1315	60	45	45	-	-	23.8	23.7	322	451	290	0.35	11.1	0.5	1	151.7		
	28-1	K-K	139.7	6.3	48.3	3.2	840	60	45	45	-	-	23.8	23.7	322	451	290	0.35	11.1	0.5	1	-		
	29-1	K-K	139.7	6.3	48.3	3.2	840	60	45	45	-	-	23.8	23.7	322	451	297	0.35	11.1	0.5	1	117.4		
	30-1	K-K	139.7	6.3	48.3	3.2	840	90	45	45	-	-	60.4	58.5	367	494	343	0.35	11.1	0.5	1	120.9		
	31-1	K-K	139.7	6.3	48.3	3.2	840	90	45	45	-	-	60.4	58.5	367	494	329	0.35	11.1	0.5	1	123.4		
	32-1	K-K	139.7	6.3	48.3	3.2	840	90	45	45	-	-	60.4	58.5	367	493	343	0.35	11.1	0.5	1	116.7		

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APPENDIX A3.6 FINITE ELEMENT DATABASE

(To be added)

BOMEL ENGINEERING CONSULTANTS

APPENDIX A3.7 DATABASE ON STATIC AND DYNAMIC YIELD PROPERTIES

(To be added)

APPENDIX A3.8 LENGTH FORMULAE FOR OVERLAPPING JOINTS

(To be added)