JOINT INDUSTRY PROJECT

COMPARATIVE EVALUATION OF MINIMUM STRUCTURES AND JACKETS

EFFECT OF VESSEL IMPACT ON INTACT AND DAMAGED STRUCTURES

DOC REF C209R007 Rev 1 July 1999

Purpose of Issue	Rev	Date of Issue	Author	Agreed	Approved
Issued to WS Atkins	0	March 1999	AFD	NWN	AFD
Final Report	1	July 1999	AFD	NWN	AFD

COMMERCIAL - IN - CONFIDENCE

JOINT INDUSTRY PROJECT

COMPARATIVE EVALUATION OF MINIMUM STRUCTURES AND JACKETS

EFFECT OF VESSEL IMPACT ON INTACT AND DAMAGED STRUCTURES

DOC REF C209R007 Rev 1 July 1999

MSL Engineering Limited
MSL House
5-7 High Street, Sunninghill,
Ascot, Berkshire. SL5 9NQ

Tel: +44 (0)1344-874424
Fax: +44 (0)1344-874338
E-mail: MSLCENG@aol.com

NUMBER	DETAILS OF REVISION
0	Issued to WS Atkins for Distribution to Project Steering Committee (PSC).
1	Final report including new appendix and Figures 3.5 to 3.8, plus some editorial changes.

COMPARATIVE EVALUATION OF MINIMUM STRUCTURES AND JACKETS

EFFECT OF VESSEL IMPACT ON INTACT AND DAMAGED STRUCTURES

CONTENTS

1. INTRODUCTION

This report describes the work undertaken by MSL Engineering Limited (MSL) for the sponsors of the Joint Industry Project (JIP) entitled "Comparative Evaluation of Minimum Structures and Jackets"[(1)]. In particular it addresses the estimation of reliabilities of three minimum structures and a standard jacket structure during and following a vessel impact. Both intact and damaged structures are considered.

The overall objective of the JIP is to develop practical procedures to evaluate the life-cycle reliability and risk characteristics of minimum structures. The scope of work has been derived in four main stages as follows:

Stage I:	Comparative reliability of three monotower structures and a jacket considering natural causes of failure (e.g. extreme storm).
Stage II:	Analysis of human and organisational factors.
Stage III:	Parametric and sensitivity analysis.
Stage IV:	Multi-criteria decision analysis.

Presently, only the first two stages have been funded. Stage I is split into three tasks:

Task I.1:	Conceptual design of the structures.
Task I.2:	Reliability under extreme storm and fatigue conditions.
Task I.3:	Reliability under ship collision conditions.

Stage II also consists of three tasks:

Task II.1:	Methodology and software development.
Task II.2:	Quantification of error probabilities.
Task II.3:	Reliability analysis for error scenarios.

MSL's contribution lies in Tasks I.3 and II.3.

All four structures were designed by Ramboll (under Task I.1) to API RP2A WSD 20th edition. The four structures considered are:

- 3-Pile Monotower.
- 4-Legged Jacket (4 piles).
- Vierendeel Tower Jacket (4 piles).
- Braced Caisson.

All were designed for the same location (approximately 34m water depth) and for the same environmental criteria. Ramboll have summarised the designs in Reference 2.

The structures are illustrated in Figures 1.1 to 1.4. The locations of ship and dropped object impacts are indicated on the figures and are discussed in Section 2 of this report.

Section 2 presents the methodologies used in this study and covers both the structural and reliability analyses. Section 3 is concerned with the results of analyses conducted on the intact structures, ie. ship collision, pushover and reliability calculations. Section 4 addresses the behaviour of the structures following damage caused by dropped objects. Conclusions are presented in Section 5.

2. METHODOLOGY

A consistent approach to analyses was applied across all structures so that valid comparisons could be made between their respective behaviours. This approach is outlined below, together with the various inputs used in the analyses.

2.1 Structural Analysis

Structural analyses were generally undertaken using the USFOS program. USFOS was specifically written for pushover and ship impact analyses.

The first step was to create the structural models including boat loadings, appurtenances and marine growth within USFOS. Nodal co-ordinates and element topology were initially taken from the ROSA (Ramboll's analysis package) input files. The structural models were then checked against Ramboll's drawings and modified, if necessary, to agree with the drawings. During the course of the project there were several design changes (such as increase of can and pile thicknesses and properties), and these were also implemented in the USFOS models. Soil spring data were derived according to API RP2A 20th Edition from the specified soil data[(3)] using an EXCEL spreadsheet.

The following loads were taken into account in the analyses:

- Gravity loads (including C.O.G offset)
- Out-of-verticality (installed lean)
- Buoyancy
- Wind
- Current
- Wave
- Vessel impact loads
- Inertial forces (for dynamic analyses).

The topside operational weight was taken as 400 tonnes with a centre of gravity 1m from the vertical axis of symmetry. An out-of-vertical tolerance of 1.5° was simulated by a horizontal load located at the level of the topsides. Both the C.O.G and out-of-vertical loading were arranged such that they induced additional load in the critical member in the pushover collapse mechanism. The substructure steel density was increased by 5 per cent to account for the weight of sacrificial anodes. Wind loads were simulated by point loads distributed over the topsides structure. Stream Function Theory was used to calculate wave loads in the extreme 100 year storm event.

The loads were checked by comparing base shears, over-turning moments and axial loads in selected members to values obtained by Ramboll and WS Atkins. Satisfactory agreement was obtained.

The minimum specified yield strength was increased by 15% to reflect typical delivered strengths.

During pushover analyses, only the loads due to wave and current were increased (by factoring up the 100 year storm values), all other loads were kept constant.

All bracing members were automatically given an initial bow and assigned certain plasticity factors[4], the imperfection being such that buckling strength to API RP2A was accurately captured. This allows the members to buckle out-of-plane should they be disposed to do so.

2.2 Ship Impact Analysis

The four structures were originally designed by Ramboll to withstand an impact of a 2500 tonnes ship travelling at 2.0 m/s. However, this design case rather dominated the design of the structures. On the advice of the Project Steering Committee, this design condition was removed and the structures were accordingly resized.

In anticipation of the reliability calculations, MSL considered a range of vessel mass and velocities in their analyses. A separate study[5] funded by HSE, one of the Sponsors of the JIP, allowed realistic ranges of these parameters to be specified (500 to 3500 tonnes, velocity up to 2.5m/s). Reference 5 is reproduced in the Appendix.

The ship impact analyses were conducted dynamically in the time domain. Still water conditions with gravity loading were assumed at the time of the impact.

Two non-linear springs were inserted in series into the model at the impact location. One spring represented the member denting process and the P-δ non-linear stiffness relationship was obtained from the work of Pettersen and Johnsen[6]. The other spring simulated the deformation characteristic of the vessel. The P-δ relationship specified by DNV[7] was used for this spring.

After applying gravity, buoyancy and other 'static' loads, a mass representing the vessel and associated added mass was given the initial velocity and applied to the end of the (ship) non-linear spring. Appropriate levels of damping were used during this phase of the analysis. Normally, following a short period, the response of the structure and vessel was such that separation occurred. After separation, the damping levels were increased to damp out structural vibrations quickly, in preparation for the quasi-static pushover analysis under environmental conditions of the now dented structure. For the monotower structure, certain combinations of vessel mass and velocity caused collapse of the structure during the impact stage, thus negating the need for a subsequent pushover analysis.

The above ship impact analysis was complicated by three further considerations. The first concerns the introduction of the dent in the structure. Whereas USFOS will automatically insert a growing dent, arising during an impact, in the structural model for a static analysis, a dent has to be explicitly modelled for a dynamic analysis. The structure does not 'know' it has suffered a dent during a dynamic analysis unless it has been previously modelled. It does, however, retain damage in the form of member bowing. It was necessary, therefore, to carry out a pair of analyses. After the first analysis, the output from the dent spring was interrogated and the residual dent depth established. A dent of this magnitude was then explicitly modelled before repeating the impact analysis and the subsequent pushover analysis.

The second complicating consideration was a recognition that failure of the structure could occur during the impact itself. For this it was necessary to model the maximum dent depth, rather than the residual dent depth, in case such an imperfection weakened the impacted member sufficiently to predispose failure at the impact location rather than elsewhere. Sufficient check runs were made to confirm that failure during impact, if it occurred at all, always involved bracing members near the mudline.

The third consideration involved the direction of the impact. Baseline pushover analyses, without a vessel impact, established which were the critical members involved in the collapse mechanism. The ship direction was then chosen to put these members in compression, in case the impact caused yielding and buckling of the critical members thereby weakening them prior to the pushover analysis. This vessel direction generally introduced a dent which was on the tension side of the member when the structure was subsequently subjected to the pushover load. The dent is therefore pulled flat under this load regime. Additional runs were carried out with the impact direction reversed so that the dent was put into compression during the pushover stage, again in case the collapse mechanism changed from failure in the lower bays to failure at the dent location. It was confirmed that failure at the dent did not occur; collapse was always associated with failure of bracing members near the mudline.

2.3 Dropped Object Study

Under Task II.3 of the JIP, the reliability of damaged structures subject to ship impact was investigated. The damage considered here is that which would be caused by a dropped object impacting on critical members of the structure. This subsection describes how the magnitude of damage was derived. Several possibilities exist for defining the level of damage including:

- Specifying a level of dent depth either as an absolute value or as a proportion of the member diameter.
- Specifying a dent, which varies with the geometry of the struck member, that leads to a certain reduction in the axial capacity of the member.
- Consider a specific scenario which leads to denting, eg. dropped object with a defined kinetic energy.

It was felt that the third option should be pursued as it allows a fairer comparison to be made between the performance of the structures. The first two options are somewhat arbitrary and the second option presents additional difficulties in estimating the reduced strength of a damaged member.

It was recognised that a dropped object will cause not only a dent but also bowing of the struck member. Depending on the energy of impact and member geometry, the magnitude of bowing may exceed the dent depth. As a consequence, MSL embarked on a series of studies to identify the degree of denting and bowing for the critical member(s) of each structure. The steps involved were:

- Identify critical member(s)

  This essentially involved identifying those members which participate in the pushover collapse mechanism and which could be exposed to a dropped object. Figures 1.1 to 1.4 indicate the selected critical members. For the Vierendeel structure, two members were considered worthy of study. However, a ship impact followed by a pushover analysis with the horizontal member removed gave no reduction in the reserve strength. This member was therefore eliminated from subsequent investigation.

- Determine denting characteristics

  To mimic the member denting process, a non-linear P-δ characteristic was obtained from the work of Pettersen and Johnsen[6].

- Structural analysis

  Non-linear analyses were conducted with a point load of increasing magnitude applied at the end of the dent spring. This allows the non-linear bowing response of member to be accurately established.

- Data reduction

  The P-bow relationship was extracted from the USFOS results and entered into an EXCEL spreadsheet, together with the P-dent relationship. These relationships are shown in Figure 2.1. Numerical integration of the area under each curve gave the absorbed energy for denting and bowing as a function of the impact load. The total energy was found by summation and, again, was related to impact load. The topmost diagrams in Figures 2.2 to 2.5 illustrate the absorbed energy for the four structures.

- Selection of energy levels

  The energy curves were inspected and two energy levels (ie. 0.5 MJ and 1.0 MJ) were selected for further processing. To put a perspective on these energy levels, 0.5 MJ corresponds to an object of 10 tonnes travelling at 10 m/s or 65 tonnes (eg. pile) at 4 m/s.

- Determine bow and dent depth

  The maximum impact loads, corresponding to the two energy levels, were then back-substituted into the P-bow and P-dent relationships. This determines the maximum bow and dent as given in Table 2.1 below. However, both bow and dent will be subject to elastic recovery. The residual bow and dent were found by unloading from the values at P_{max} along lines drawn parallel to the initial loading slope. The residual values are given in Table 2.2.

Structure	Impact member ϕ (m)	No elastic spring back considered				
		E = 0.5 MJ				
		Force (MN)	Bow (δ/D)	δ_{bow} (m)	Dent (δ/D)	δ_{dent} (m)
Monopod	0.900	2.450	0.085	0.077	0.245	0.221
Jacket	0.660	1.420	0.480	0.317	0.300	0.198
Vierendeel	0.762	2.190	0.350	0.267	0.061	0.047
Braced Caisson	1.524	3.100	0.110	0.168	0.065	0.099
		E = 1.0 MJ				
Monopod	0.900	2.950	0.170	0.153	0.350	0.315
Jacket	0.660	1.660	0.750	0.495	0.375	0.248
Vierendeel	0.762	2.260	0.530	0.404	0.660	0.503
Braced Caisson	1.524	4.200	0.150	0.229	0.105	0.160

Table 2.1: Maximum bows and dents

Structure	Impact member ϕ (m)	Elastic spring back considered				
		E = 0.5 MJ				
		Force (MN)	Bow (δ/D)	δ_{bow} (m)	Dent (δ/D)	δ_{dent} (m)
Monopod	0.900	2.450	0.006	0.005	0.185	0.167
Jacket	0.660	1.420	0.340	0.224	0.225	0.149
Vierendeel	0.762	2.190	0.120	0.091	0.028	0.021
Braced Caisson	1.524	3.100	0.000	0.000	0.032	0.049
		E = 1.0 MJ				
Monopod	0.900	2.950	0.090	0.081	0.270	0.243
Jacket	0.660	1.660	0.620	0.409	0.280	0.185
Vierendeel	0.762	2.260	0.310	0.236	0.032	0.024
Braced Caisson	1.524	4.200	0.000	0.000	0.062	0.094

Table 2.2: Residual bows and dents

The bow and dent values pertaining to E = 0.5MJ in Table 2.2 above were used to set the damage levels for subsequent analyses. The node at the impact point was translated in the USFOS model to represent the bow, and the dent was explicitly modelled.

It can be seen that the (pile) member for the braced caisson has suffered relatively minor denting and no bowing compared to the members in other structures. The jacket member is severely damaged. It is pertinent, perhaps, to see how the calculated values of bows and dents compare with measured values.

Figure 2.6 presents recorded dents, normalised with respect to member diameter, pertaining to the North Sea. These were taken from in-house data. The data have been categorised according to the cause: vessel collision or dropped object. It is seen that dents up to 0.3 of the diameter have occurred in practice. The calculated values in Table 2.2 lie very well with the measured values. Figure 2.7 presents measured bows. Again, the calculated values are in accord with the measured values.

2.4 Reliability Analysis

System reliability analyses were generally carried out using first order reliability methods (FORM).

The analyses were conducted with the aid of the VaP program[8], written by the Institute of Structural Engineering (ETH) in Zürich. The program was verified against an in-house package.

The limit state function (LSF) was defined in terms of base shear as follows:

$$LSF = X_{model} \cdot R_{init}\,(1 - f\,(M, v)) - X_{hydro}\,(\alpha\,(X_{wave} \cdot H)^{\beta}) - X_{mwind} \cdot X_{wind}\,WIND$$

where:

X_{model}	=	distribution factor for uncertainty in modelling
X_{hydro}	=	distribution factor for uncertainty in base shear
X_{wave}	=	probability distribution for wave height
X_{mwind}	=	distribution factor for uncertainty in wind force
X_{wind}	=	probability distribution for wind force
R_{init}	=	base shear for pushover of structure under factored 100 year storm load
f(M,v)	=	function to account for degradation of system strength due to ship impact (see below)
α, β	=	structure dependent parameters, fitted from analysis results, to relate base shear to wave height
H	=	mean value of the annual maximum wave height
WIND	=	base shear due to wind.

The function f(M,v) depends on the mass (M) and velocity (v) of the ship. The results of the analyses described in Sections 3 and 4 suggest that f(M,v) = 0 for all structures except the monopod. The Monopod structure failed during the ship impact for certain combinations of mass and velocity. The limit state failure function had a step, and was not amenable to FORM. The function is therefore detailed further under the discussions for the monopod in those sections. The vessel sizes which could visit a structure were modelled using a uniform (rectangular) distribution between 500 and

3500 tonnes. (This does not include the added mass which was taken into account during analyses.) For a given vessel the uncertainty in its mass was modelled using a normal distribution with a coefficient of variation of 0.15. The velocity of impact was taken to be exponentially distributed with a mean of 0.3 m/s and a standard deviation of 0.3 m/s.

The other distribution parameters have been defined in Reference 9. The distribution types and statistical values are summarised here for completeness, see Table 2.3. Pictorial representations of the distributions are given in Figure 2.8.

Variable	Distribution Type	Statistics
X_{model} (Modelling uncertainty)	Normal	Mean = 1.0 COV = 0.15
X_{hydro} (Base shear uncertainty)	Normal	Mean = 1.0 COV = 0.15
X_{wave} (Wave Ht. Distribution)	Gumbel	Mean = 1.0 COV = 0.097
X_{mwind} (Wind uncertainty)	Lognormal	Mean = 1.0 COV = 0.15
X_{wind} (Wind distribution)	Lognormal	Mean = 1.0 COV = 0.20
X_M (Ship mass distribution)	Rectangular	500 to 3500 t
X_{mship} (Ship uncertainty)	Normal	Mean = 1.0 COV = 0.15
X_v (Ship velocity dist.)	Exponential	Mean = 0.3 m/s St. dev. = 0.3 m/s

Table 2.3: Distribution types and parameters

3. RESULTS OF ANALYSES OF INTACT STRUCTURES

Preliminary Analyses

After model verification analyses, a number of preliminary analyses were conducted for the purposes of establishing:

- The α and β values relating the wave height to base shear (see Section 2.4).
- A baseline system strength (strength of intact structure not subjected to ship impact).

The results of these preliminary analyses are tabulated below.

Structure	α	β	Base Shear (MN)			Load Factor (λ)	RSR
			Wind	100yr wave and current	Factored 100yr wave and current		
Monotower	0.0208	1.795	0.346	3.147	11.675	3.71	3.44
Jacket	0.0511	1.798	0.420	7.749	23.635	3.05	2.94
Vierendeel	0.0238	1.881	0.374	4.604	12.707	2.76	2.63
Braced Caisson	0.0274	1.744	0.368	3.620	13.610	3.76	3.51

Table 3.1: Results from preliminary analyses

In the above, the load factor (λ) relates to the wave and current loading only; the 100 year storm values being increased until collapse occurs. The wind was held constant. The reserve strength ratio (RSR) was obtained as the total base shear at collapse divided by the total base shear for the 100 year storm.

The member failure sequences leading to collapse of the structures are indicated in Figures 3.1 to 3.4.

Ship Impact Results

A series of dynamic ship impact and subsequent pushover analyses were conducted to establish the degradation of system strength, if any, due to the impact. The results are presented in Table 3.2. For the range of vessel mass and velocities considered (500 to 3500 tonnes and up to 2.5 m/s) it can be seen that only the monotower's system strength was affected.

Structure and ship impact location	Ship Mass (Tonnes)	Ship Velocity (m/s)	Energy (MJ)	Dent (m)	d/D	Post Impact Pushover Strength λ
3P Monopod	1000	1.78	2.275	0.200	0.083	3.71
Caisson ϕ=2.400m	1000	2.00	2.870	0.270	0.113	"
+4.0m	1000	2.50	4.488	0.370	0.150	"
	1000	3.25	7.585	0.600	0.250	3.65
	1000	3.30	7.821	-	-	Failed during impact
	2500	1.78	5.687	0.420	0.180	3.71
	2500	2.00	7.180	0.550	0.230	"
	2500	2.35	9.915	0.600	0.250	3.445
	2500	2.50	11.219	-	-	Failed during impact
	3500	1.50	5.654	0.440	0.180	3.71
	3500	1.78	7.962	0.580	0.240	"
	3500	1.90	9.074	0.600	0.250	3.65
	3500	2.00	10.052	-	-	Failed during impact
4 Legged Jacket	1000	1.50	1.800	0.580	0.410	3.05
Leg ϕ=1.422m	1000	2.00	3.200	0.870	0.610	"
-2.0m	1000	2.50	5.000	1.000	0.700	"
	2500	1.25	3.125	0.870	0.610	"
	2500	1.50	4.500	1.000	0.700	"
	3500	1.10	3.388	0.870	0.610	"
	3500	1.25	4.375	1.000	0.700	"
	3500	2.50	17.500	1.000	0.700	"
Vierendeel	1000	1.00	0.800	0.070	0.083	2.76
Column ϕ=0.840m	1000	2.00	3.200	0.375	0.446	"
-2.0m	3500	2.00	11.200	0.588	0.700	"
	3500	2.50	17.500	0.588	0.700	"
Braced Caisson	1000	1.00	0.719	0.058	0.030	3.76
Column ϕ=2.134m	1000	2.00	2.876	0.315	0.150	"
+2.0m	3500	2.00	7.876	0.800	0.370	"
	3500	2.50	12.306	1.000	0.470	"

Notes: 1) For each structure limit of denting is d/D=0.700
2) For 4 legged jacket removal of X-bracing for sternside. X bracing impact had no effect on reducing pushover strength.

Table 3.2: Summary of results from ship impact analyses (Intact Structures)

Figures 3.5 to 3.8 show typical responses of the four structures to ship impact. The figures relate to a ship mass of 3500 tonnes and, except for the monotower, an impact velocity of 2.5 m/s. For the monotower, collapse occurred with this velocity and therefore a lower value, 1.78 m/s, was used in Figure 3.5. The state of the structure in each figure is at the time when the force between the ship and structure is at or near the maximum value. Significant distress of the bracing members can be seen in the monotower, Figure 3.5, which is indicative of imminent collapse. The struck jacket leg in Figure 3.6 shows a well-developed plastic hinge mechanism, but other members do not appear to be unduly distressed. A well-developed hinge mechanism also occurs in the Vierendeel, Figure 3.7. Plastic hinges also form at the top of the piles in the braced caisson, but no mechanism is formed, see Figure 3.8.

For the monotower, certain combinations of ship mass and velocities led to structural collapse during impact. Additional analyses were undertaken so that the failure surface could be mapped out. An approximation to the failure surface, in terms of ship mass and velocity, is illustrated in Figure 3.9 and is given by:

$$f_s = -M + 411.5\,v^2 - 3971\,v + 9560$$

When f_s is less than zero, the monotower fails under ship impact. When f_s is greater than zero, the structure withstands the ship impact with little or no degradation of system strength under subsequent pushover analysis. It is only when the failure surface is closely approached that system strength is affected. This indicates that the surface describing system strength is flat until a near-vertical cliff, representing f_s, is met.

Reliability Analyses

Reliability analyses were conducted using the limit state function presented in Section 2.4. For all structures, except the monotower, the f(M,v) term was set to zero. For the monotower, a continuous function f(M,v) was sought which could approximate the step function (ie. the cliff) observed in the pushover results. The following function, based on tanh x, was derived:

$$f(M,v) = 0.5\,(\tanh(L\,(X_M.X_{Mship} - 411.5\,X_v^2 + 3971X_v - 9560)) + 1)$$

where L is an arbitrary large number that controls the steepness of the cliff

X_M is the probability distribution of the ship mass

X_{Mship} is the distribution factor for uncertainty in mass

X_v is the probability distribution of the ship's velocity.

It was discovered that the above limit state function for the monotower gave rise to numerical difficulties for FORM. Consequently, the limit state function was split into two parts: one dealing with the reliability assuming no ship impact and the other with the reliability given an impact. For the later, the limit state function was based on f_s defined above but with the probabilistic distributions assigned to M and v. The probability of failure given an impact was calculated as 6.36 E-04. In Task II.2, the probability of impact was established as 9.0E-03 per annum based on historic collision data for North Sea structures. Combining these two probabilities gives an overall probability of failure due to ship impact of 5.72E-06 equivalent to a reliability index of 4.39.

The results of the reliability analyses, in terms of the β index and probability of failure, are tabulated below.

Structure	β Index	Annual Probability of Failure
Monotower (no ship impact)	5.13	0.15×10^{-6}
Monotower (given ship impact)	4.39	5.72×10^{-6}
Jacket	4.72	1.2×10^{-6}
Vierendeel	4.46	4.0×10^{-6}
Braced Caisson	5.18	0.11×10^{-6}

Table 3.3: Results from reliability analyses

4. RESULTS OF ANALYSES OF DAMAGED STRUCTURES

Ship Impact Results

Using the methodology set out in Section 2.3, damage in the form of a bow and a dent arising from a dropped object having a kinetic energy of 0.5MJ was put into each structure. The pre-damaged structures were then subjected to dynamic ship impact analyses and subsequent pushover analyses.

The ship impact and pushover analyses were conducted in a similar manner to that used for intact structures in Section 3. The results are presented in Table 4.1. Once again, it is only the monotower that appears to be affected by damage.

It may seem surprising at first that the other three structures are not affected. However, inspection of the table shows that only relatively minor damage from the dropped object was sustained by the Vierendeel and Braced Caisson structures. The jacket member, on the other hand, suffered significant damage both in bow and dent size. A check analysis was therefore performed with the impacted member removed from the jacket model. The resulting load factor λ from the check run (3.00) was found to be close to the value obtained from the complete, intact, configuration (3.05). It can therefore be concluded that the dropped object damage, although quite severe, is not that important from a system reserve strength standpoint.

The monotower proved to behave in a more complex manner. It will be recalled from Section 3 that, provided the structure survived the ship impact, the pushover load factor (λ) was 3.71. The load factors in Table 4.1 all lie below this value but approach it for the higher mass collisions. A run with an extremely low ship energy gave a result of 3.46 and clearly the dropped object damage has a deleterious effect on the pushover strength. This confirms that the damaged member is truly a critical member in the pushover collapse mechanism. What is more difficult to understand is the variation between 3.46 and 3.71. The bow damage is very small (ie. 5mm) and the dent depth is fixed at 0.185D during the ship impact and subsequent pushover analysis. Therefore geometric effects, such as straightening of the bow and/or dent, can be discounted. Interrogation of the USFOS output files suggests that a ship impact introduces a degree of prestraining in the member, depending on the ship mass and impact velocity. Due to the dynamic nature of the structure, the prestraining mainly occurs when the structure rebounds and this induces tensile prestraining of the damaged member. During the pushover analysis compression in the damaged member is only induced when sufficient load is acting to overcome the tensile prestrain. The higher the prestrain, the higher the pushover load can be sustained. Since ships of higher mass tend to lead to greater rebound and prestraining, collisions involving them tend to lead to higher load factors.

It is also noted that, for the monotower, the results were numerically sensitive to input values, eg. changing the ship velocity by just 0.05m/s sometimes changed the load factor by an equivalent amount. This leads to a 'bumpy' failure surface. In the following reliability analyses, a smoothed load factor (λ) of 3.50 was adopted. This may introduce a small amount of conservatism as failure of the structure tends to be at higher ship mass and velocities, for which λ could be slightly greater.

Structure and Ship Impact Location	Damaged Member (1)		Ship Mass (Tonnes)	Ship Velocity (m/s)	Pushover Load Factor (λ)
	Bow (mm)	δ_{dent} / D			
3P Monotower, Caisson ϕ = 2.400m, + 4.0m	5	0.185	~ 0	~ 0	3.46
			1000	0.50	3.64
			1000	1.78	3.43
			1000	2.00	3.45
			1000	2.40	3.42
			1000	2.45	3.45
			1000	2.50	2.84
			1000	2.55	Failed during impact
			2000	0.50	3.65
			2500	0.50	3.62
			2500	1.50	3.67
			2500	1.60	3.63
			2500	1.65	3.33
			2500	1.70	Failed during impact
			3000	0.50	3.67
			3500	0.50	3.53
			3500	1.50	3.63
			3500	1.78	3.53
			3500	1.80	3.09
			3500	1.85	Failed during impact
Legged Jacket, Leg ϕ = 1.422m, - 2.0m	340	0.225	1000	1.50	3.05
			2500	1.50	3.05
			3500	2.50	3.05
	-	-	-	-	3.00(2)
Vierendeel, Column ϕ = 0.840m, - 2.0m	91	0.028	1000	1.0	2.76
			1000	2.0	2.76
			3000	2.0	2.76
			3500	2.5	2.76
Braced Caisson, Caisson ϕ = 2.134m + 2.0m	0	0.032	3500	2.5	3.76

Notes:

1. See Figures 1.1 to 1.4 for damaged member location.

2. This pushover analysis was performed with the damaged member removed and with no ship impact.

Table 4.1: Summary of results from ship impact analyses (Damaged structures)

As before, certain combinations of ship mass and velocity lead to failure during the impact, see Figure 4.1 which also shows the intact structure results. For a ship mass of 3500 tonnes, the damaged and intact results lie close together. It is, perhaps, a manifestation of the numerical sensitivity of the results and not of real structural behaviour that enhances the damaged result. It was considered prudent to translate the parabola for the intact result so that it passes near the remaining two 'damaged' data values. The selected function to approximate the failure surface is:

$$f_s = -M + 411.5\,v^2 - 3971v + 8209$$

Reliability Analyses

Reliability analyses were only conducted for the monotower as the damage from the dropped object did not affect the pushover strength for the other three structures. The results given in Table 3.3 are again applicable for these three structures.

For the monotower, a similar two part FORM analysis as performed for the intact structure was carried out, see Section 3. The probability of failure given a ship impact was calculated as 0.00368. Combining this with the probability of an impact (9.0E-03) gives an overall probability of failure due to ship impact of 3.31 E-05 equivalent to a reliability index of 3.99.

The results of the reliability analyses, in terms of the β index and probability of failure, are tabulated below.

Structure	β Index	Annual Probability of Failure
Monotower (damaged, but no ship impact)	5.00	0.28×10^{-6}
Monotower (damaged given ship impact)	3.99	33.1×10^{-6}

Table 4.2: Results from reliability analyses

5. CONCLUSIONS

A ship impact study has been conducted on the reliability of three minimum structures and a standard 4-pile jacket, both for the intact structures and when the structures have been subjected to damage from a dropped object. The ship impact analyses have been based on the dynamic response of the structures. The following observations and conclusions can be drawn from the study.

- The baseline reliability of the four structures, ie. when they are not subject to ship impact or dropped object damage, are reasonably similar with the β index ranging from 4.5 to 5.2. This is not unexpected as all structures were designed for the same location and to the same metaocean data, with the intent that they had similar utilisations under 100 year storm loads.

- Ship impacts generally introduced dents at the impact locations. For the same value of ship kinetic energy, but different combinations of ship mass and velocity, various dent depths were obtained. This emphasises the need to consider the dynamic interaction between the ship and the structure.

- Although the dent must have a weakening effect on the struck member, the member did not participate in the collapse mechanism under pushover conditions. Therefore, provided the structure survived the ship impact itself, the reserve strength under subsequent pushover conditions remained unaffected.

- For certain impact cases, very high dent depths (up to 0.7 of the member diameter) were obtained without global collapse and without a significant influence on the pushover capacity. In reality, the well conductors and risers within the impacted member may be severely damaged before these dent depths are reached. In order to capture this effect correctly a detailed modelling of the conductor package would be necessary. There is also a danger that following this approach would make the results specific to the system used. Therefore, it was agreed by the Project Steering Committee that the impact analysis would ignore the presence of conductors/risers and aim to determine the maximum capacity of the structures to withstand ship impact. If necessary, the Operators can set a lower limit taking into account the exact configuration of the conductor/riser system.

- For the range of ship mass (500-3500 tonnes) and velocities (up to 2.5m/s) considered, only the monotower structure failed during the ship impact event (for certain M and v combinations). This had the effect of reducing the baseline reliability (β index) for this structure from 5.1 to 4.4.

- A sub-study was conducted to determine the levels of damage (bows and dents) that would be sustained by each structure when hit by a dropped object of given energy. Increasing levels of damage were sustained by the braced caisson, vierendeel, monotower, and jacket structures respectively. The jacket structure, in particular, had significant bowing and denting. The levels of damage were shown to be consistent with measured data.

- The ship impact analyses were repeated for the damaged structures. It was again found that only the monotower appeared to be affected by the incorporated damage. The monotowers reserve strength was generally degraded (from the baseline intact structure value) and also the size of the envelope of ship mass and velocity combinations that would induce collapse during the impact event was increased.

- Although minimum structures are generally thought of as non-redundant structures, the fact that even significant damage can be sustained without affecting reserve strength points to redundancy in the framing at the foundation level.

In summary, all structures except perhaps the monotower have proven to be robust against ship impacts with or without damage caused by dropped objects. Even for the monotower, the reliability index remains at a comfortably high level. However, it should be noted that the above conclusions are based on not limiting the dent depth which, in some cases, reached 0.7 of the diameter of the struck member. No account was made of possible damage which could be caused to the conductors/risers within the impacted member (caisson/leg).

REFERENCES

1. "Joint Industry Project: Comparative Evaluation of Minimum Structures and Jackets. Invitation for Sponsors." Proposal prepared by WS Atkins, University of California, MSL Engineering, Ramboll, Doc. Ref. AM7565/JIPMIN/Rev. 2, October 1996.

2. Ramboll. "Conceptual Design – Summary Report." Doc. Ref. 340_005, January 1999.

3. Ramboll. "Design Premises." Rev 0, September 1997. (Attached to Ramboll fax dated 25 September 1997).

4. Hellan, Ø., Moan, T. and Drange, S. "Use of Nonlinear Pushover Analyses in Ultimate Limit State Design and Integrity Assessment of Jacket Structures." Behaviour of Offshore Structures Conference, BOSS '94, Massachusetts, 1994.

5. MSL Engineering Limited. "Collision Database Study". Doc. Ref. C223R001 Rev 2, May 1999.

6. Pettersen, E. and Johnsen, K.R. "New Non-Linear Methods for Estimation of Collision Resistance of Mobile Offshore Units." OTC Paper 4135, Offshore Technology Conference, May 1981.

7. Det Norske Veritas. "Load Impacts from Boats." DNV Technical Note TN A202, 1981.

8. ETH (Institute of Structural Engineering). "VaP 1.6 for Windows." Program Manual. Zurich.

9. WS Atkins. "Probabilistic Modelling of Environmental Loading". Doc. Ref. WSA/AM3681/Tech Note. I.2.2-1, December 1997.

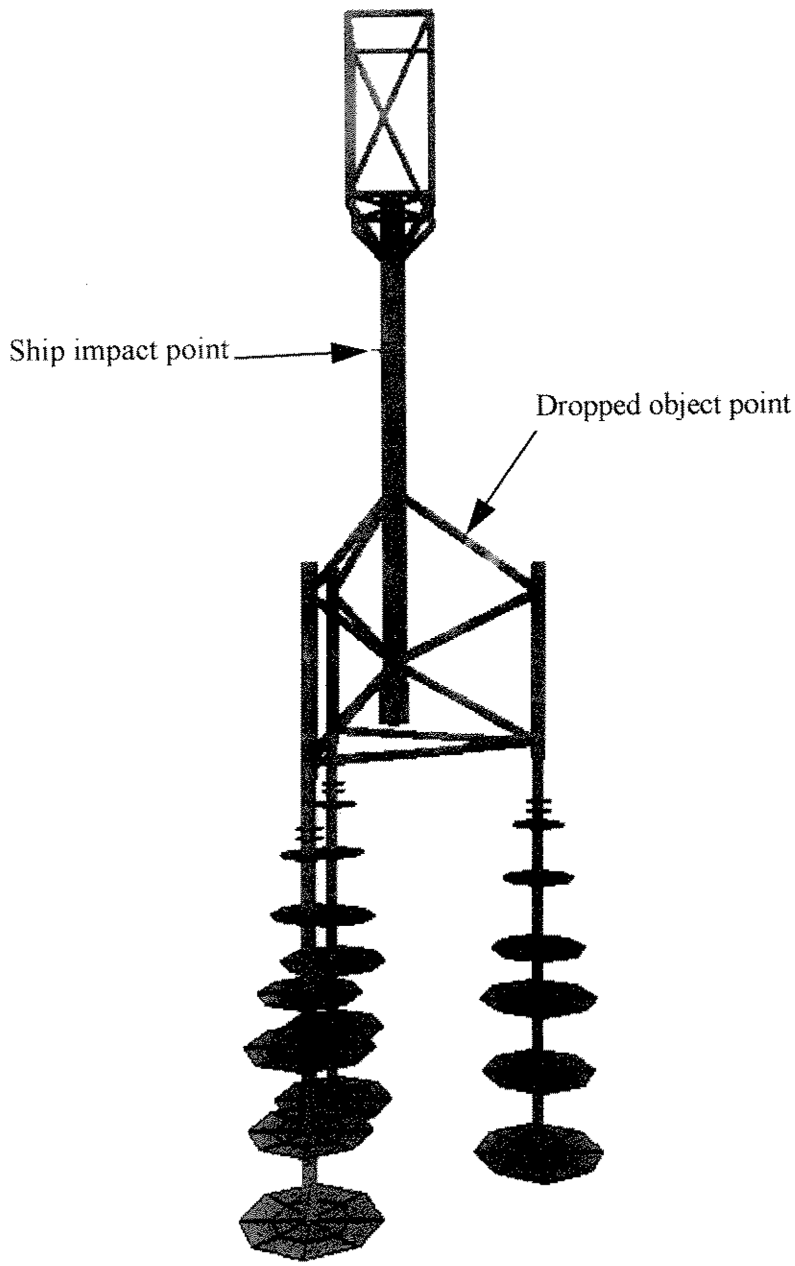

Figure 1.1: 3-pile monotower with ship impact and dropped object locations

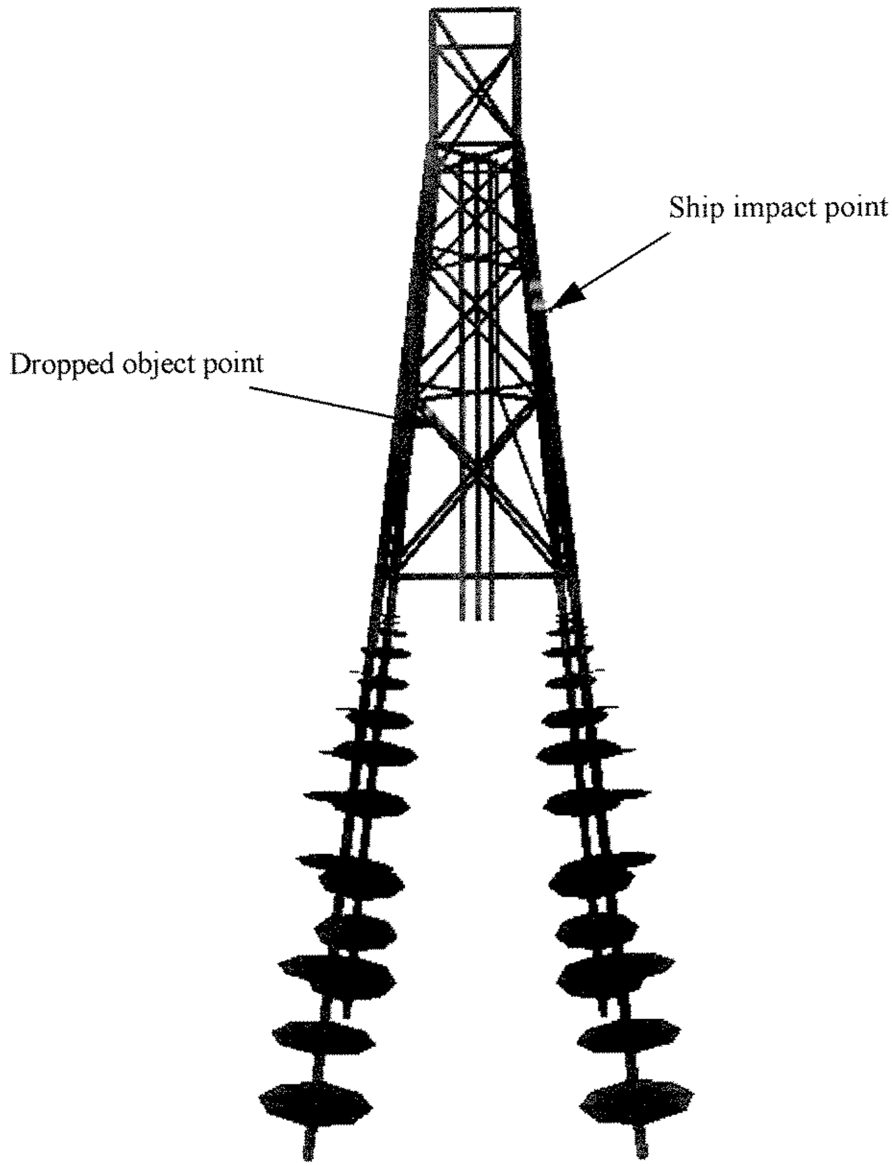

Figure 1.2: 4-legged jacket with ship impact and dropped object locations

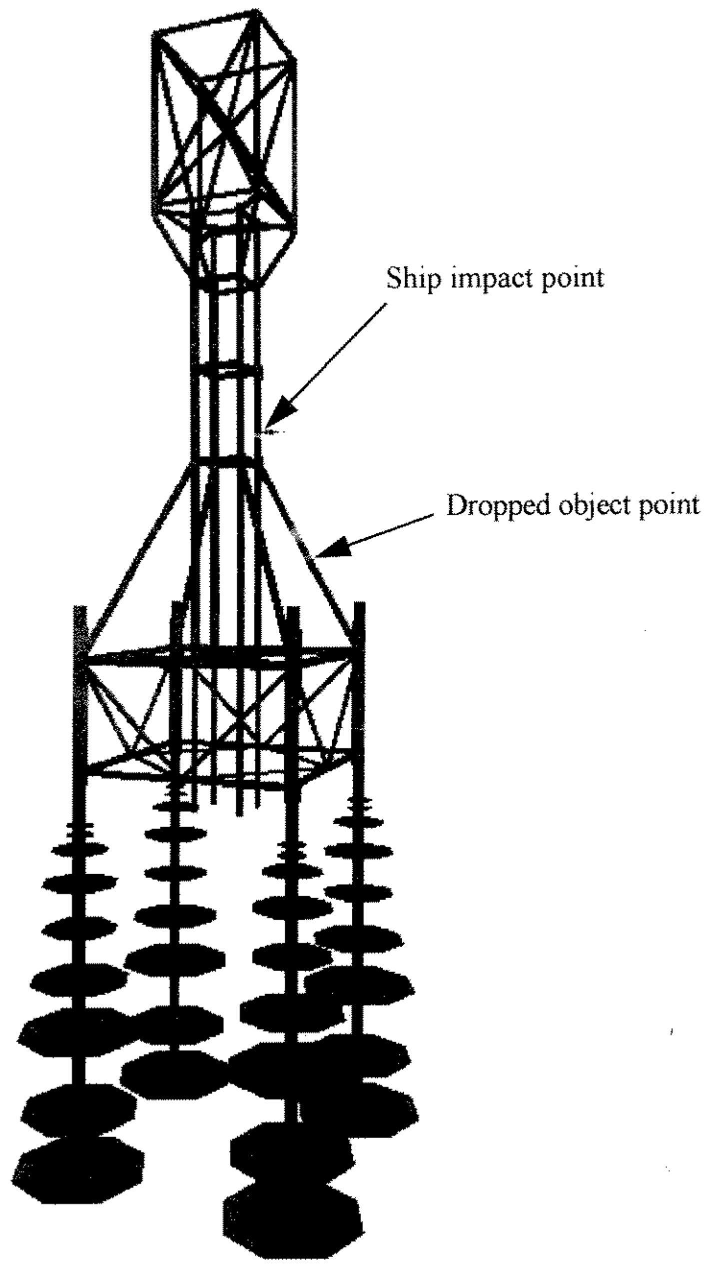

Figure 1.3: Vierendeel with ship impact and dropped object locations

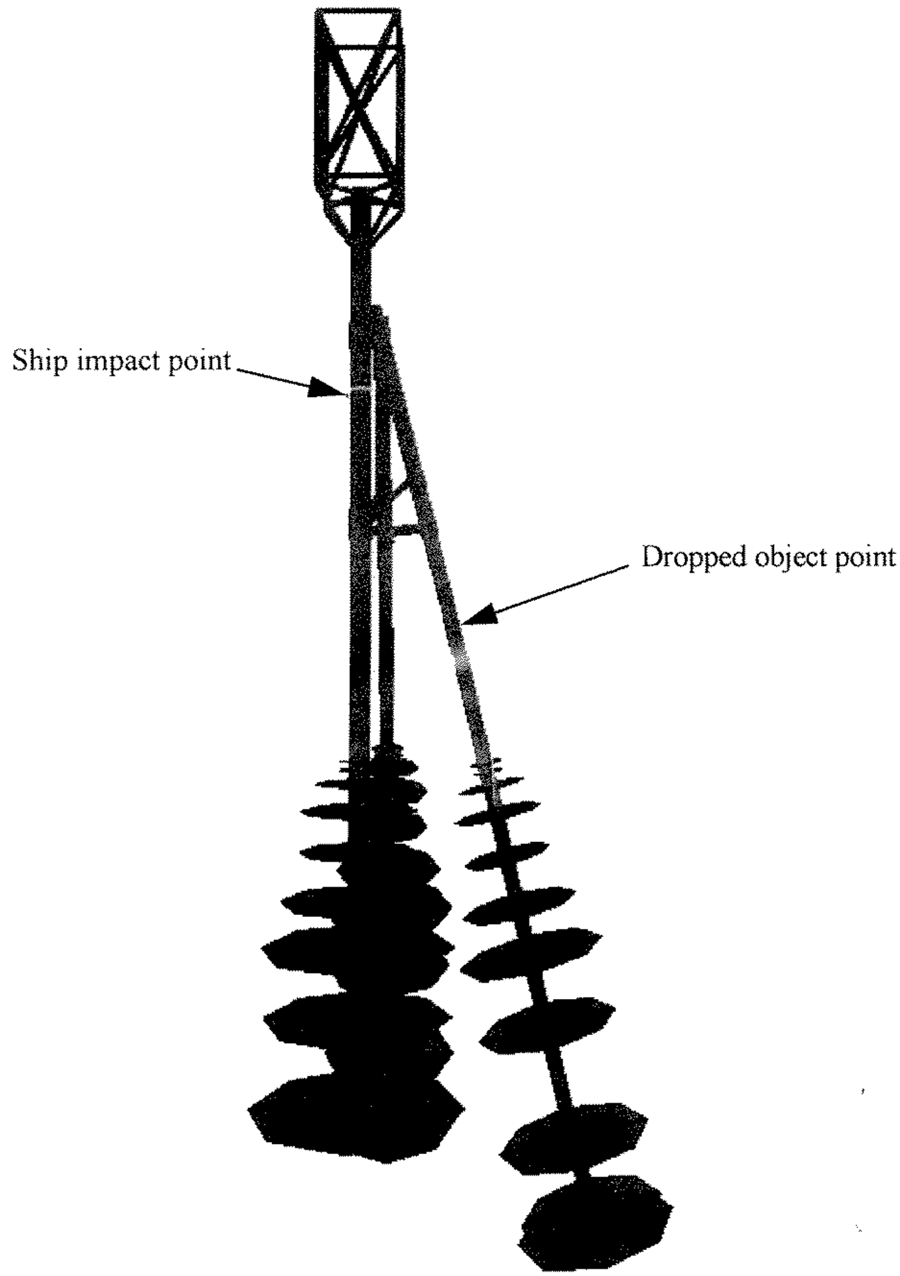

Figure 1.4: Braced caisson with ship impact and dropped object locations

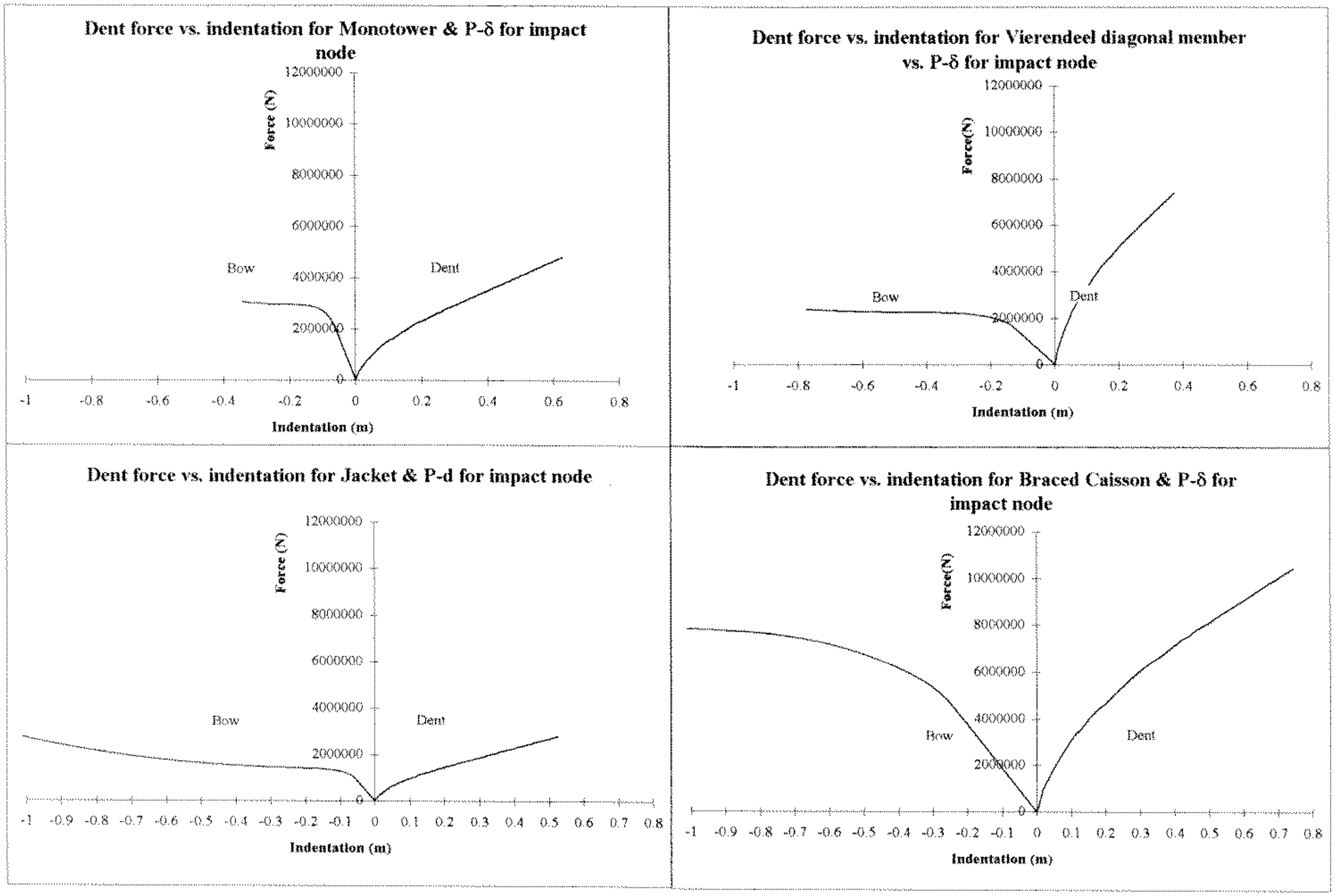

Figure 2.1: Dropped Objects: P-dent and P-bow relationships

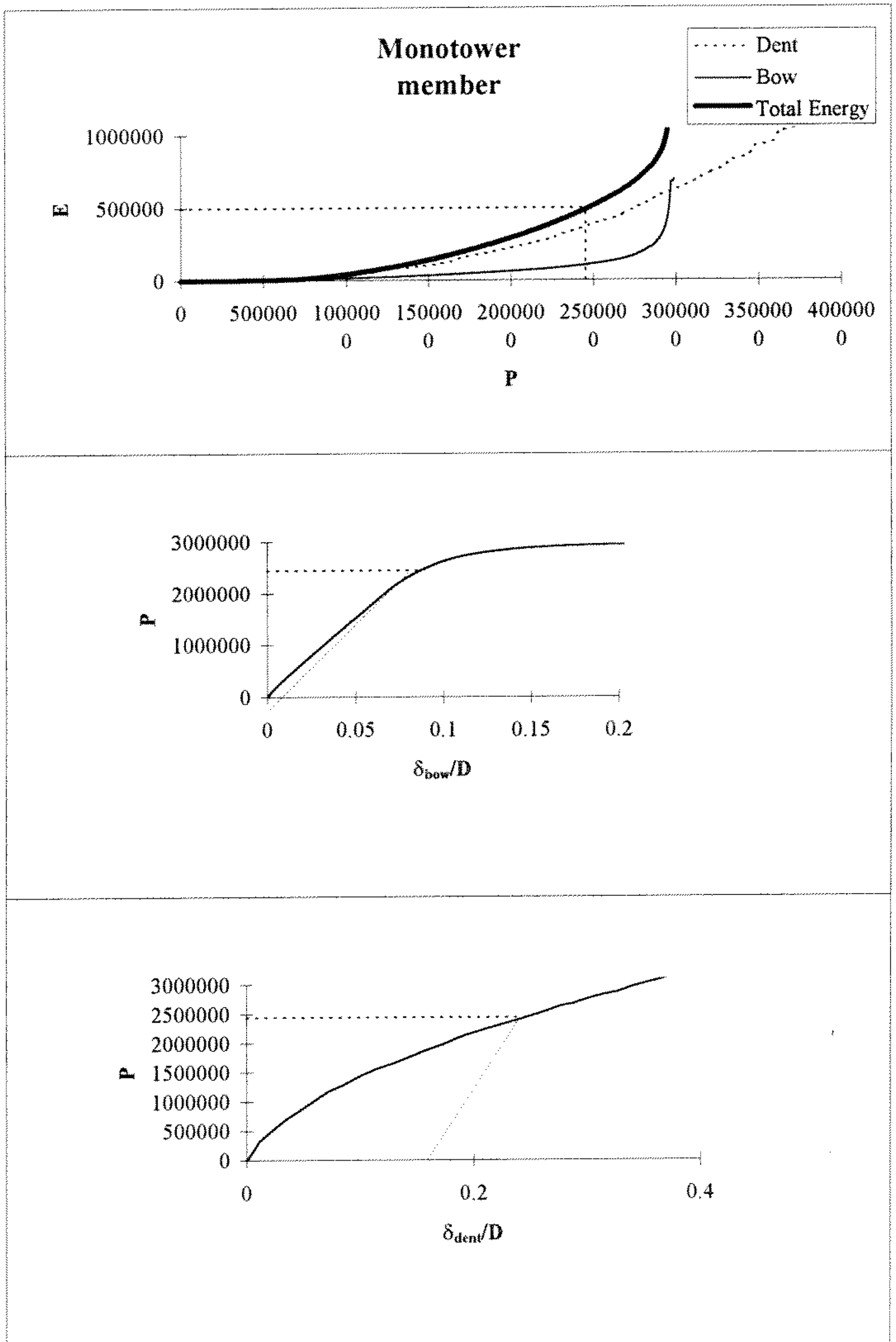

Figure 2.2: 3-Pile monotower: establishment of dent and bow

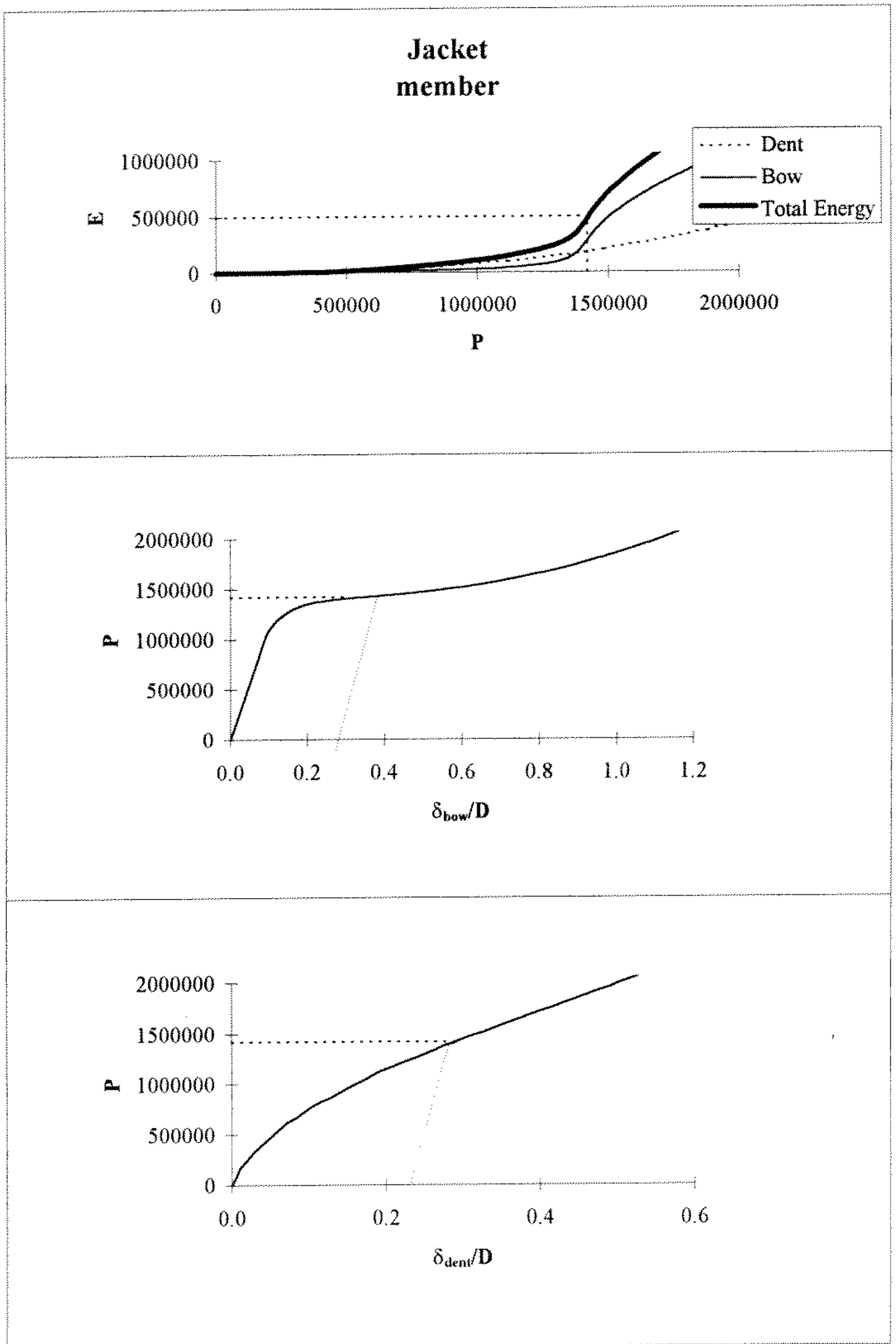

Figure 2.3: 4-Legged jacket: establishment of dent and bow

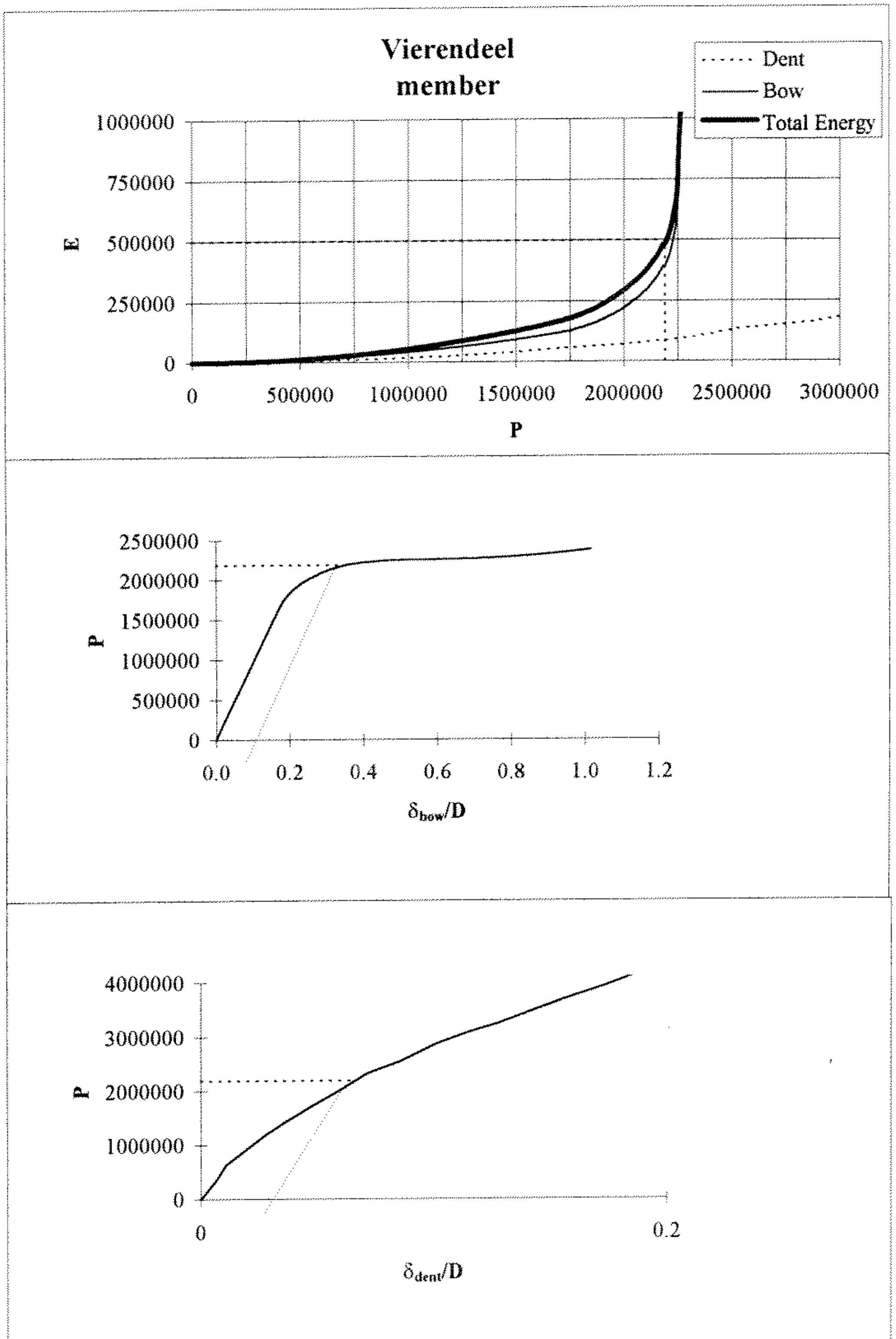

Figure 2.4: Vierendeel tower: establishment of dent and bow

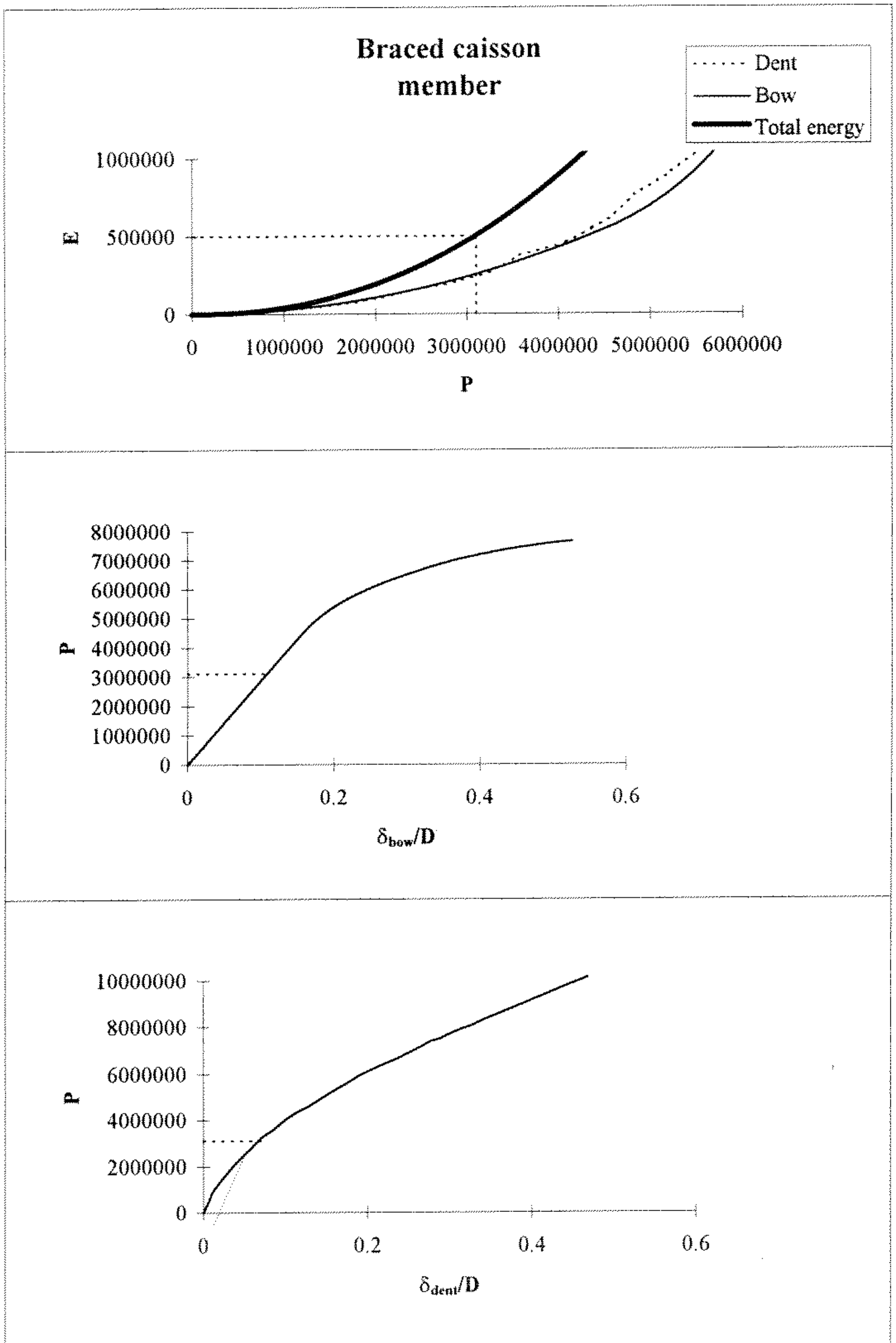

Figure 2.5: Braced caisson: establishment of dent and bow

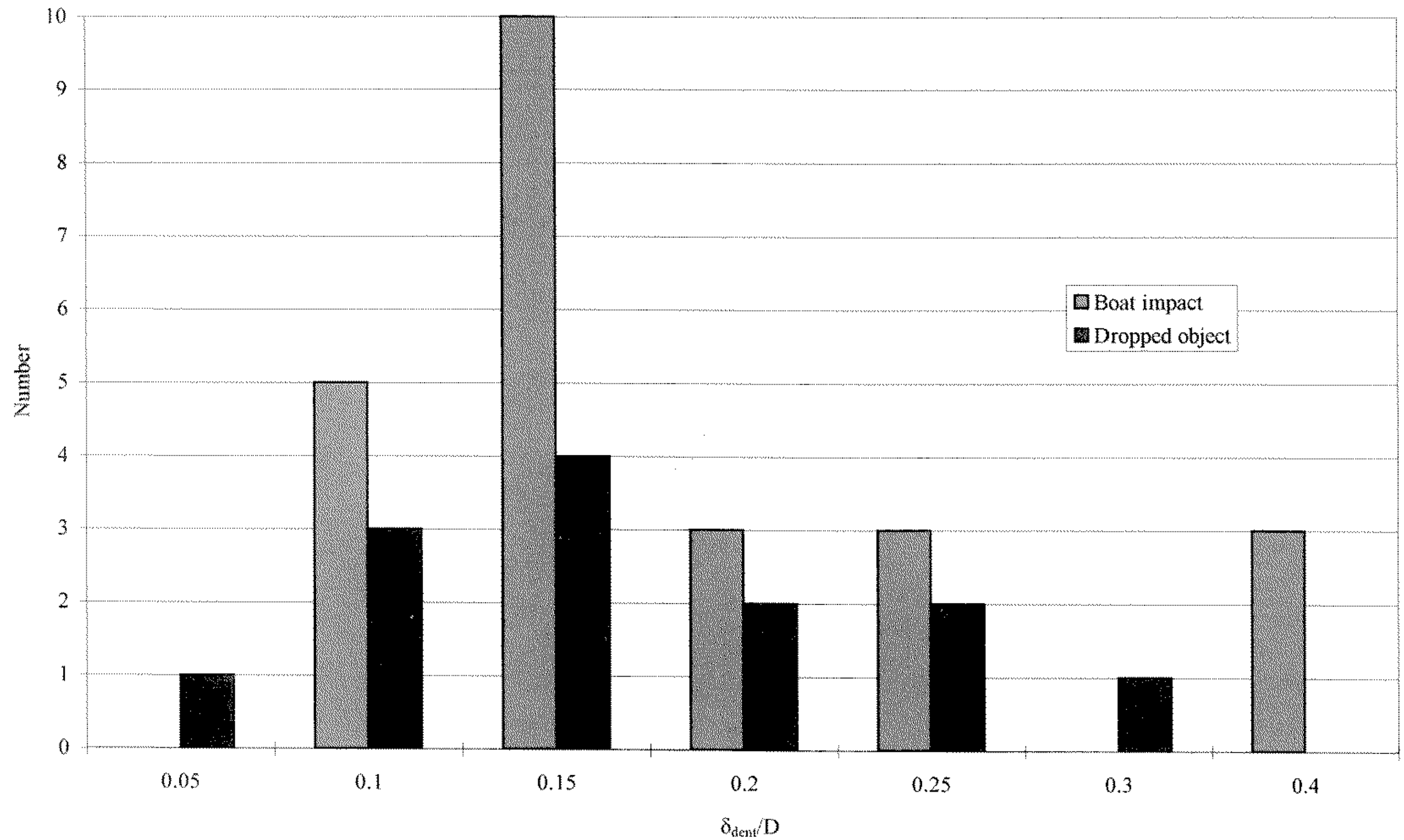

Figure 2.6: Measured values of dent/diameter ratios

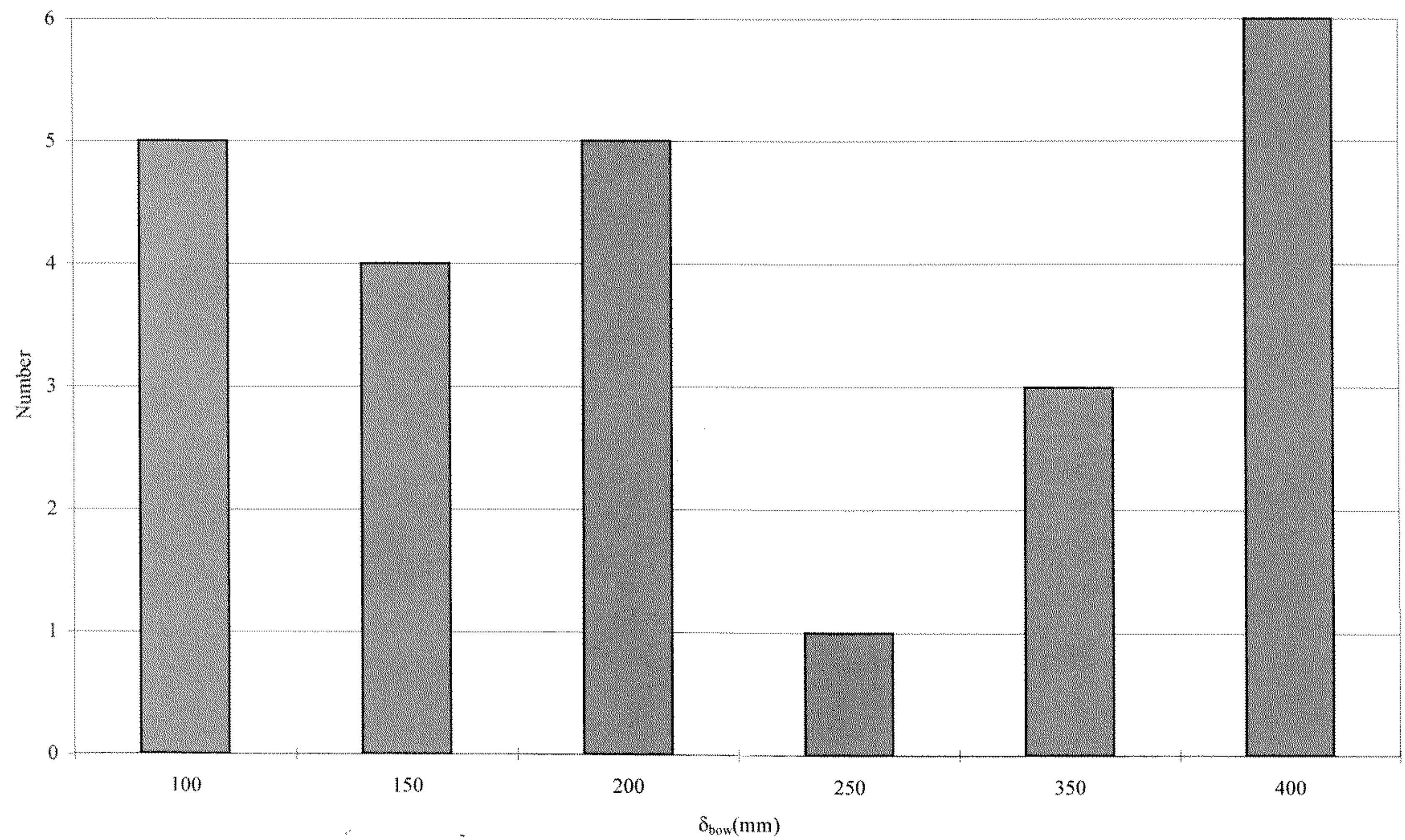

Figure 2.7: Measured values of bows

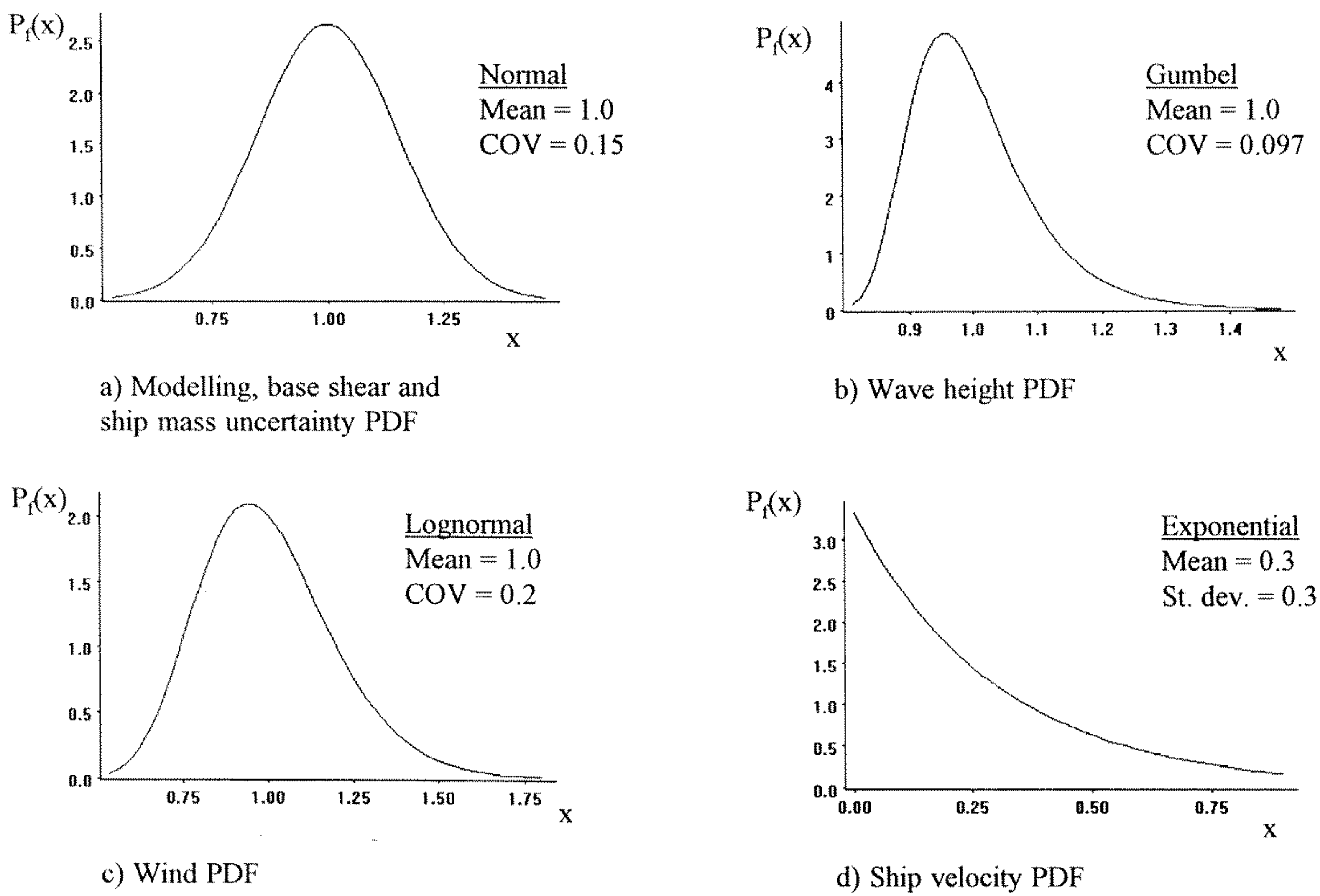

Figure 2.8: Probability distribution function (PDF)

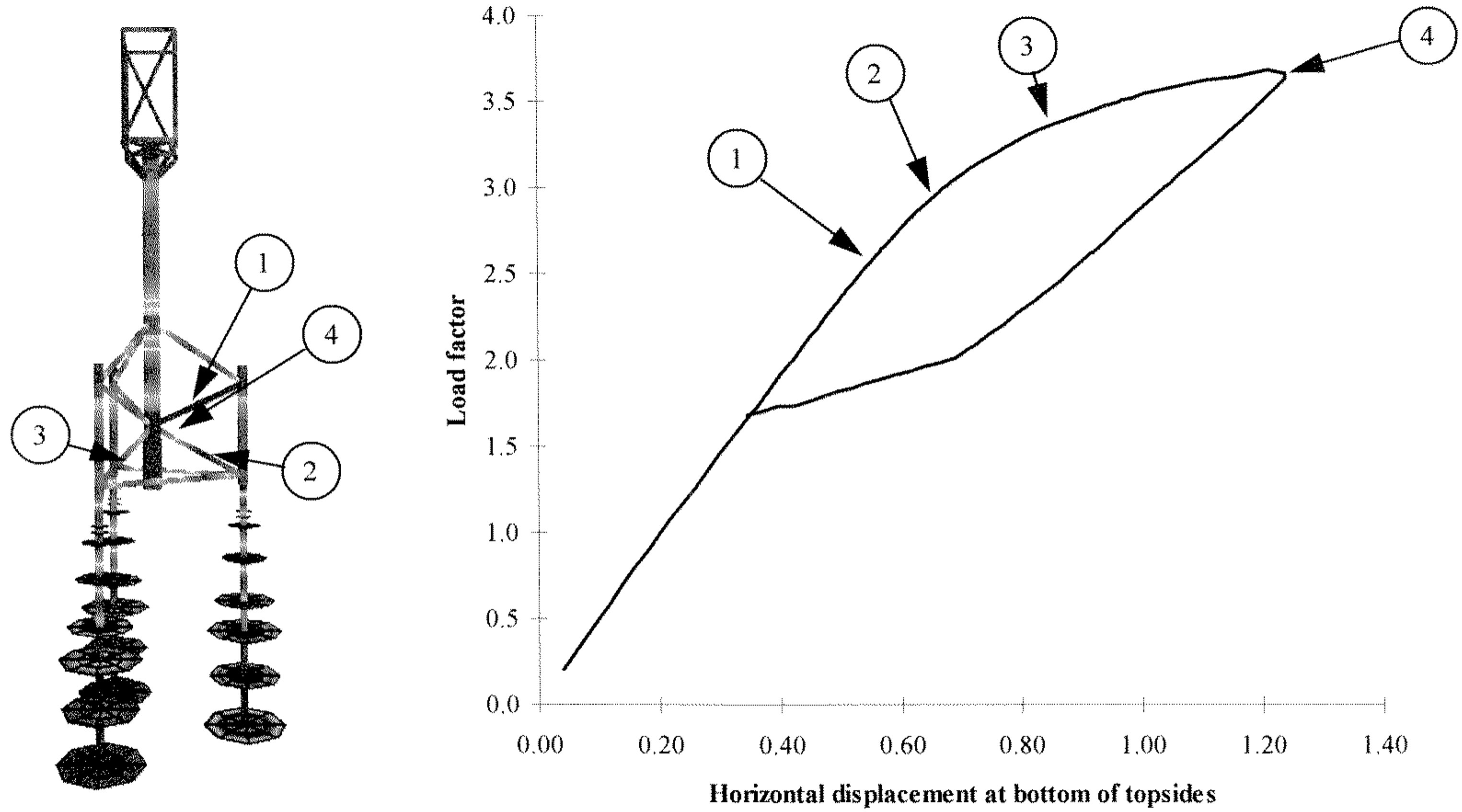

Figure 3.1: Failure sequence for monotower structure

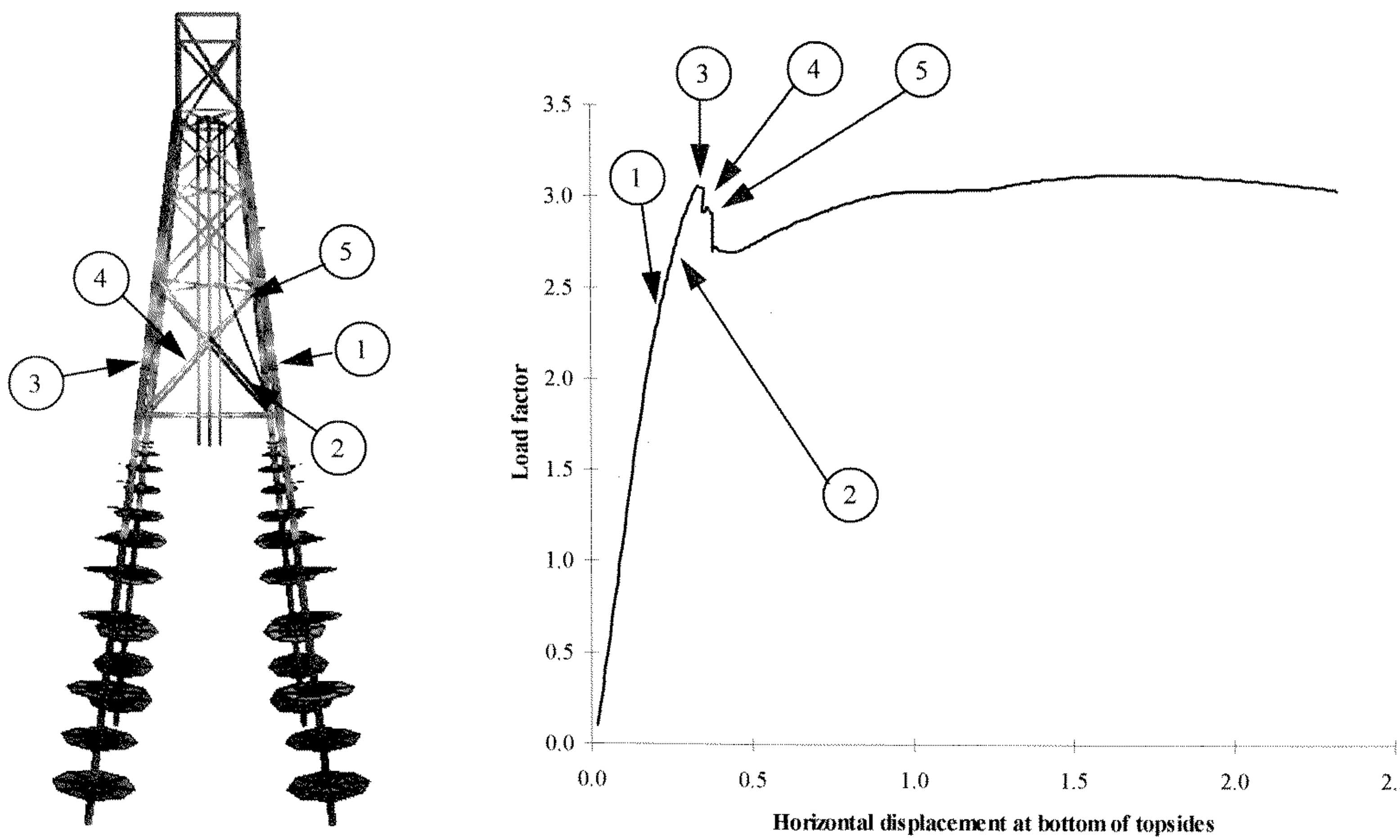

Figure 3.2: Failure sequence for jacket structure

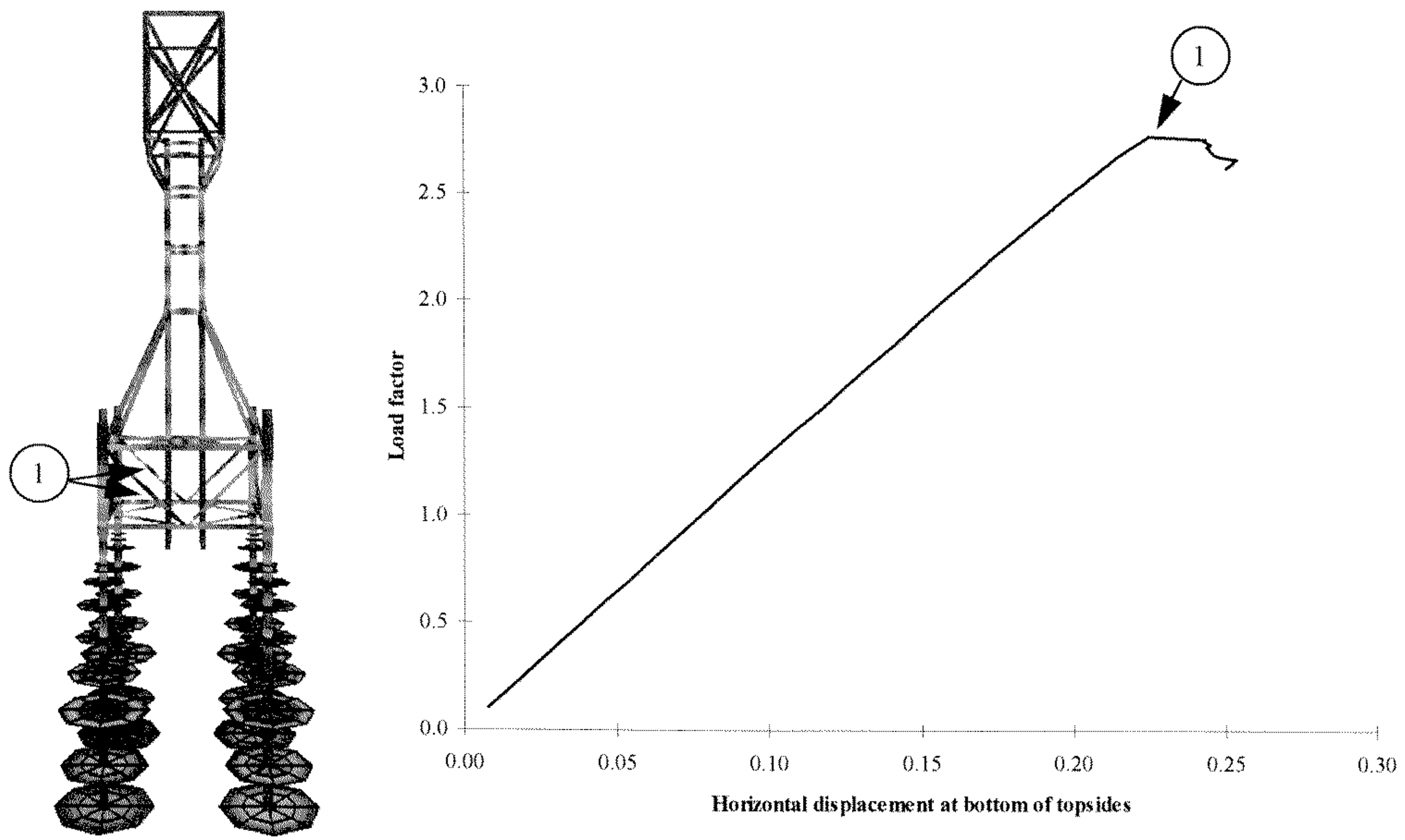

Figure 3.3: Failure sequence for vierendeel

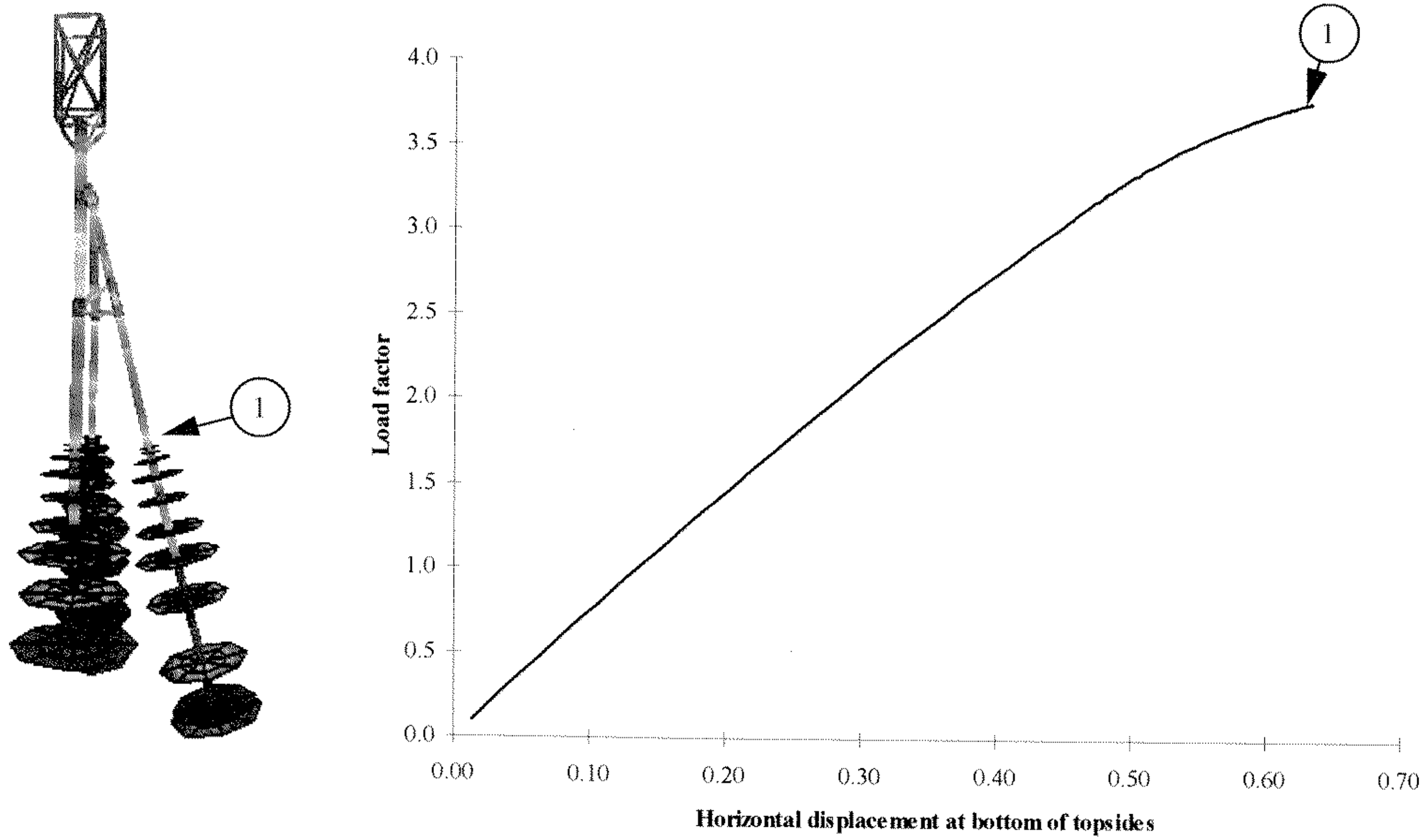

Figure 3.4: Failure sequence for braced caisson

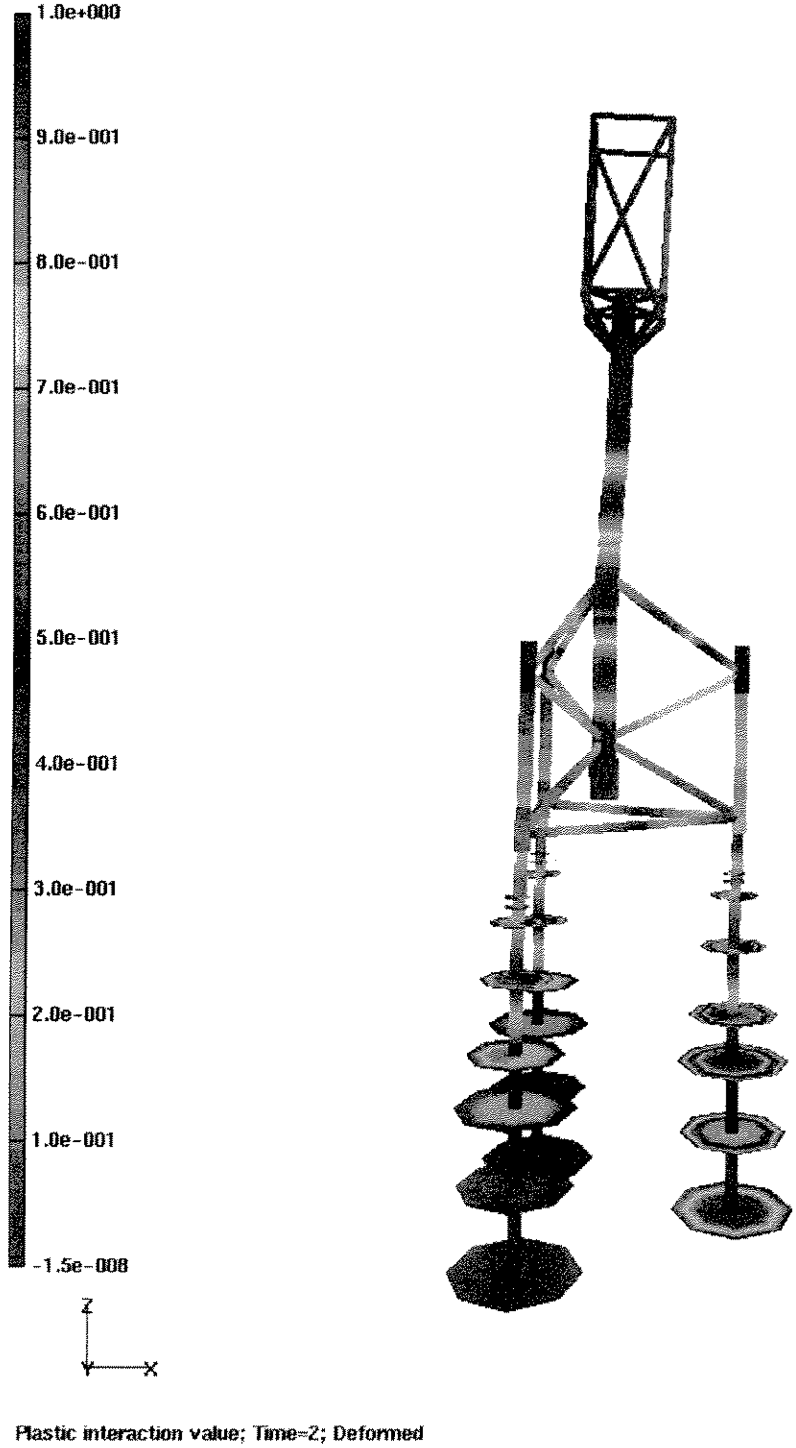

Figure 3.5: Monotower under ship impact (M=3500t, v=1.78m/s, deformation magnification factor = 3.0)

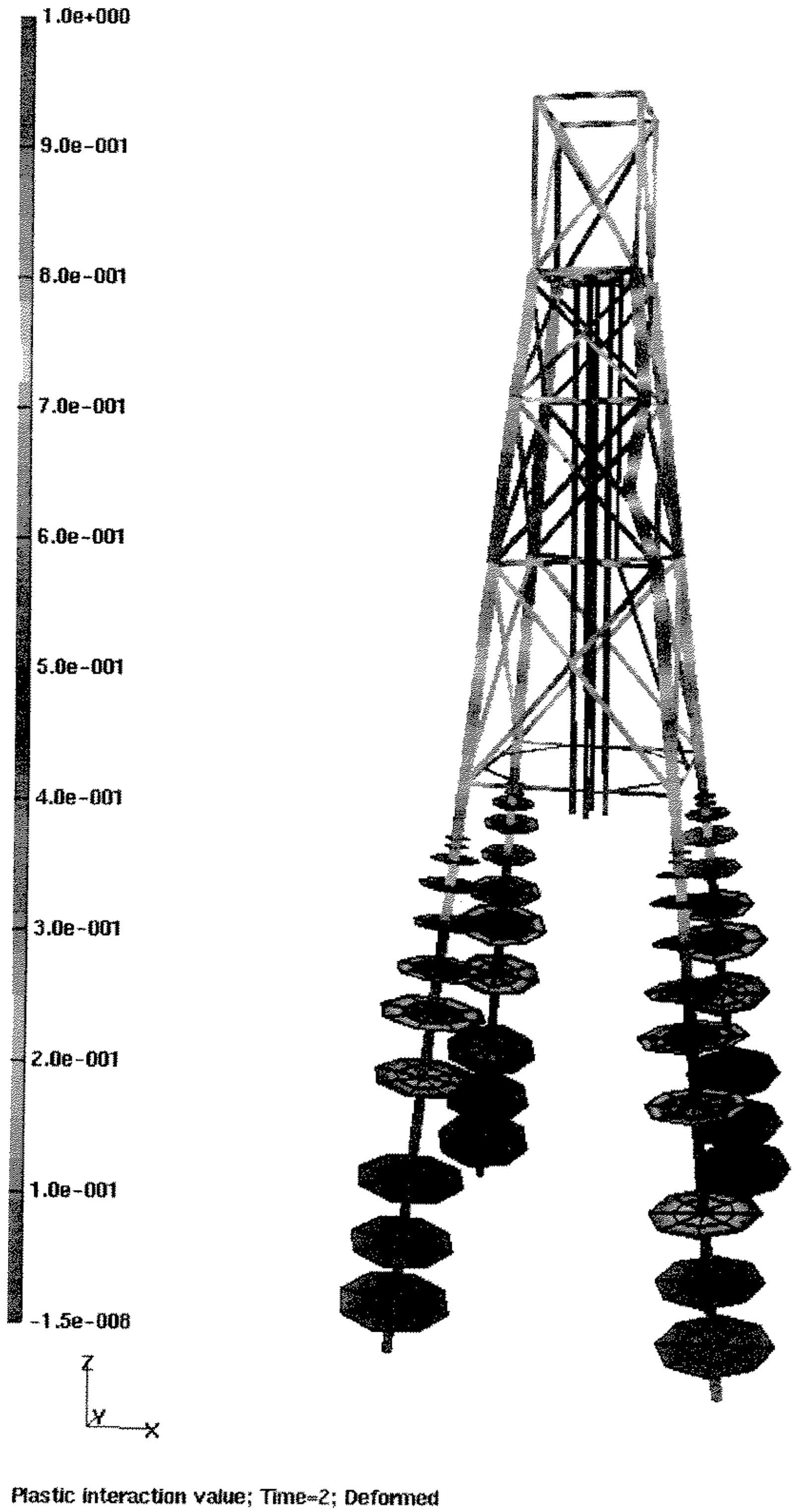

Figure 3.6: Jacket under ship impact (M=3500t, v=2.50m/s, deformation magnification factor = 3.0)

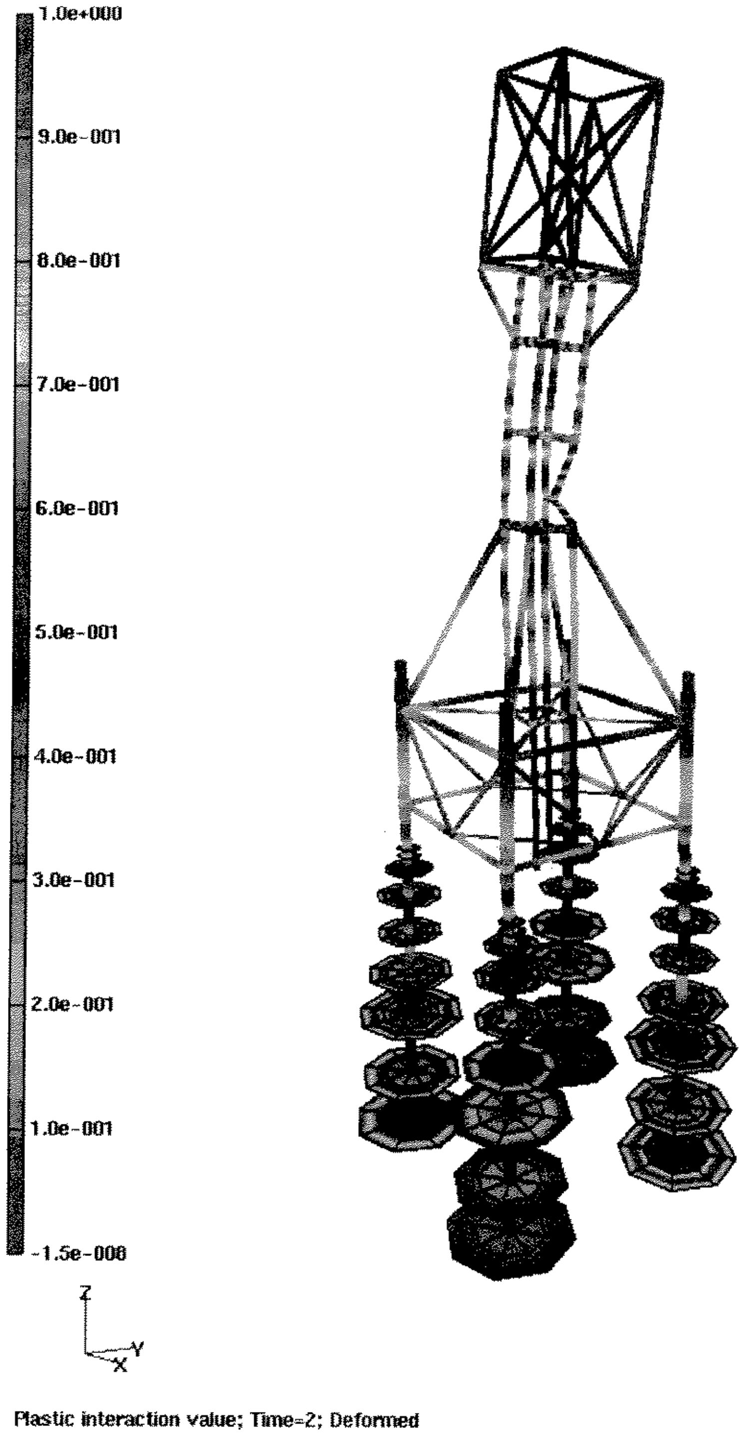

Figure 3.7: Vierendeel under ship impact (M=3500t, v=2.50m/s, deformation magnification factor = 3.0)

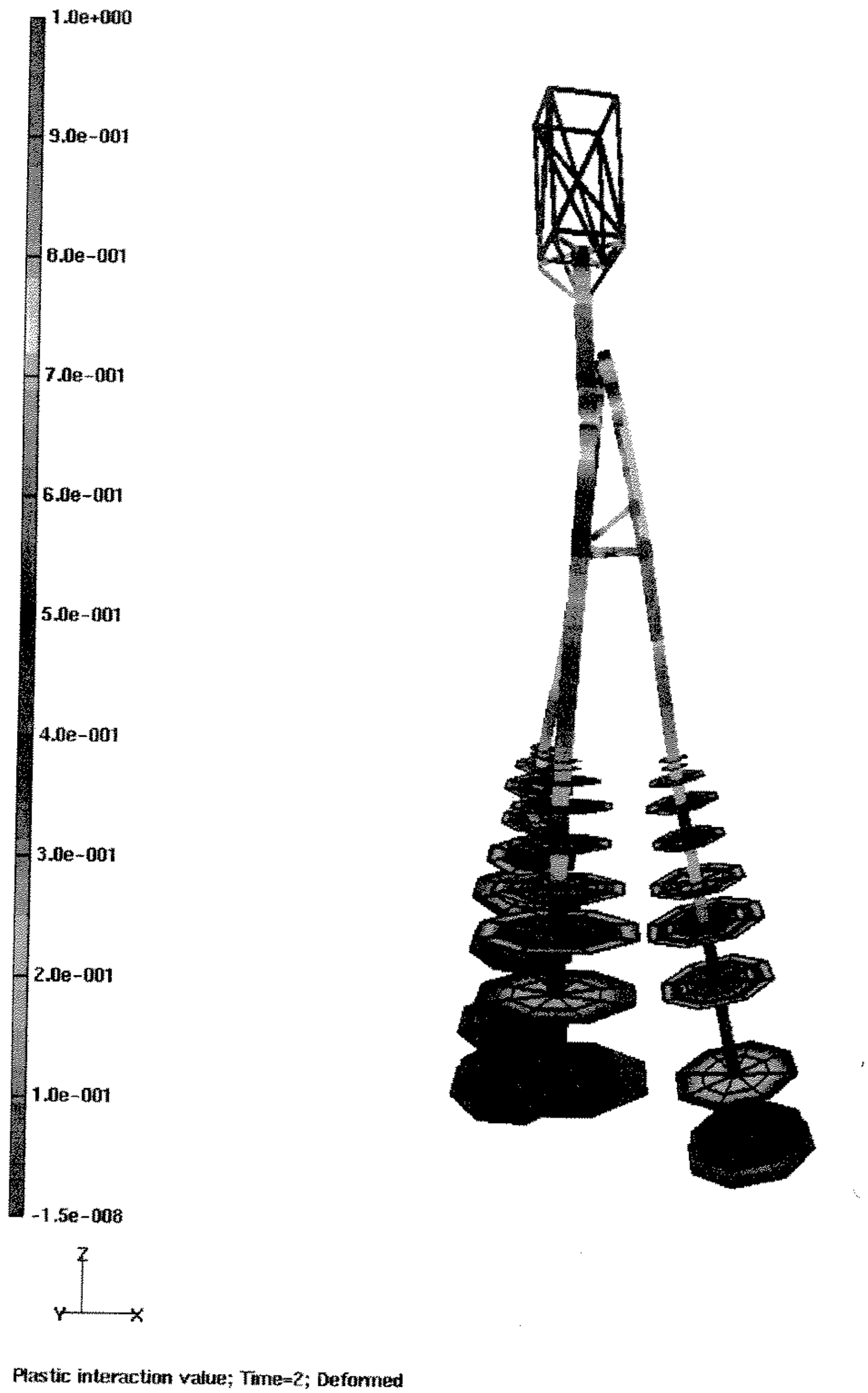

Figure 3.8: Braced Caisson under ship impact (M=3500t, v=2.50m/s, deformation magnification factor = 3.0)

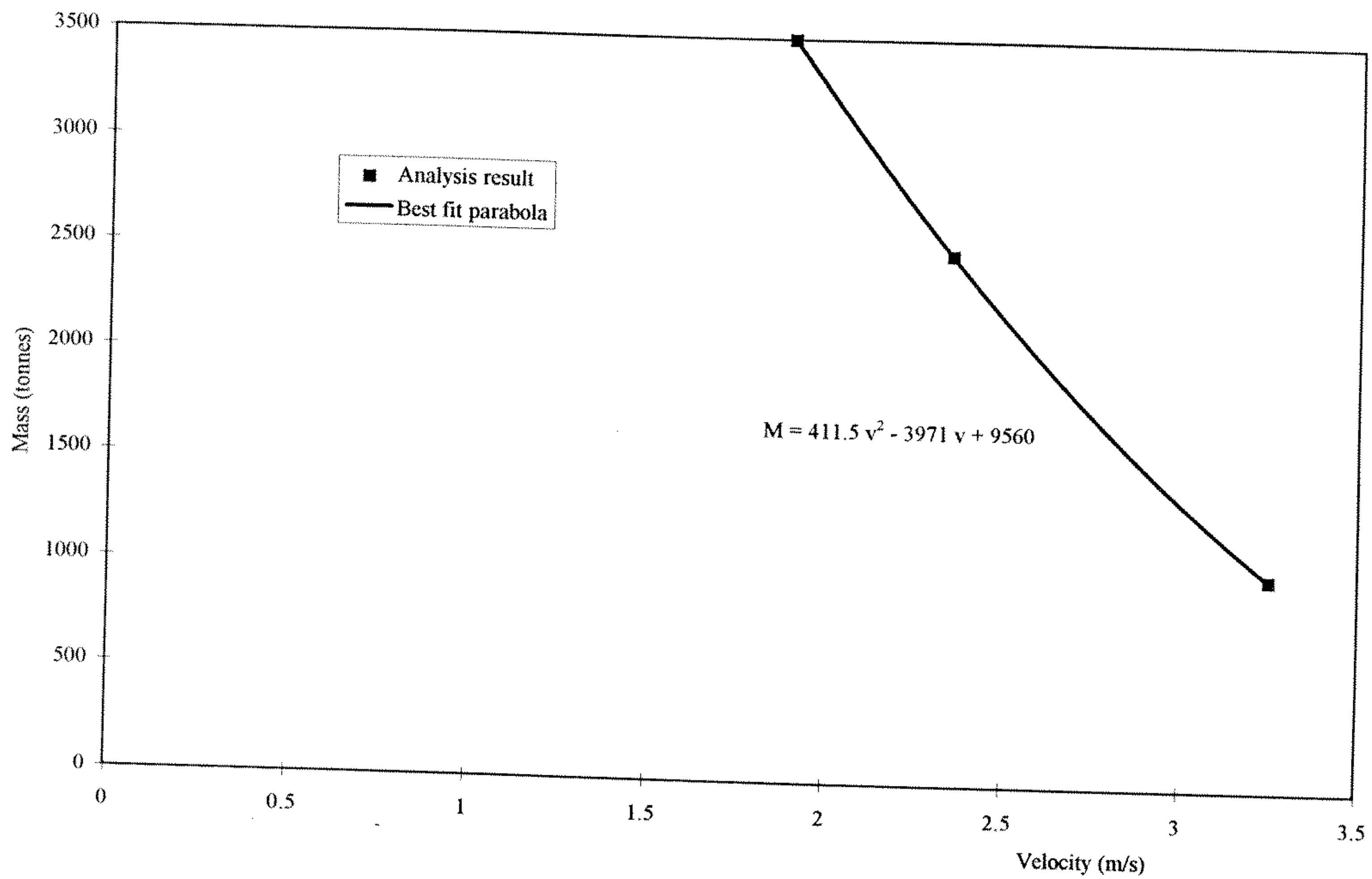

Figure 3.9: Failure function during ship impact (intact structure)

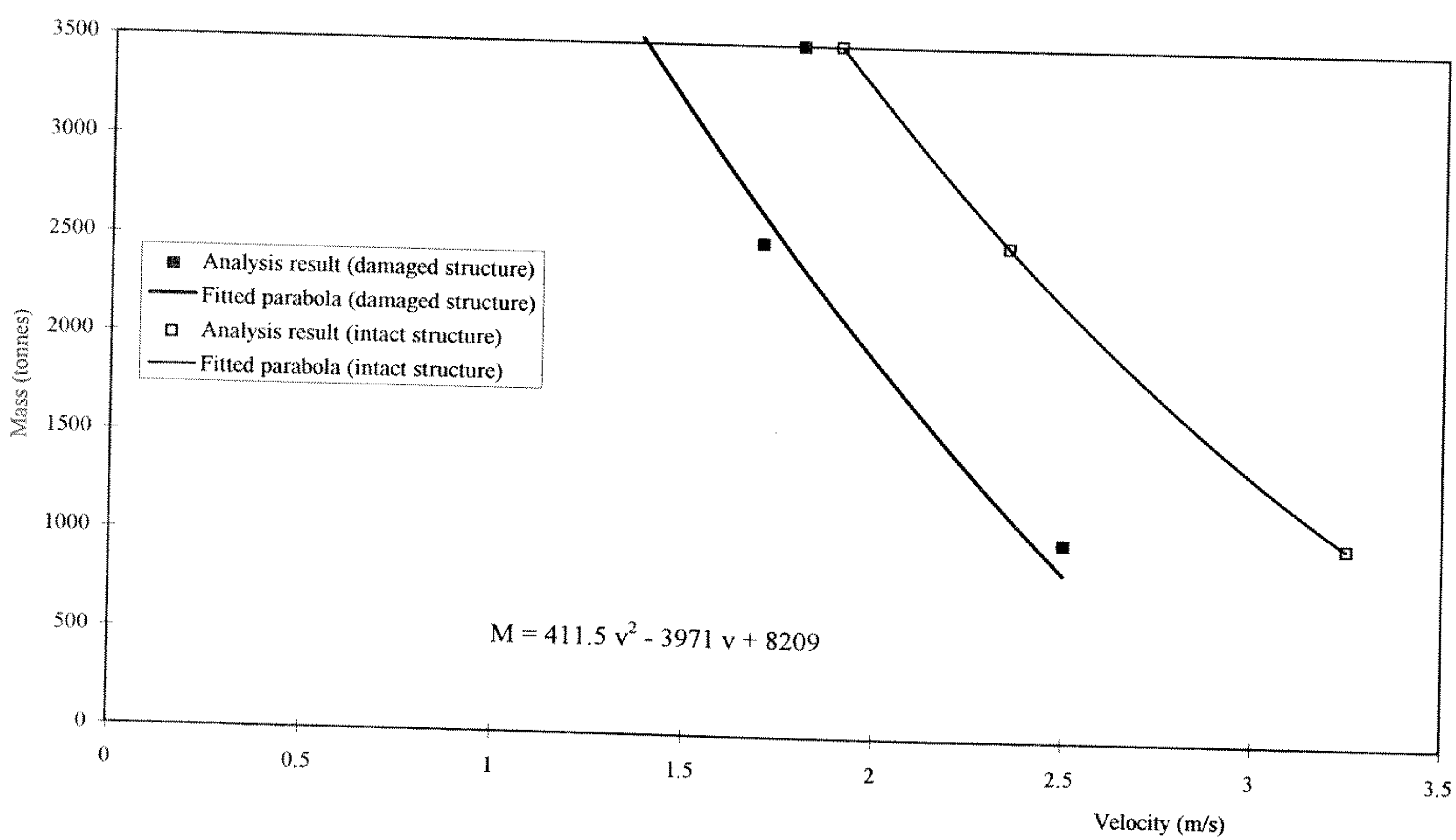

Figure 4.1: Failure function during ship impact (damaged structure)

APPENDIX

Collision Database Study

Purpose of Issue	Rev	Date of Issue	Author	Agreed	Approved
Issued to HSE	0	February 1999	NN	AFD	AFD
Incorporating HSE Comments	1	February 1999	NN	AFD	AFD
Final Report	2	May 1999	NN	AFD	AFD

COMMERCIAL - IN - CONFIDENCE

HEALTH & SAFETY EXECUTIVE

COLLISION DATABASE STUDY

DOC REF C223R001 Rev 2 May 1999

MSL Engineering Limited
MSL House
5-7 High Street, Sunninghill,
Ascot, Berkshire. SL5 9NQ

Tel: +44 (0)1344-874424
Fax: +44 (0)1344-874338
E-mail: MSLCENG@aol.com

NUMBER	DETAILS OF REVISION
0	Issued to HSE, February 1999
1	Incorporating HSE Comments, February 1999
2	Final Report, May 1999

COLLISION DATABASE STUDY

CONTENTS

1. INTRODUCTION

This report has been prepared by MSL Engineering Limited (MSL) for the Health & Safety Executive (HSE) and covers the work undertaken on the HSE Collisions Incident Database (1,2). The original Incident Database developed by AME for the HSE (3) relates to data up to 1991. In 1995, MaTSU undertook a study for HSE to update the Incident Database to July 1995 (1) and subsequently updated this in 1997 (2). The objectives of the study were as follows:

- To undertake baseline statistical appraisal of the most recent Collisions Incident Database (2) for internal use by HSE on other related projects.
- To enable information from the database to be used in the Joint Industry Project (JIP) on Minimum Structures currently being executed by W S Atkins, MSL Engineering (MSL), Ramboll and University of California on behalf of the Offshore Safety Division of the Health & Safety Executive and a number of oil companies and design houses.

MSL's scope of activities within the JIP on Minimum Structures cover reliability studies of four minimum structures subjected to ship collision. The request to undertake an appraisal of the Collisions Incident Database stemmed from a desire to use the most up-to-date information in the JIP on Minimum Structures.

The scope of work is presented in Section 2. Analysis of the database is presented in Section 3 and conclusions are given in Section 4.

2. SCOPE OF WORK

The scope of work was essentially to undertake baseline statistical appraisal of the updated Collisions Incident Database for HSE use and release of same to JIP with HSE approval.

The baseline analysis involved the following:

(i) Authorised vessels servicing the installation.

(ii) By-passing ships and fishing vessels.

For each of the above the following assessments were to be undertaken

(i) Variation of incident frequency with time.

(ii) Weather conditions, vessel speed, wave height.

(iii) Vessel size, location and orientation at time of impact.

(iv) Operating circumstances and cause of incident.

3. ANALYSIS OF DATABASE

This section presents an assessment of the collision database. It is important to note that as a result of the subsequent updated Collisions Incident Database being made available, the statistics relating to incident frequencies with time have been considered in some detail and have been presented by MaTSU in Reference (2). Therefore efforts were concentrated on obtaining information on the parameters which are important in evaluating the energy due to an impacting vessel and assisting in the reliability studies of ship impact for the Minimum Structures JIP.

The vessel impact energy E is defined as follows:

$$E = 0.5.a.m.v^2$$

where a = 1.4 or 1.1 (added mass factor for broadside and bow/stern impact respectively).

m = Displacement tonnage of vessel.

v = Speed of vessel.

The speed of vessel is related to the following:-

$$v = 0.5.H_s \text{ per second}$$

where H_s is the significant wave height.

It can be deduced from the above that the energy during impact is dependent on a number of important parameters.

To assist in the reliability ship collision studies for the Minimum Structures JIP information on the distribution of these parameters caused either by non-human error (i.e. mechanical failure) or human error (i.e. misjudgement) as defined in Reference (2) are also considered.

Assessments for each of the sectors of the North Sea (i.e. Northern, Central and Southern) were undertaken for each of the following parameters:

- Vessel size - authorised vessels only (i.e. Supply, Standby, Diving Support).
- Vessel orientation (i.e. broadside, stern, bow).
- Weather conditions (i.e. sea state).
- Causes of incidents (i.e. Causation Factors - external factors, mechanical control failure, human control failure, watch-keeping failure).

3.1 Distribution of Vessel Size

On examining the contents of the database MSL identified that information relating to the displacement tonnage of the vessels was not available (i.e. only the gross tonnage was given). This information is particularly important in evaluating both the distribution of vessel sizes within each of the sectors of the North Sea and the impact energy (as the impact energy is based on the displaced tonnage of the vessel) to be used within the JIP on Minimum Structures.

MSL identified a number of possible references which could possibly contain details of the displaced tonnage for each of the vessels identified (e.g. References 4-9). Despite a detailed review of these documents, the required information was not available. It was therefore decided after consultation with HSE that an approximation would be made by reference to BS 6349 (9) which contains some guidance on factors which can be applied to the gross tonnage for various vessel types. The Database was therefore updated to reflect this for subsequent analyses.

Assessments of the database were undertaken for each of the sectors of the North Sea as follows:

(i) All incidents involving attendant vessels (gross and displaced tonnage) as shown in Figures 1 and 2 respectively.

(ii) All incidents involving supply vessels only (gross and displaced tonnage) as shown in Figures 3 and 4 respectively.

(iii) Comparison of the displaced tonnage for supply vessels used in this study with that from AME (3) is shown in Figure 5.

(iv) Incidents with and without human control error involving supply vessels and displaced tonnage only, is shown in Figures 6 and 7 respectively.

The data presented in Figures 1-5 for items i-iii above have been evaluated and are presented in Table 1. The following observations can be deduced from Table 1:

- The largest impacting vessel sizes occur in the Northern and Central sectors of the North Sea.
- The largest vessels involved vessels which were not generally supply vessels.
- The 95% percentile based on results from this study for the Northern North Sea is in the range 5001-6000 tonnes for all authorised vessels and supply vessels only.
- The 95% percentile based on results from this study for the Central North Sea is in the range (5001-6000) tonnes for all authorised vessels and (4001-5000) tonnes for supply vessels only.

- The 95% percentile based on results from this study for the Southern North Sea is in the range (3001-4000) tonnes for all authorised vessels and supply vessels only.

- The maximum displaced tonnage and 95% vessel size for supply vessels from the AME study are higher for the Northern and Central North Sea when compared to the results from this study.

- The maximum displaced tonnage for supply vessels from the AME study (i.e. 4001-5000) are lower for the Southern North Sea when compared with the results from this study (i.e. 5001-6000).

- The 95% percentile vessel size for supply vessels from the AME study for the Southern North Sea are similar when compared with the results from this study (i.e. 3001-4000).

- A significant number of incidents involved vessels which were unknown (i.e. 51 equivalent to nearly 25% of the total number of incidents (207) as shown in Figure 1).

- The AME Database contained 95 Incidents for supply vessels only compared to 105 from this study.

- The AME Database contained a total of 138 incidents for all authorised vessels compared to 207 from this study.

Information presented in Figures 6-7 for item iv. above are presented in Table 2. The following observations can be deduced from Table 2:

- The maximum displaced tonnage and 95% Percentile of vessel size for incidents involving non-human error are similar to that observed for supply vessels given in Table 1 for the Northern and Central Northern Sea.

- The maximum displaced tonnage and 95% Percentile for incidents involving human error are similar to that observed for supply vessels given in Table 1 for the Southern North Sea.

3.2 Impact Orientation

Assessments were undertaken for each of the sectors of the North Sea as follows:

(i) All incidents involving attendant vessels as shown in Figure 8.

(ii) All incidents involving supply vessels only as shown in Figure 9.

(iii) As (ii), for incidents with and without human control error, as shown in Figures 10 and 11 respectively.

From Figures 8-11 the following can be observed:

- Information concerning the direction of impact for over 100 of the total of 207 incidents was not specified as shown in Figure 8.
- All sectors of the North Sea involved impacts mainly from stern, bow or side as shown in Figures 8 and 9.
- It would appear from Figures 8-11 that no one direction of impact is more prevalent than another for each of the sectors of the North Sea. However, there is some evidence to suggest that the Central Sector of the North Sea experienced significantly more impacts from the Stern direction as shown in Figure 9.
- The number of incidents involving human error only are significantly higher for the stern direction and occur more frequently in the Central sector of the North Sea as shown in Figure 11.
- The number of incidents involving human error only are lower than those involving no human error when one compares Figure 10 and 11 respectively.

3.3 Weather - Sea State Condition

Assessments were undertaken for each of the sectors of the North Sea as follows:

(i) All incidents involving attendant vessels as shown in Figure 12.

(ii) All incidents involving supply vessels only. as shown in Figure 13.

(iii) Incidents involving supply vessels with out human error as shown in Figure 14.

(iv) Incidents involving supply vessels with human error as shown in Figure 15.

From Figures 12-15 the following can be observed:

- Information concerning the sea state condition at impact for over 130 of the total of 207 incidents was not specified as shown in Figure 12.
- The range of sea states recorded varied between 0-6m although most incidents tended to occur in sea states less than 4.1 metres, as shown in Figures 12 and 13 respectively. Note that 4m corresponds to a velocity of impact of 2m/s (i.e. $v=0.5.H_s$).
- Given the limited number of incidents, trends comparing the sea state condition and causation factor (i.e. human or non-human error) during impact for the different sectors of the North Sea could not be obtained.

3.4 Primary Cause

Assessments were undertaken for each of the sectors of the North Sea as follows:

(i) All incidents involving attendant vessels as shown in Figure 16.

(ii) All incidents involving Supply vessels only. as shown in Figure 17.

From Figures 16-17 the following can be observed:

- Information on the primary cause of incident was recorded for 127 of the 207 incidents.
- 37% of the total number of incidents involved human error as the primary cause.
- There was no trend that could be observed for the number of recorded incidents between the primary cause and location in the North sea.

4. CONCLUSIONS

An assessment of the current HSE Collision Database has been undertaken to evaluate the importance of key parameters which have a direct bearing on the ship impact energy during collision (i.e. vessel size, impact orientation, weather condition and primary cause). These results are seen as being of direct relevance in the ship impact reliability studies being undertaken by MSL in the JIP on Minimum Structures.

Distributions on the vessel sizes were obtained and compared with the original AME database. Due to the approximation used to calculate the displaced tonnage in this study and the different sizes of the databases, differences in results between this study and the AME database are to be expected.

The results from this study indicate that the largest vessel sizes are situated in the Northern and Central parts of North Sea. The 95% percentile vessel sizes from this study are as follows:

- Northern North Sea 5001-6000 Tonnes
- Central Northern Sea 5001-6000 Tonnes
- Southern North Sea 3001-4000 Tonnes

The maximum size of impacting vessel and the 95% percentile were evaluated for incidents involving either human or non human error as the prime cause. For the Northern and Central Sectors of the North Sea the maximum size of vessel and 95% percentile were higher involving non-human error. For the Southern Sector the maximum size of impacting vessel involving human error was higher.

Limited data were available to consider the importance of impact direction and sea state conditions. Information for nearly 50% and 65% of the incidents was not available for impact direction and sea state conditions respectively. It is therefore difficult to come to any firm conclusion as to whether there is any correlation between location, vessel size and impact direction and sea state conditions.

For those incidents for which information was available impacts from either stern, bow or side was observed. From the limited sea state condition it was noted that most incidents occurred in sea states less than 4.0m.

In analyses it is therefore considered appropriate to undertake studies for both broadside and stern directions, in sea state conditions of 4.0m.

Information on the primary cause of incident was available for approximately 60% of the total incidents. From this data it was noted that 36% of incidents involved human error as the prime cause.

REFERENCES

1. Marine Technology Support Unit, Report MaTR 0141 "Review of the Offshore Collision Incident Database and Report MaTR 0137 Update of Collision Incident Database", 1995.

2. Marine Technology Support Unit, Report MaTR 0447 "Ship/Collision Incident Database (1997)", November 1997.

3. Advance Mechanics & Engineering Ltd "Vessel Impact on Fixed Steel Platforms", P Wicks, D T Smart, K A J Williams and C P Ellinas, Structural Design against Accident Loads- As Part of the Offshore Safety Case, ERA Technology Conference Proceedings, 23-24 September 1992, London.

4. Anchor Handling Tugs and Supply Vessels of the world, Oilfield Publications Limited ISBN 1 870945 68 9.

5. Stand-by Vessels of the World, Oilfield Publications Limited. ISBN 1 870945 24 7

6. Lloyds' Maritime Directory 1986, Lloyds of London Press Ltd. ISBN 1 – 85044 -076

7. The Offshore Service Vessels Register 1991, Clarkson Research Studies Ltd, London, 1991.

8. Watson, D G M and Gilfillan, A W " Some ship Design Methods", Trans. RINA, 1976.

9. British Standards Institution (BSI) "Code of Practice for Maritime Structures, Part 4 Design of Fendering and Mooring Systems", BS6349; Part 4 - 1985, London.

Sector North Sea	Vessel Type	Maximum Gross Tonnage	Maximum Displaced Tonnage	Distribution Displaced Tonnage*	Maximum Displaced Tonnage (AME)	Distribution Displaced Tonnage** (AME)
Northern	All Authorised	8001-8500	16001-17000	5001-6000	-	-
	Supply Only	3001-3500	6001-7000	5001-6000	9001-15000	6001-7000
Central	All Authorised	4501-5000	90001-10000	5001-6000	-	-
	Supply Only	2501-3500	5001-6000	4001-5000	6001-7000	5001-6000
Southern	All Authorised	2501-3000	5001-6000	3001-4000	-	-
	Supply Only	2501-3000	5001-6000	3001-4000	4001-5000	3001-4000

* 95% percentile (ignoring vessels >10,000 tonnes) from this study.

** 95% percentile (ignoring vessels > 10,000 tonnes) from AME Database.

Table 1: Comparison of maximum vessel size and vessel size distributions for different sectors of the North Sea

Sector North Sea	Vessel Type	Maximum Displaced Tonnage Non-Human Error	Maximum Displaced Tonnage Human Error	Distribution Displaced Tonnage Non-Human Error*	Distribution Displaced Tonnage Human Error*
Northern	Supply	6001-7000	5001-6000	5001-6000	4001-5000
Central	Supply	5001-6000	4001-5000	4001-5000	3001-4000
Southern	Supply	3001-4000	5001-6000	3001-4000	3001-4000

* 95% percentile (ignoring vessels >10,000 tonnes)

Table 2: Comparison of vessels sizes and vessel size distributions with and without human error

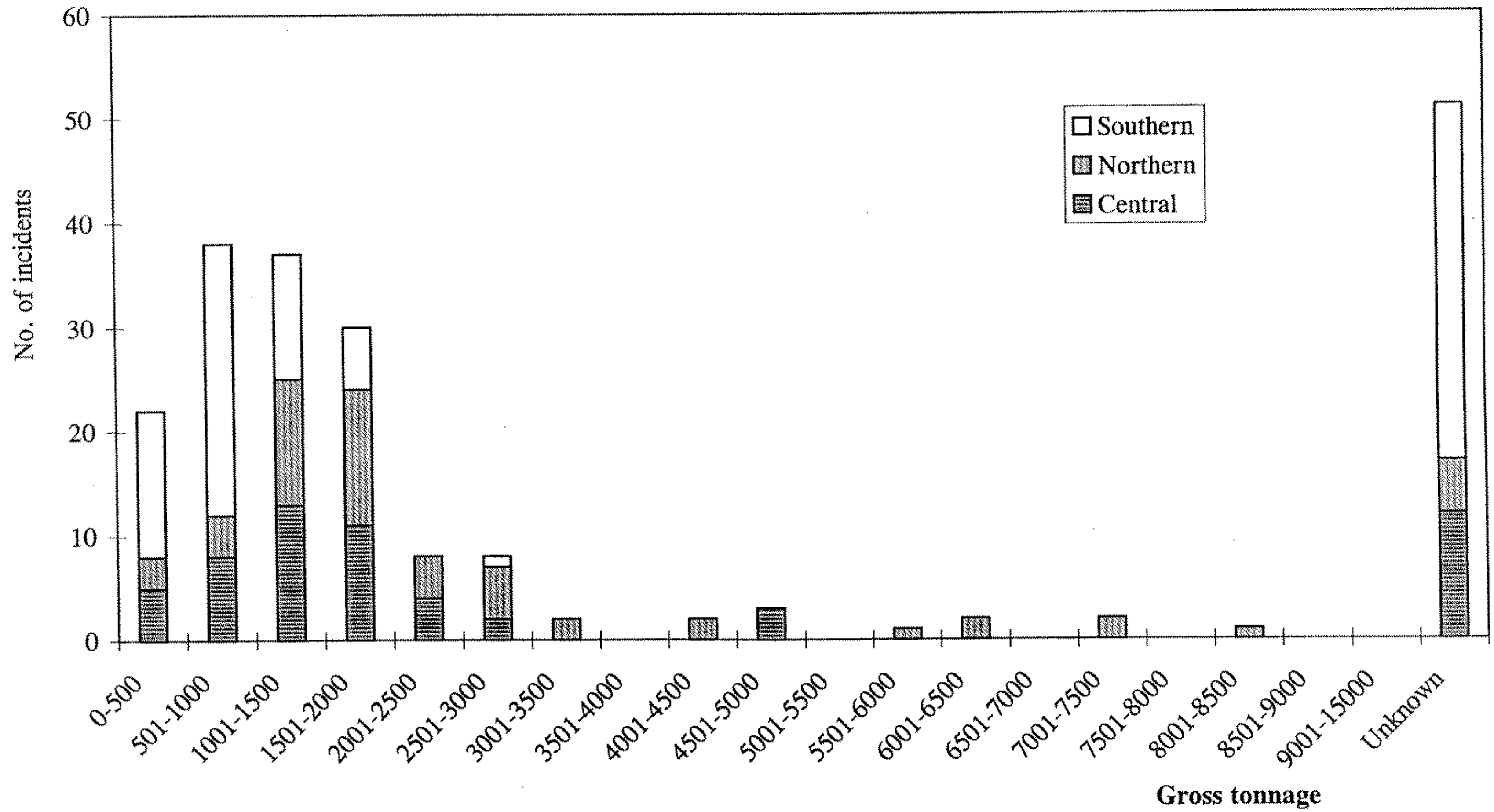

Figure 1: Number of Incidents to Fixed Steel Platforms by Location in the North Sea

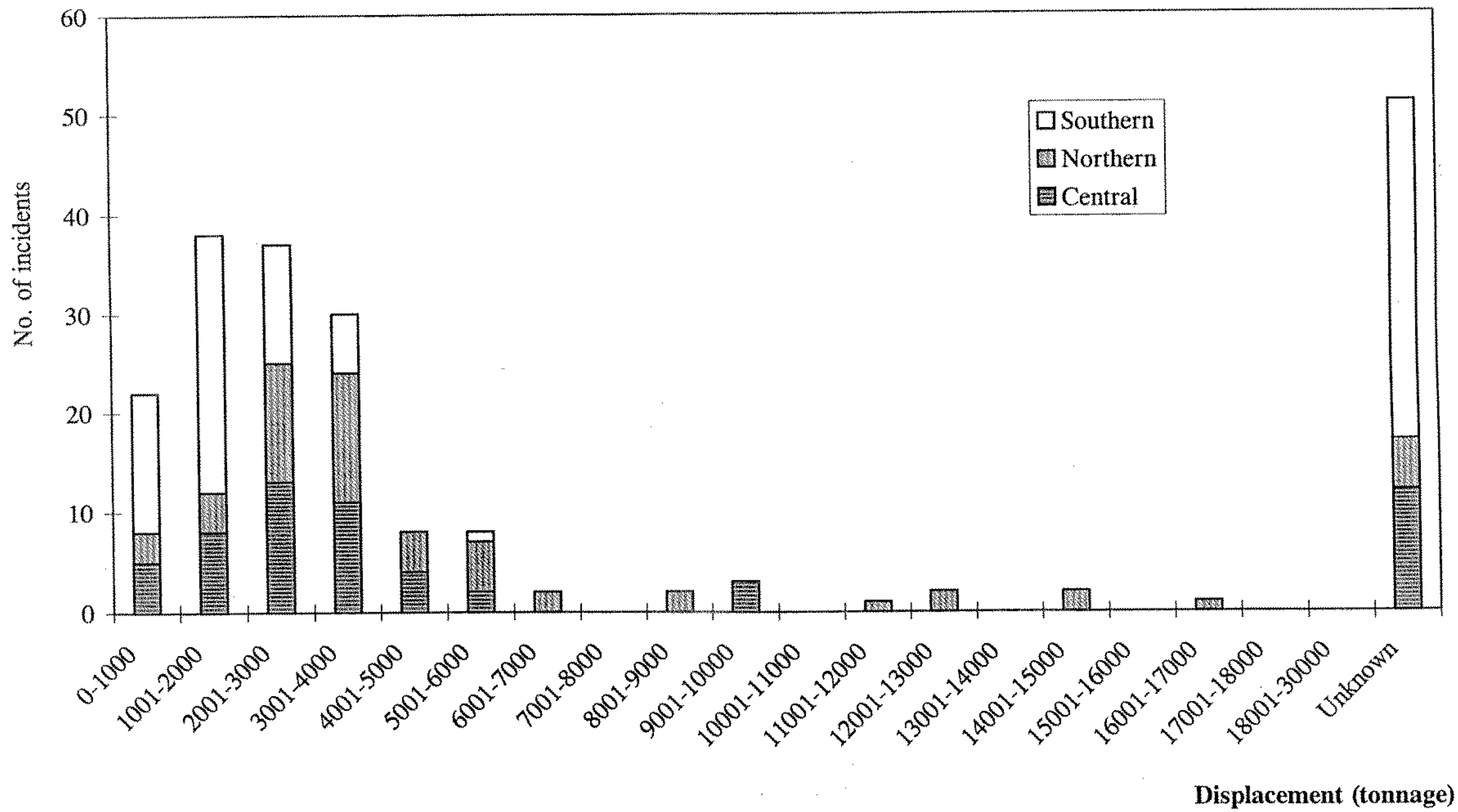

Figure 2: Number of Incidents to Fixed Steel Platforms by Location in the North Sea

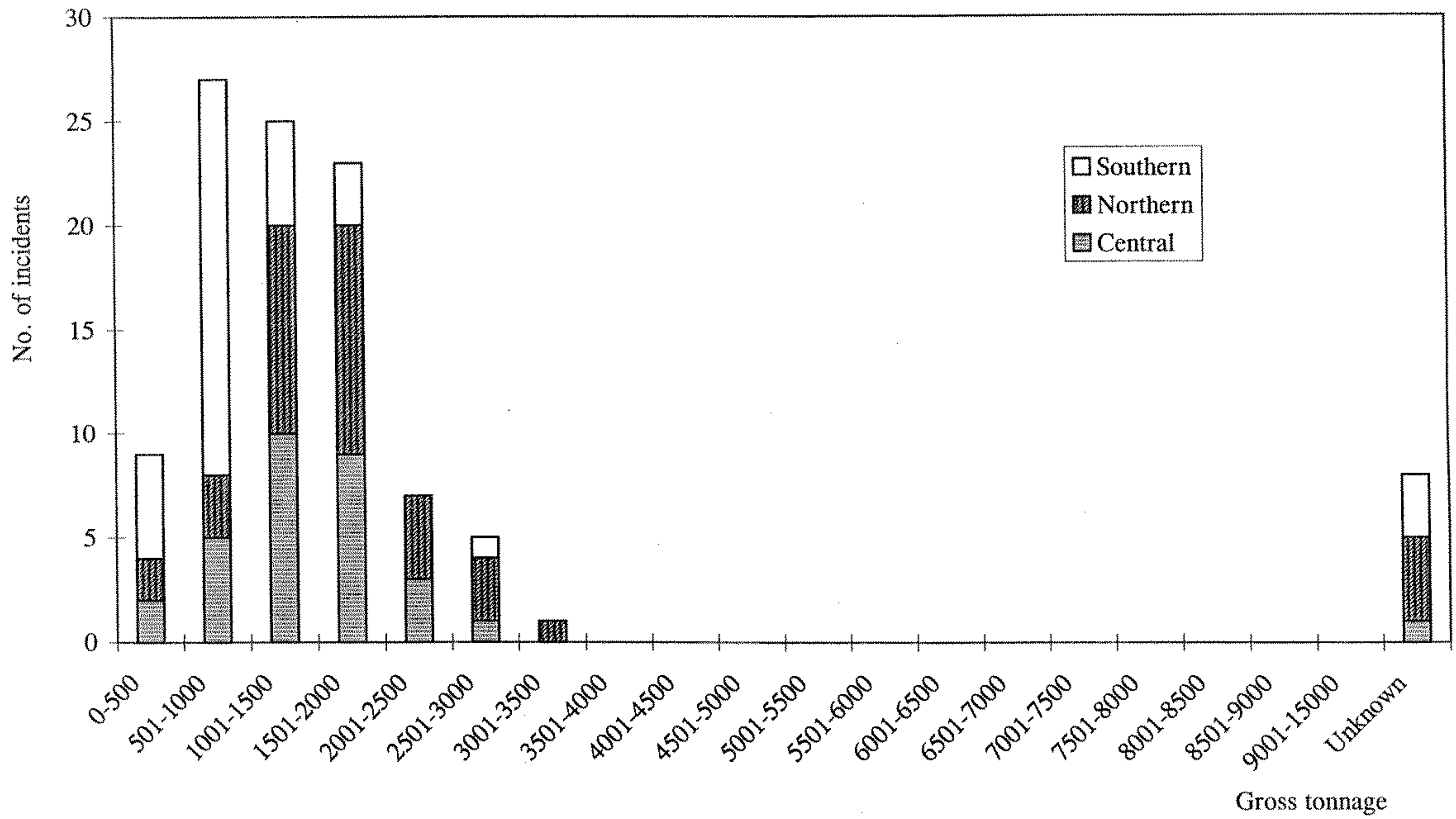

Figure 3: Number of Incidents to Fixed Steel Platforms by Location in the North Sea (Supply vessel type)

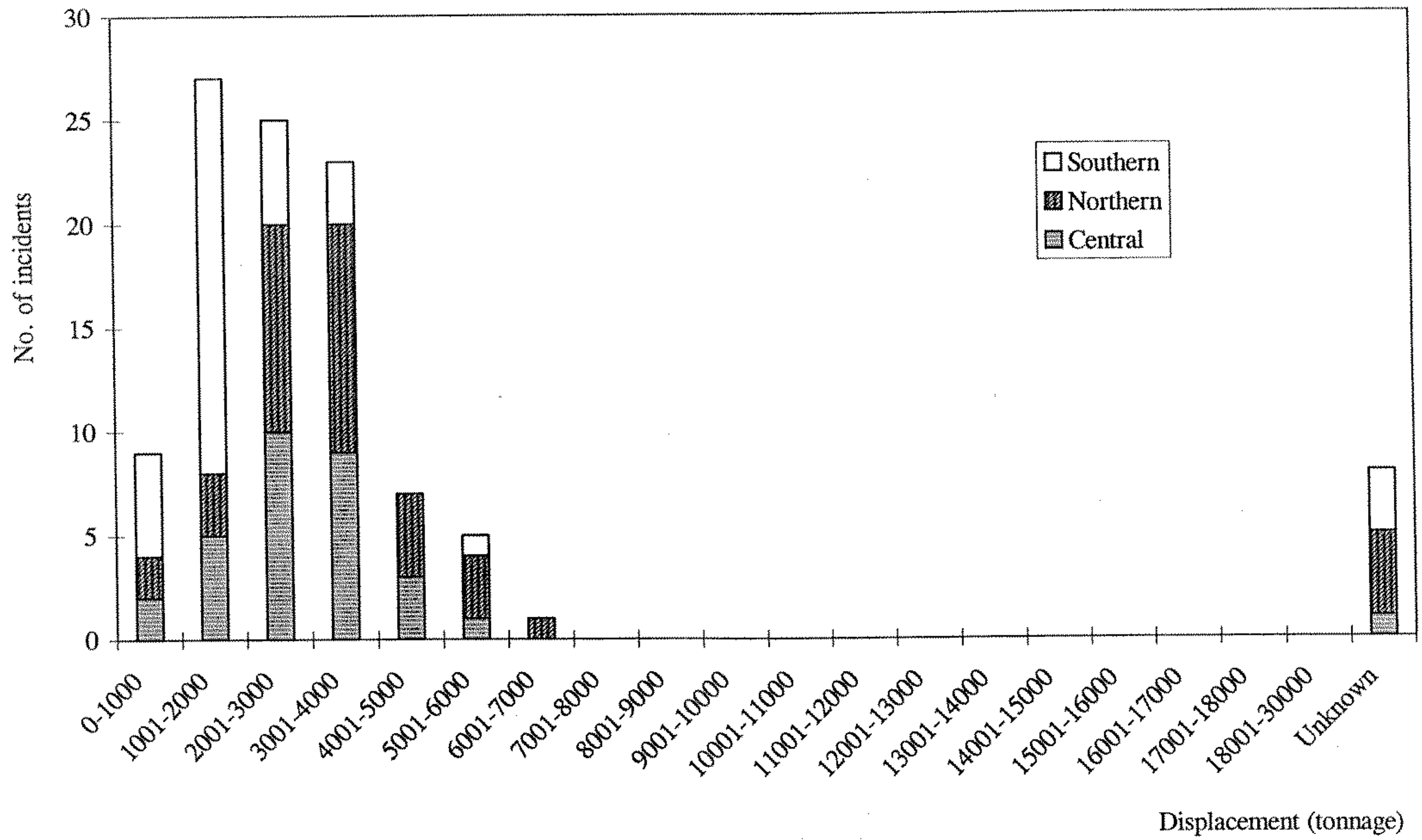

Figure 4: Number of Incidents to Fixed Steel Platforms by Location in the North Sea (Supply vessel type)

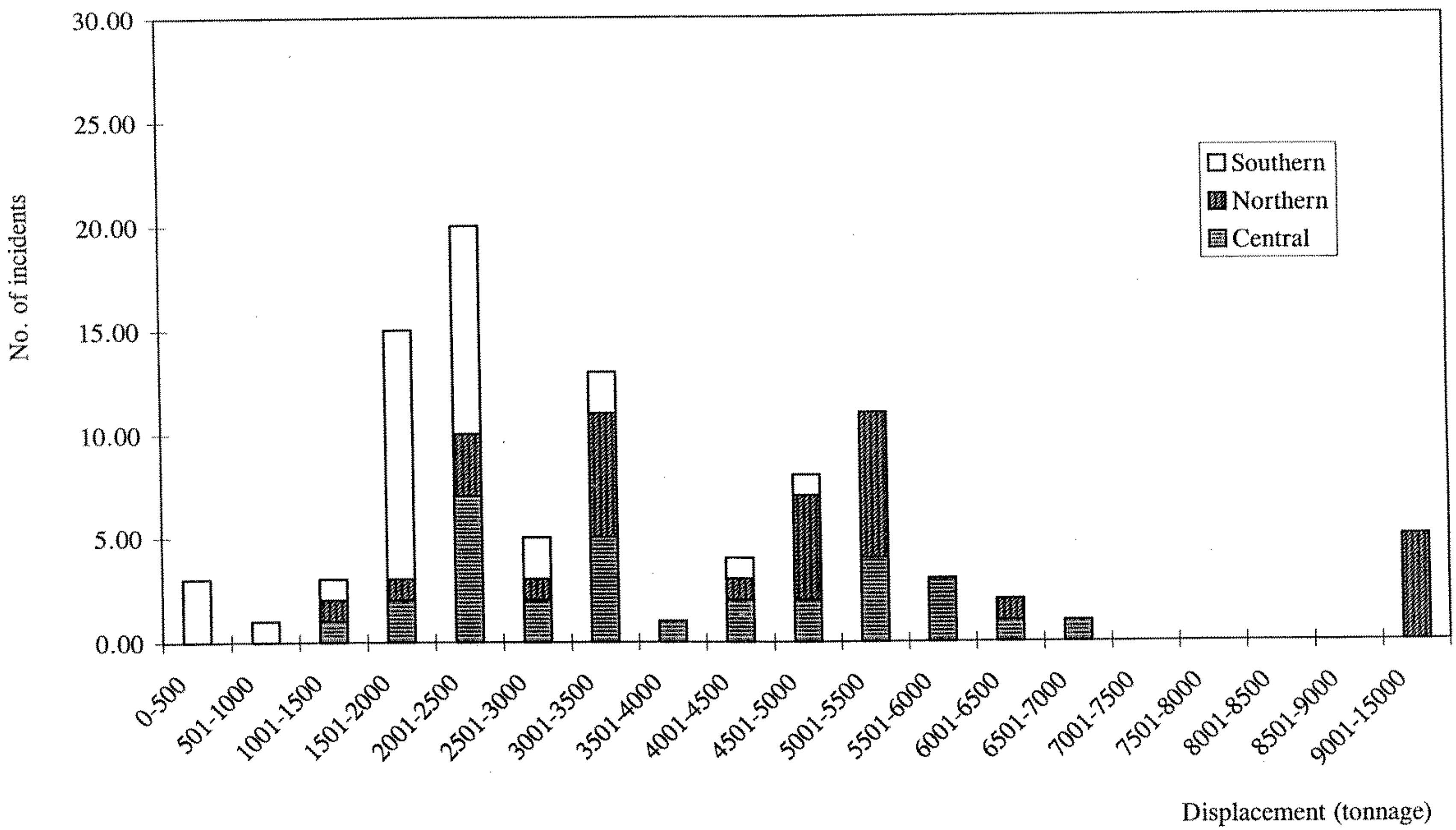

Figure 5: Number of Incidents to Fixed Steel Platforms by Location in the North Sea (Supply Vessel Type – AME Database)

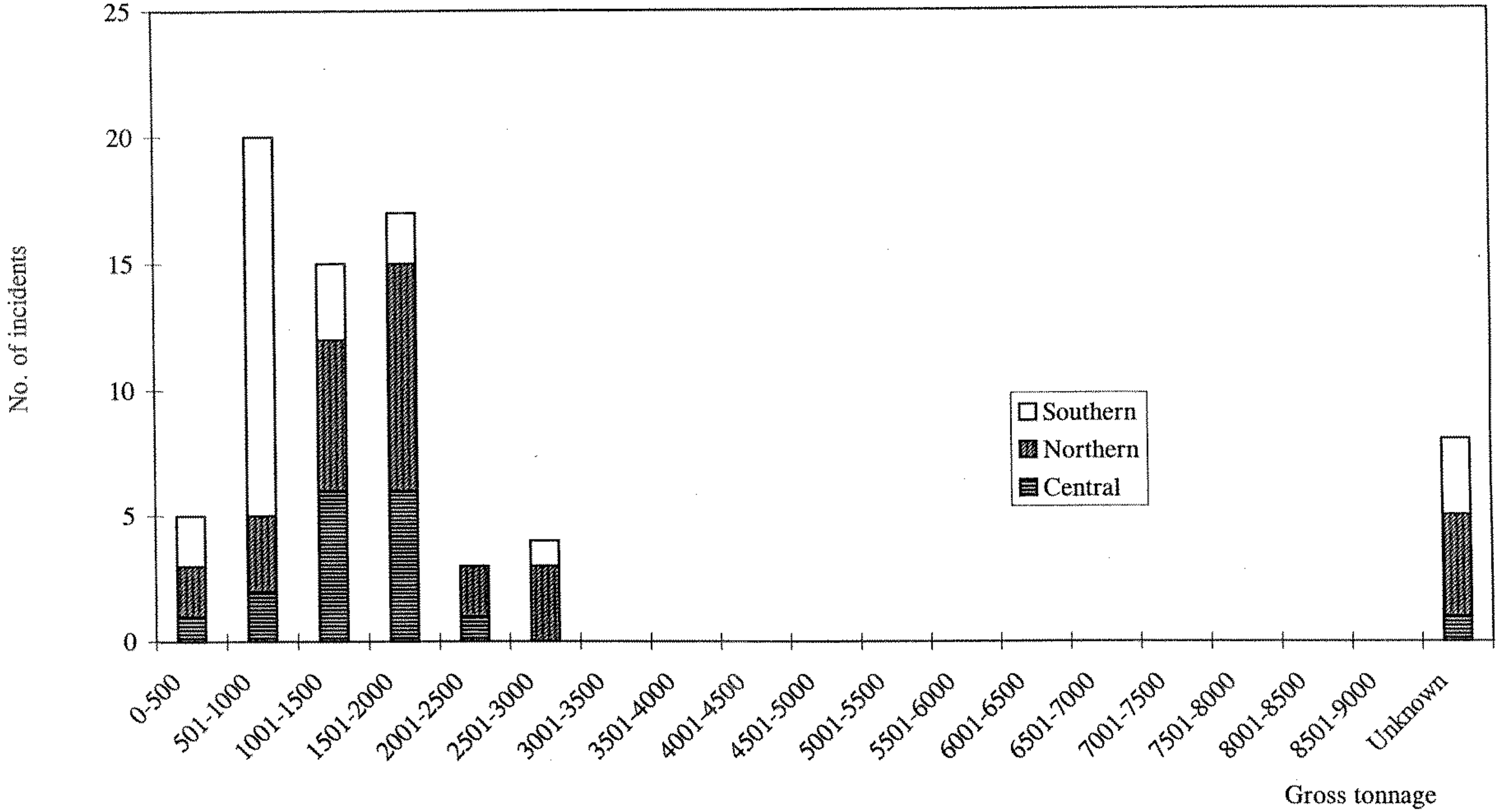

Figure 6: Number of Incidents to Fixed Steel Platforms for Supply Vessels (Human Error Only)

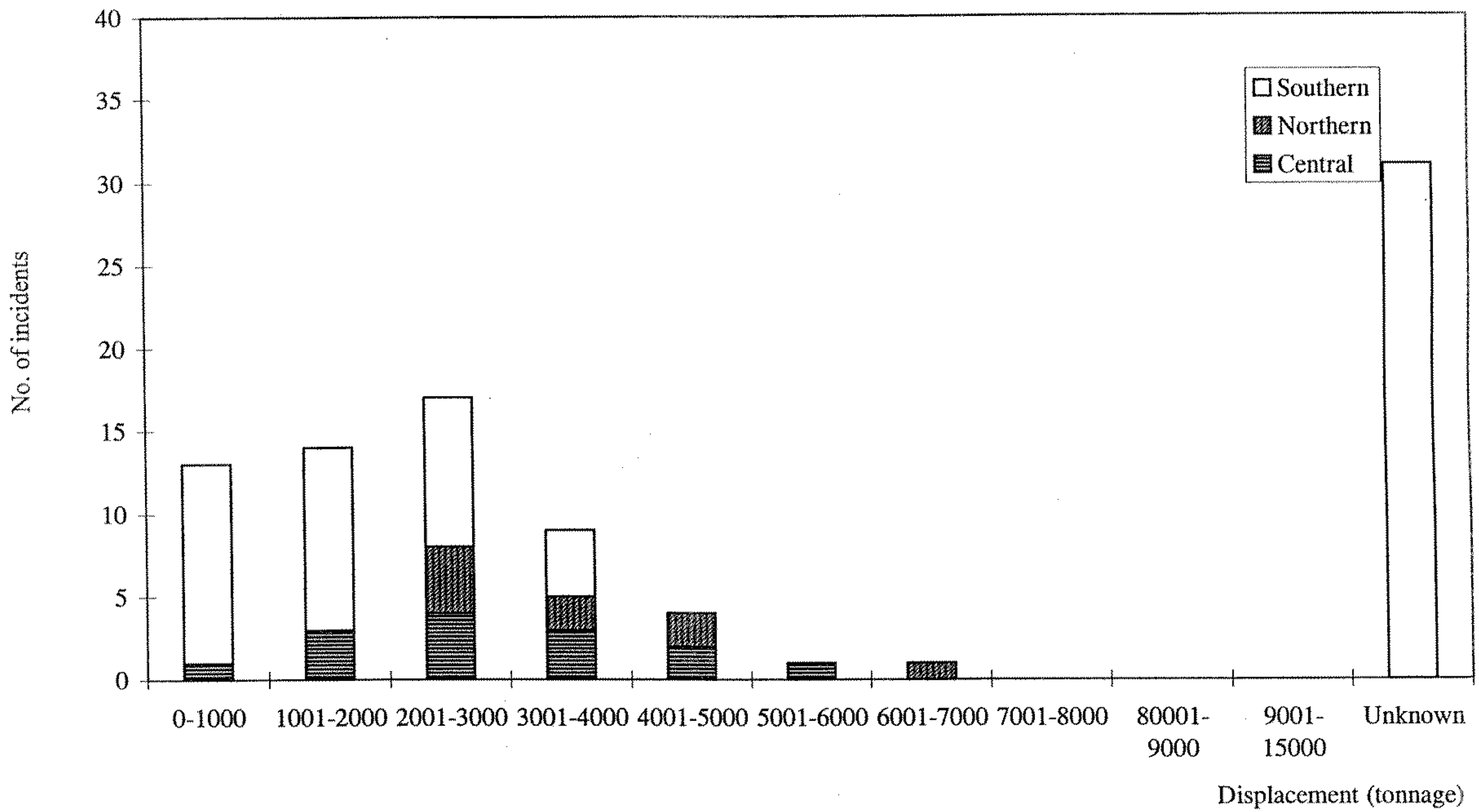

Figure 7: Number of Incidents to Fixed Steel Platforms for Supply Vessels (Non-Human Error)

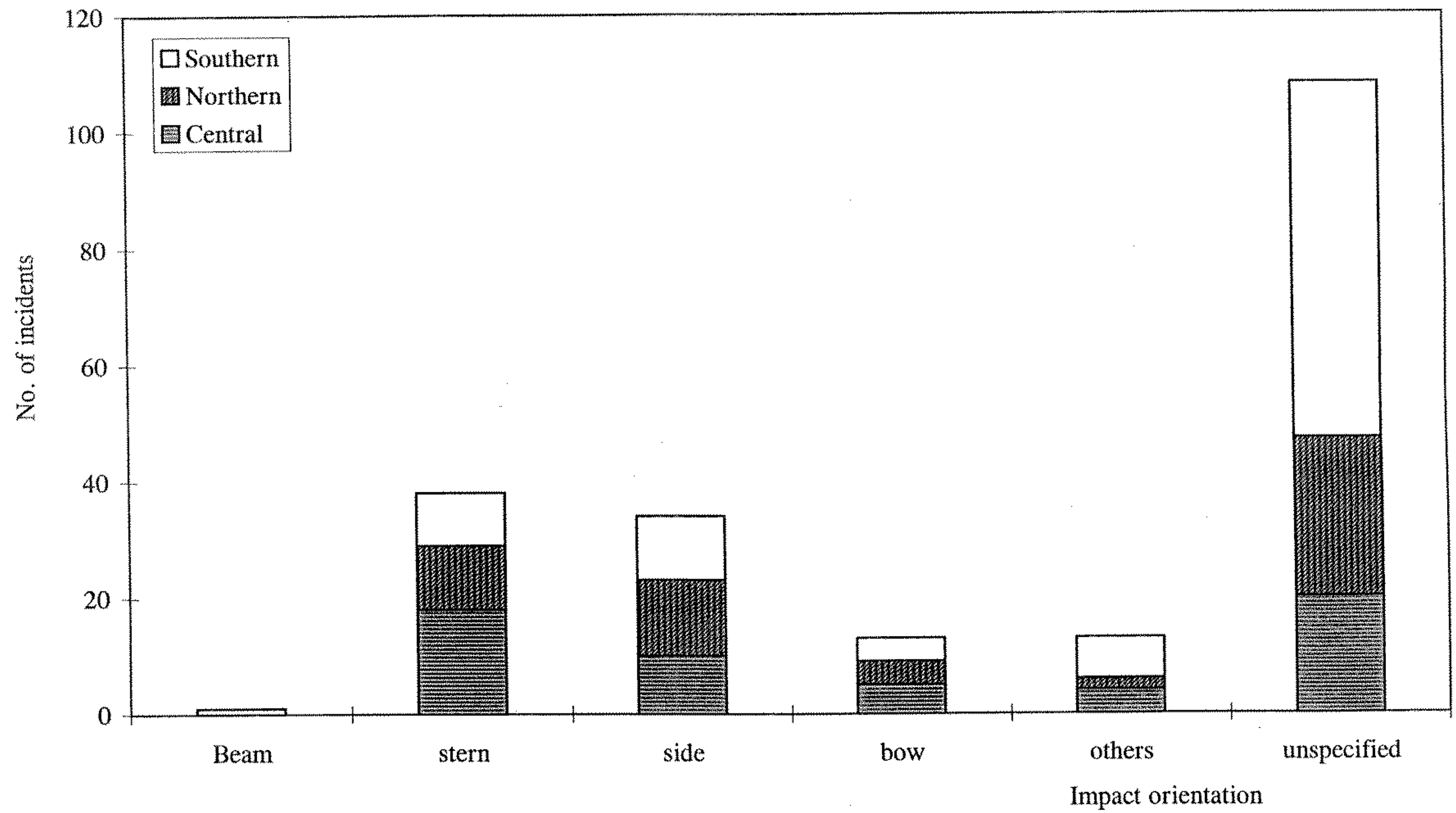

Figure 8: Distribution of Impact Orientation for all Vessels

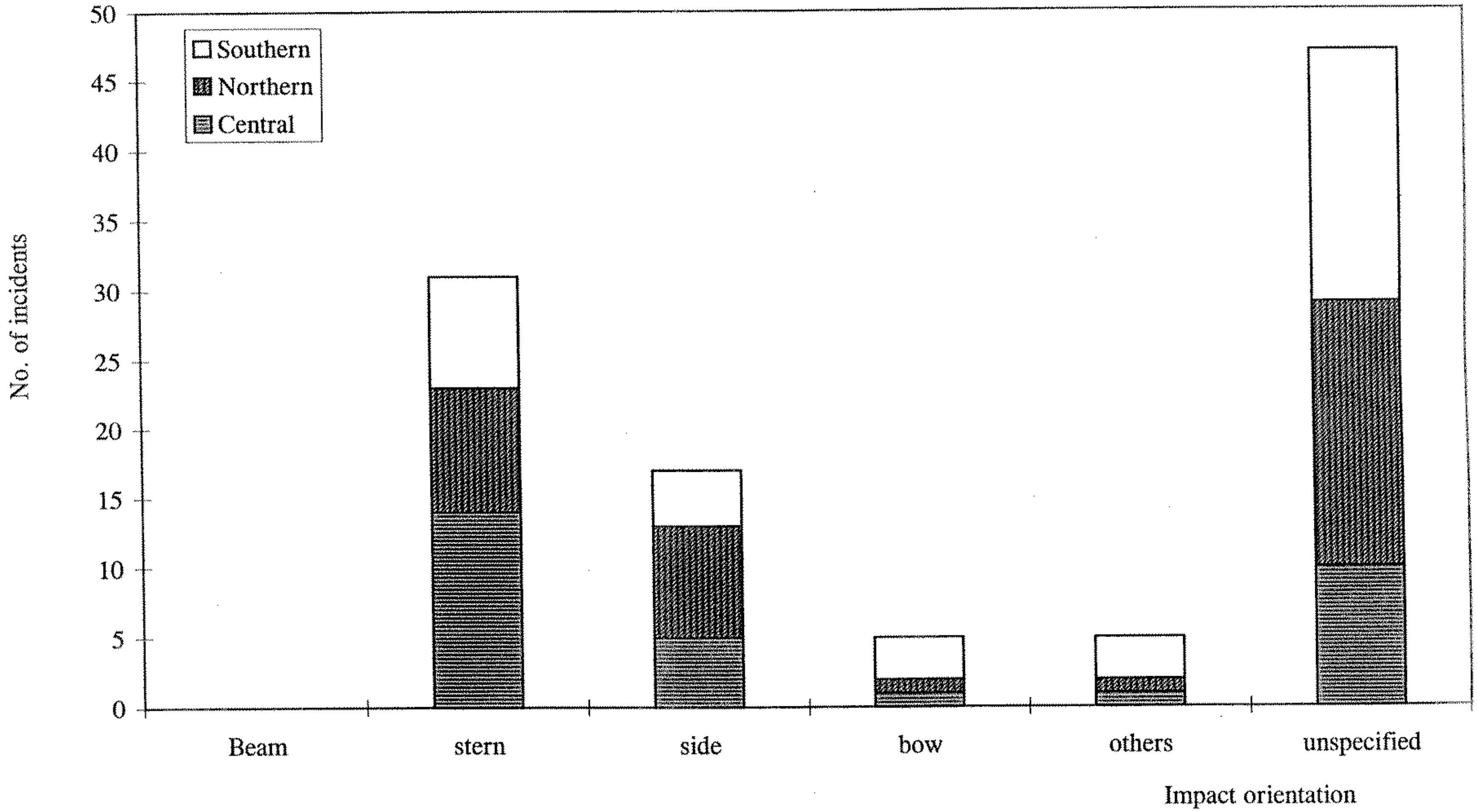

Figure 9: Distribution of Impact Orientation for Supply Vessels

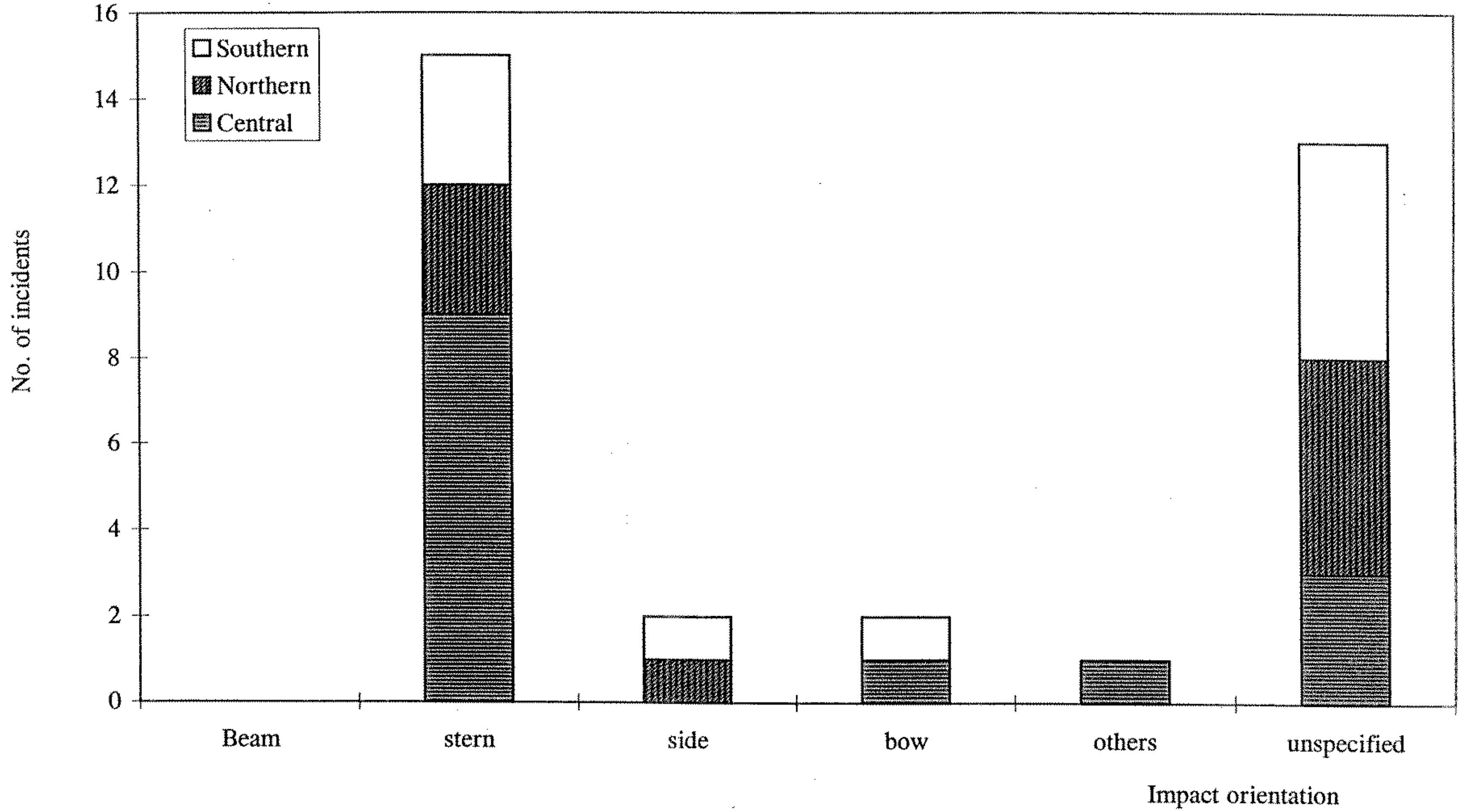

Figure 10: Distribution of Impact Orientation for Supply Vessels (Human Error Only)

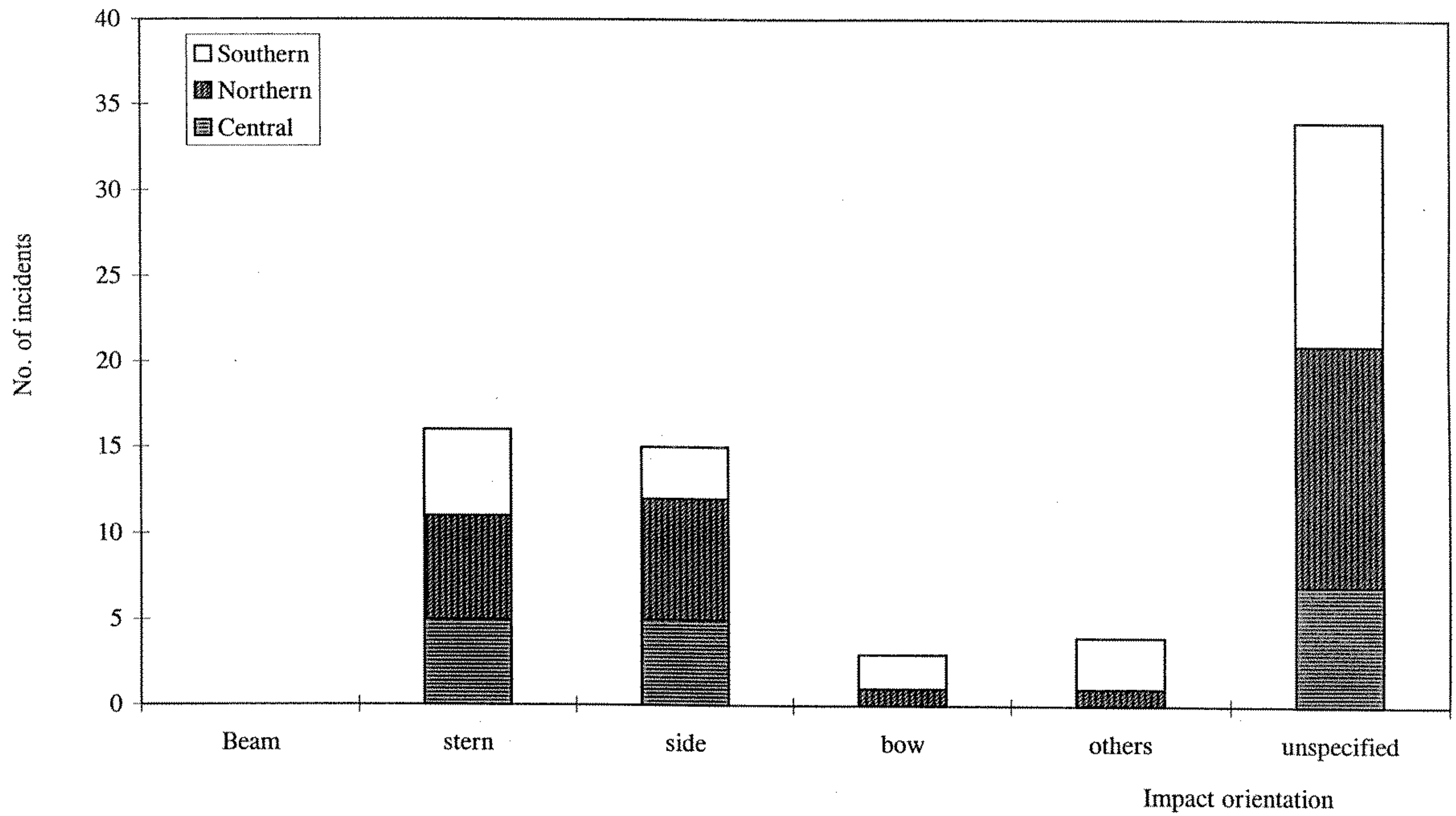

Figure 11: Distribution of Impact Orientation for Supply Vessels (No Human Error)

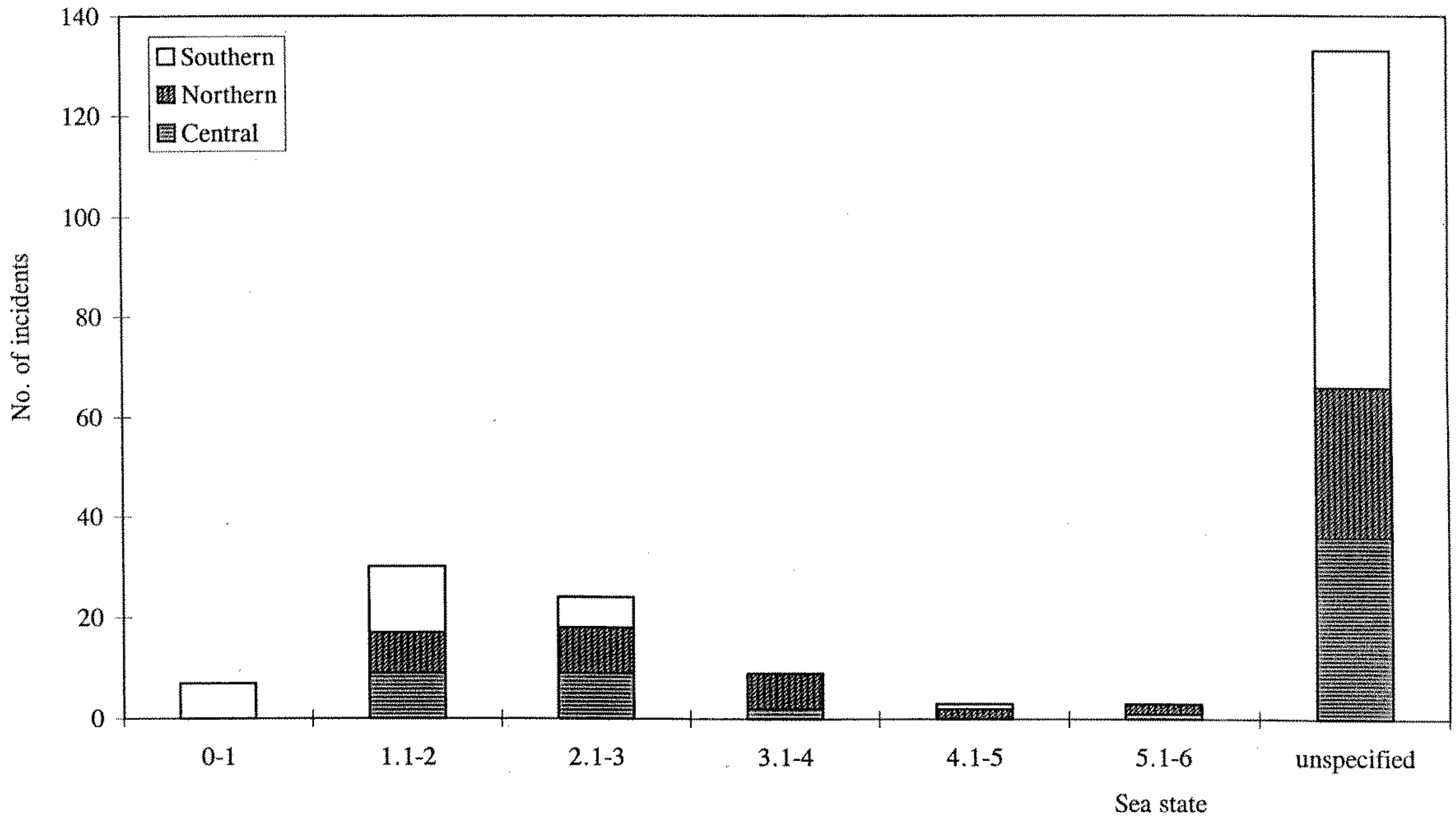

Figure 12: Distribution of Sea State for all Vessels

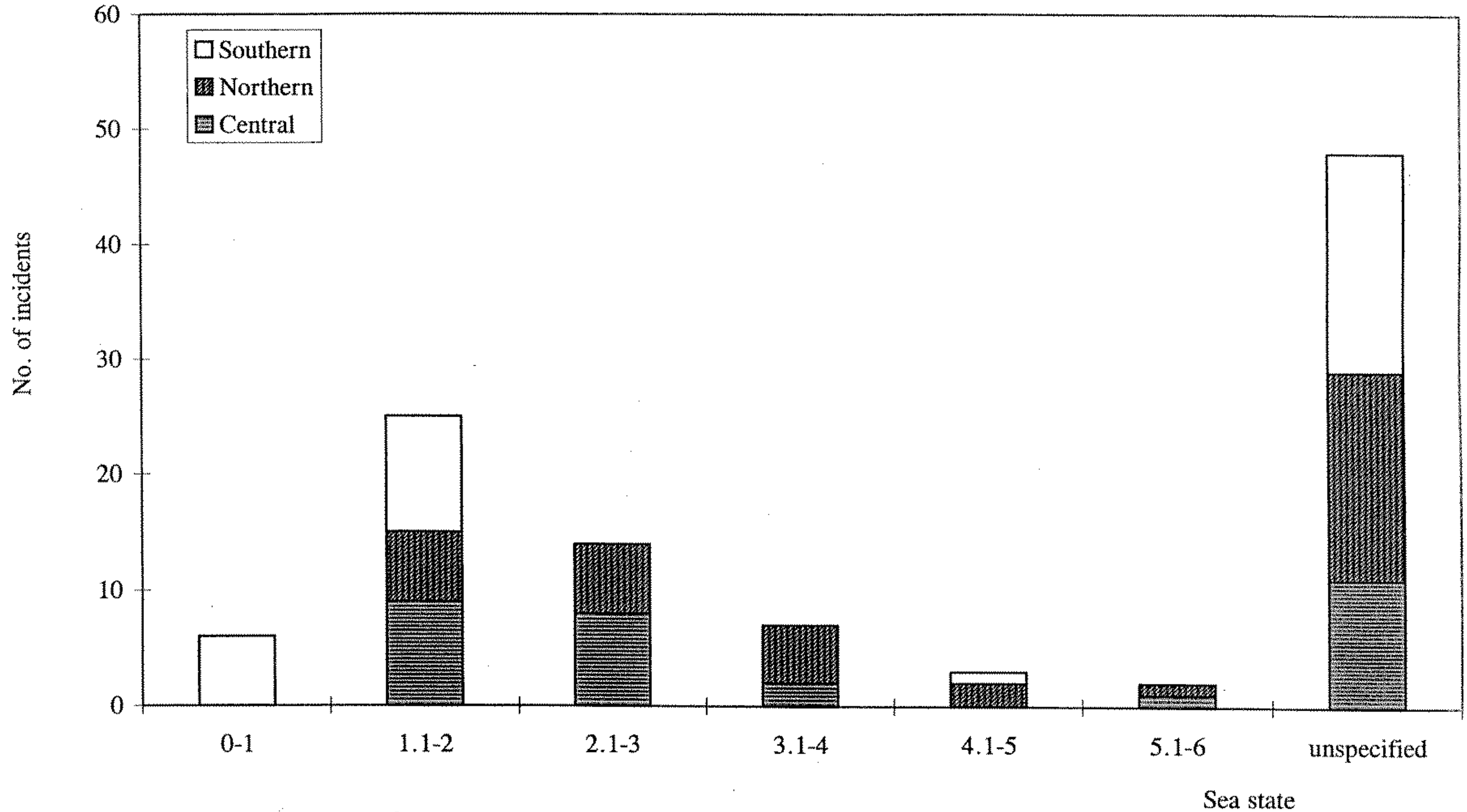

Figure 13: Distribution of Sea State for Supply Vessels

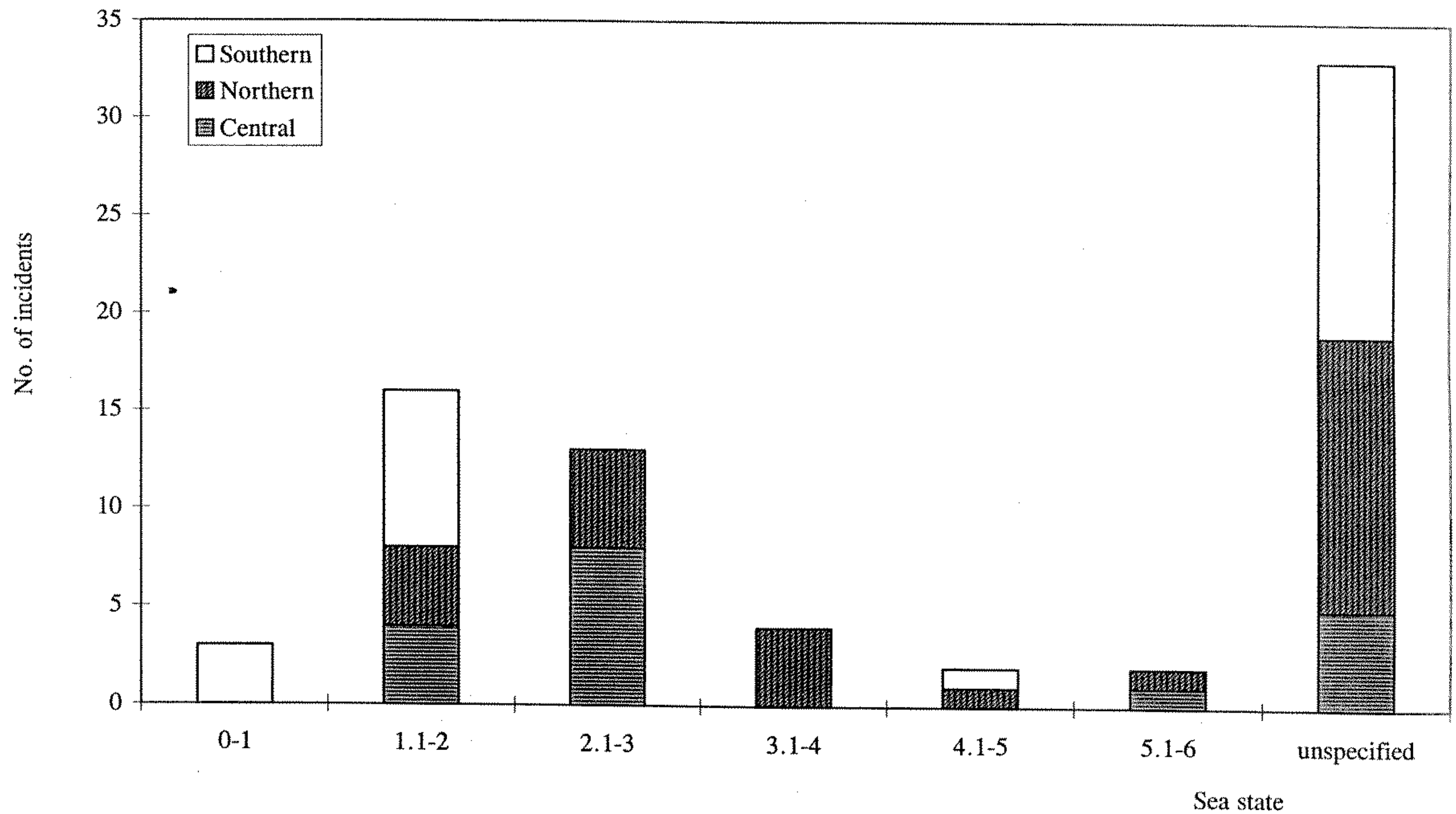

Figure 14: Distribution of Sea State for Supply Vessels (No Human Error)

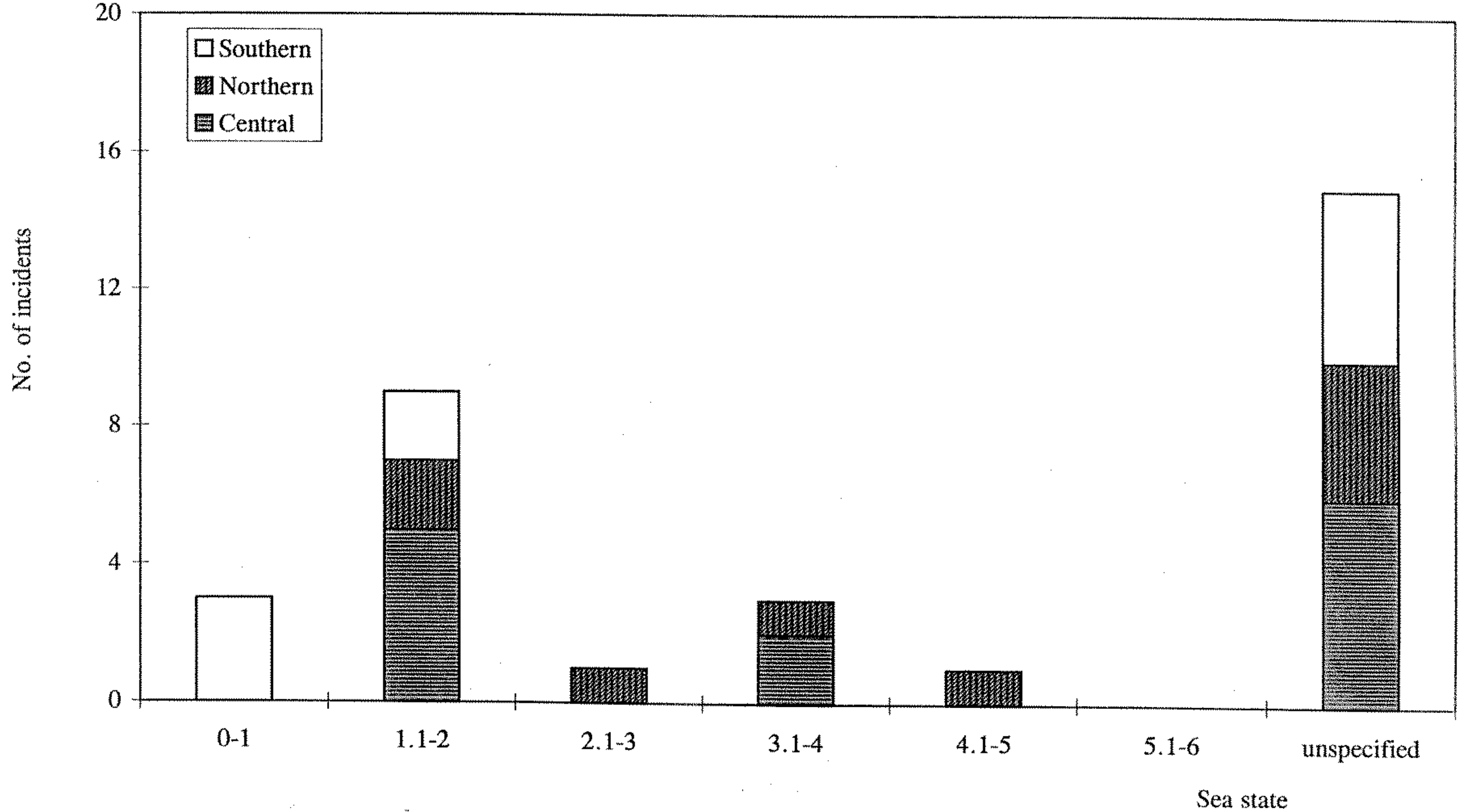

Figure 15: Distribution of Sea State for Supply Vessels (Human Error Only)

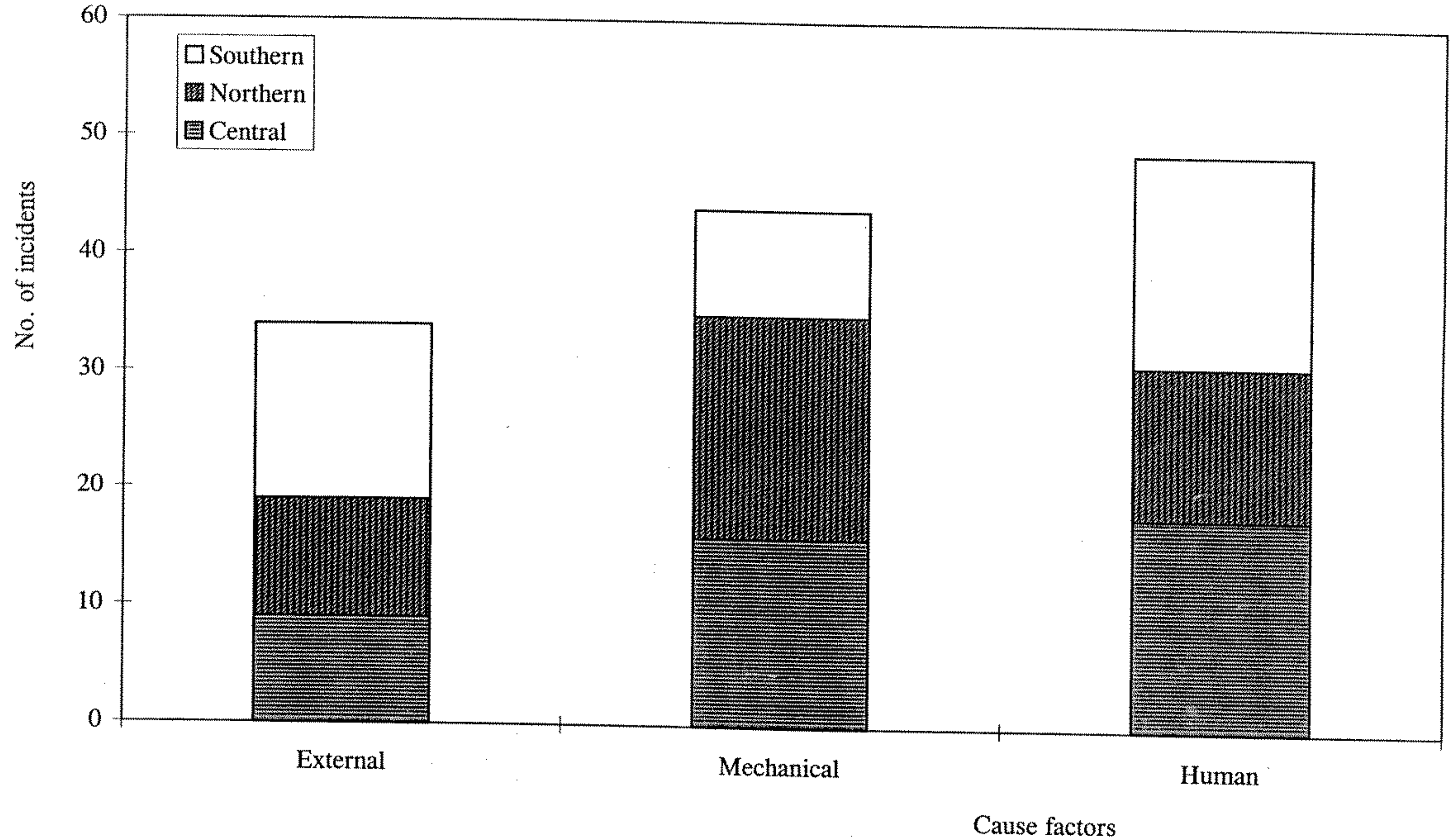

Figure 16: Distribution of Primary Cause Factors (All Vessels)

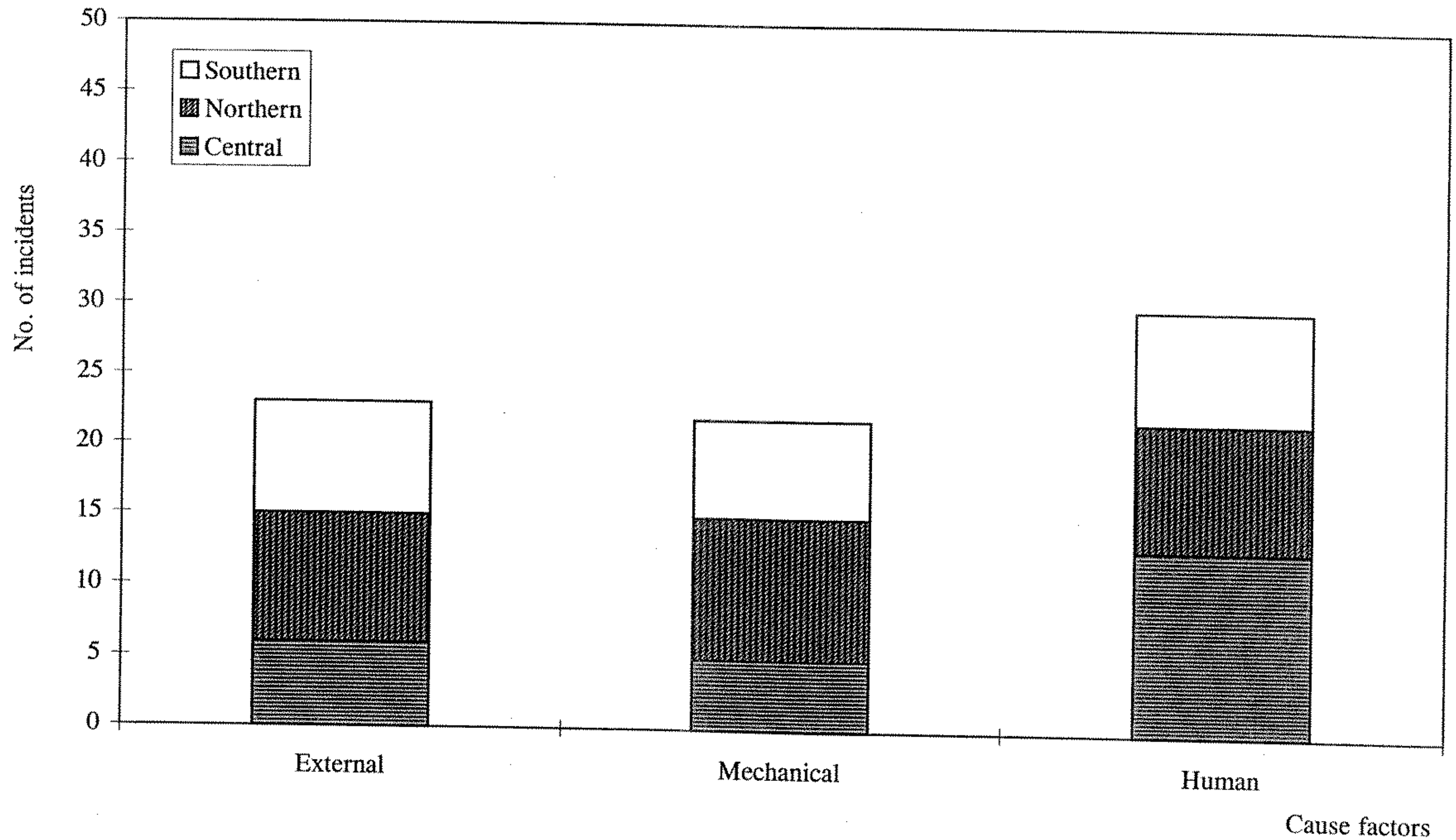

Figure 17: Distribution of Primary Cause Factors (Supply Vessels)