4

SHIP COLLISIONS WITH OFFSHORE PLATFORMS

Olav Furnes, MSc, Principal Research Engineer, Det norske Veritas
Jørgen Amdahl, MSc, Research Engineer, Det norske Veritas

ABSTRACT

Ship collisions with offshore platforms have been identified as one of the possibly major hazards in connection with production of hydrocarbons from offshore platforms.

For analysis of probability of ship - platform collisions, a new approach is presented, based on computer simulation techniques. This method and a summary of results to date, regarding collision with off-take tankers, are discussed in the paper.

Deformation characteristics and energy absorption of ship structures subject to collisions, are of major importance for a proper prediction of the impact forces. Such investigations are included in the paper. A simplified, theoretical calculation model is outlined, based on large plastic deformations on one of the sides. In this way, the relationship between impact loads and indentation deformations are obtained.

The impact resistance of concrete as well as steel platform main members subject to ship collision is discussed. Various modes of energy absorption in the platform structure are studied. Recent tests on local denting of models of tubular members of steel platforms are described.

For a concrete column the shaft strength with regard to punching shear failure and bending failure of shaft wall is compared with the loads likely to be imposed by a supply ship in sideways collision.

1. INTRODUCTION

Offshore oil activities involve several types of risks. Collisions between a ship and an offshore platform is one potential accident that has caused considerable concern. In fact, a survey of major accidents occurred to offshore structures during the period 1970-79 indicates that collisions represent one of the more significant risk contributing situations. Although the consequences of most offshore collisions have been minor to date, a ship collision is potentially an accident of highly serious character.

The event "collision" is characterized by the probability of occurrence and the inherent consequences. These must be regarded in relation. Major collisions endangering human lives, structures and environment must have low probability, while minor impacts occurring frequently must have small consequences. In principle, a collision evaluation should take into consideration the entire class of collision events, determine the probability and consequence associated with these events, and compare these with acceptance or design criteria. However, such a procedure will be very complex and in practice not very feasible. Instead, a selection of "design accidents" are defined as basis for the analysis.

It is important to realize that the probability as well as the consequences of collisions are affected by several factors such as traffic monitoring, navigational aids, field lay-out, platform topology, design and fendering, operational limits, size and manoeuvrability of the vessels, mooring equipment etc. Consequently, an acceptable safety level with regard to ship collisions should be attained by a well balanced and adequate composition of the various preventive and protective measures available.

As far as the risk of collisions is concerned the marine traffic may be divided into three groups:

i) Authorized vessels servicing the installations

ii) Tankers for offshore loading in the area

iii) All other kinds of by-passing ships.

This classification of ship traffic indicates that the nature of causes as well as the consequences may be quite different for the various groups. The most severe potential of a collision is associated with large merchant vessels or tankers running into the installation at full speed. On the other hand, the probability for this is small, thus making it rather unreasonable to design the structure as being capable of directly sustaining such a large collision load.

The most frequent type of collision is impacts from authorized vessels which operate close to the platforms. However, in most cases the consequences appear to be small concerning the structural safety of the installation.

Veritas has laid down the following guidance for the design of offshore structures against ship collisions. The following cases are considered:

i) Operational case in which no damage is allowed to occur

ii) Accidental case where local damage is accepted, but without collapse of the platform or major parts thereof.

The size of the impacting vessels is to be determined on the basis of the size of those vessels intended to operate in the area. Normally a supply vessel of 2500 tons displacement is used. The speed of the vessel is frequently taken as 0.5 m/s in the operational case and 1.5-2.0 m/s in the accidental case.

Although the criteria for certain types of collision loads are relatively specific, the knowledge of the structural response of the installations as well as the behaviour of the impacting vessel is rather sparse. To this end, Veritas has been conducting a comprehensive research project in order to improve the knowledge of impact loads, probability of collisions and structural behaviour as well as absorption and distribution of the initial impact energy. The final objective is to develop more realistic design criteria for impact loads.

2. PROBABILITY OF COLLISIONS.

Various methods are available for predicting the probability of ship collisions. NMI has conducted a rather extensive study related to the installations in U.K. waters /2/, in which the collision probability was estimated for various categories on the basis of recorded incidents, safety zone infringements, analogies with ship encounters and striking of other fixed objects (light ships, buoys) etc.

Evidently the risk of collision with by-passing vessels is closely related to the density of the traffic in the area. Platforms installed close to typical shipping routes will be more exposed to collision. In fact, the pilots tend to use them as navigational aids, thus approaching quite close to the installations /3/. As for the particular case of tankers involved in offshore loading operations the accumulated experience in the North Sea context is rather sparse and the majority of the methods mentioned above cannot directly be applied. Instead a new approach based on simulation techniques has been developed. The procedure has been described quite extensively elsewhere /4/5/ and only a brief description will be made here.

Obviously a complex variety of causes leading to a platform/tanker encounter exists. Considerable insight may be gained by applying the fault free method. However, it is an almost impossible task to evaluate the total collision probability accuratly, taking all kinds of human and technical failures into account. Thus, when performing analysis of the probability of collisions it is reasonable to consider idealized situations initially. When experience has been gained from the idealized model, one can thence proceed with a more sophisticated model.

In the present analysis it has been assumed that the tanker encounters a critical failure when approaching the loading buoy. Such a failure may be loss of propulsion, lock of rudder in the instantaneous position, blackout etc. After such failure it is assumed that no effort is made by the crew to avoid collision. The path of the tanker after failure will be influenced by the external forces acting on the ship, e.g. wind, waves, and current, position, velocity and rudder angle at failure. These factors can be considered as stochastic variables.

If F is the event that a critical failure takes place and C is the event that a collision between the tanker and an offshore platform occurs, the probability of collision is:

$$P\ (C) = P\ (C/F) \cdot P\ (F)$$

The magnitude of P (F) must be determined on the basis of experience failure data. P (C/F) is the conditional probability of collision which will be determined by simulation. By calculating P (C/F) for different arrangements of platforms relative to the buoy it is possible to choose the "best" arrangement if P (F) can be considered invariant in this context.

The method is illustrated by Figure 1. A critical failure has been assumed to occur at a distance of an offshore platform. By simulation and numerical integration the subsequent path of the tanker can be determined and its intersection with the circle through the platform can be calculated. Realizing that the path is influenced by the abovementioned stochastic parameters, the angle of intersection (Φ) will be stochastic and described by the probability density function p_{Φ} . By performing repeated (Monte Carlo) simulations this probability density function can be determined as a function of the distance at failure to the loading buoy.

The conditional probability of collision is indicated by the hatched area in the figure. Assuming that the tanker heads into the wind, the density function of the distance at failure can be derived from the velocity profile of the tanker and the long-term distribution of the wind. In this way it is possible to find the total conditional probability of collision by numerical integration over the entire domain of failure distances.

The numerical simulation solves the differential equations of ship motion as described in /6/ using the general simulation programme GASP IV.

The numerical technique outlined above has been used on a number of special situations. Consider the situation shown in Figure 2 , where a tanker is approaching a buoy on a course very close to a platform ($\theta = 15^{o}$). In the figure the probability of collision, P(r) related to critical failure at a distance r from the buoy is shown. As one could expect the collision probability has a peak when the ship passes the platform. The curve is based on calculations carried out at a number of points each representative of a 10 minute interval.

For any wind direction θ a similar curve can be determined. Based on such a set of curves it is possible by simple integration to compare the probability of collision $p(\theta)$ for different directions. For the situation shown in Figure 2 one gets e.g. the following values:

θ	$p(\theta)$
15^{o}	$1.7\cdot10^{2}$
105^{o}	$4.4\cdot10^{4}$
195^{o}	$\sim10^{5}$

As one would expect, these figures show that a course of the tanker close to the platform is more dangerous than a course farther away. When figures such as given above are known for all wind directions $\theta\varepsilon[0\ ;360^{o}]$ and if the long-term distribution of the wind is known for the site, the relative probability of collision $P(C|F)$ can be computed. In the case presented above one arrives at the following result:

$$P(C|F) = 6\cdot10^{-3}$$

using the wind rosette probability distribution of the site.

Although only the relative probability of collision can be determined by this method the simulation technique used herein seems to have promising potential. An important aspect is that it is possible to find the most favourable position of a buoy relative to the platforms. The buoy should, as expected, be placed on the main leeward side of the platform. However, the optimum and safest location is much more difficult to assess when there are several prevailing wind directions and many nearby platforms. For such cases, analysis of the sort outlined above are recommended.

Presently Veritas is developing an interactive ship simulator /7/ which will provide an efficient means to include the influence by the ship pilot. Besides studying the collision probability, the simulator will be well suited for simulation of selected critical situations with the purpose of investigating manoeuvrability requirements to tankers, alternative avoidance manoeuvres, time margins, requirement to tug assistance etc.

3. IMPACT ANALYSIS

A consistent design for impact loads requires a study of the collision mechanics fulfilling

- energy conservation
- force equilibrium

The kinetic energy of the impacting boat has to be transferred into elastic and plastic deformation of the ship and the platform structure itself including possible fendering. In the case of an eccentric collision some of the energy may remain as rotational kinetic energy of the ship after the initial stages of collision. This is discussed by Costa /8/. The energy conservation law may then be expressed as

$$E_k = E_b + E_p + E_f + E_r$$

E_k = kinetic energy of the boat immediately before collision

E_b = energy absorbed by the boat

E_p = energy absorbed by the platform

E_f = energy absorbed by fenders

E_r = rotational kinetic energy of the boat

For design of an unfendered structure the worst case is a central impact which means that the line through the centre of gravity of the ship and the point of contact coincides with the direction of the ship movement.

This eliminates the two last terms in the preceding equation and inserting $E_k = \frac{1}{2}mv^2$ we remain with

$$\tfrac{1}{2}\, mv_o^2 = E_b + E_p$$

with

m = mass + added mass of the ship
v_o = impact velocity

With known load-deformation characteristics for the boat as well as the platform, it is possible to calculate the energy absorption to maintain force equilibrium for different load levels by integrating the area below the respective curves. This procedure reveals that in a collision situation parts of the kinetic energy of the vessel has to be absorbed as strain energy in the colliding bodies. The amount of energy to be absorbed is determined by the impact geometry characterized by the relative orientation of the colliding bodies and the location of the contact zone. Thus, there exists an infinite number of possible impact situations. To consider all possibilities is not feasible. Instead, it has been common practice to study a number of simple and idealized situations.

The assumptions above are valid for collisions against fixed structures. In fact, some of the impact energy will be transferred to kinetic energy such as vibrations in the subject structure. For collision with a floating or buoy-type structure the global motion of the structure itself may as well become significant. The amount of energy to be absorbed is given by the expression:

$$E_s = \tfrac{1}{2} m v_o^2 \,\frac{\left(1 - \frac{v_p}{v_o}\right)^2}{1 + \frac{m}{m_p}}$$

where m_p is the mass and hydrodynamic added mass of the hit structure and v_p is the velocity of the structure at the instant of compact. This formula is also valid for an articulated column m_p is replaced by J/z^2 where J is the moment of inertia including hydrodynamic added inertia of the tower about the universal joint and v_p is the horizontal velocity of the column at water level. z is the distance from location of impact to the universal joint. The formula has been derived on the assumption that the effect of external forces (waves, mooring, buoyancy forces etc) can be neglected during the impact. Depending on the phase lag between the velocities and the mass ratio, the energy to be absorbed will differ from that of a fixed structure. Especially for floating structures of a certain extent in the wave direction this may be true.

It appears that if the bodies have opposed directions of velocity, situations may arise where the amount of energy to be absorbed may exceed the kinetic energy represented by the vessel.

The preceding considerations are valid irrespective whether the energy is absorbed by elastic or plastic deformation of the bodies. So, if the force-deflection relationship for the type of loading for each body involved is known, it is an easy matter to estimate the maximum load developing and the extent of damage.

Impact velocity

The kinetic energy is proportional to the second power of impact velocity which clearly emphasizes the significance of determining this magnitude with good degree of confidence.

Evidently one cannot discard the probability that a vessel may run into an installation at full speed due to negligence or lack of experience by the bridge crew. Whilst this may be a likely cause of collision with a by-passing vessel, this possibility is judged to be much smaller for dedicated vessels (service vessels, tankers for offshore loading) as the crew will be aware of the presence of near-by platforms. Therefore it is not considered reasonable to design for the large kinetic energy of say a tanker at full speed. Instead the probability should be kept at a low level by defining adequate preventive measures.

Various authors have proposed /9/10/ to take a supply vessel, drifting sideways in a given sea state, as the design basis accident. In the steady state condition the wind and wave drift forces will be balanced by the hydrodynamic resistance forces. In addition the vessel will excert sway oscillations with the same frequency as the waves. The instantaneous magnitude of the sway velocity will be normally distributed. Assuming the probability of hitting a fixed structure being proportional to the velocity, an approximate probability distribution may be derived.

In Figure 3 the cumulative distribution of impact velocity in different sea states is shown for a drifting supply ship with displacement 2500 tons. A reasonable criterion is to select the velocity associated with 5% probability of being exceeded. It appears from Fig. 3 that a design velocity of 2.0 m/s corresponds to a sea state H_s=3.5m. Experience has shown that this sea state is about the worst sea state for supply boat operation. If the long term distribution of the sea states is known, the velocity may also be related to a long term probability of being exceeded.

Obviously it is far more complicated to determine the corresponding impact velocities in the case of buoy-ship encounters, as both structures exert motions. As previously stated the relative phase lag between the sway motions is very important. The energy that has to be absorbed may be several times greater when the vessel motion is in opposed phase with the buoy motion, compared with the in-phase motion. While it is reasonable to anticipate a relative small phase lag for the buoy type of structure, the phase lag may become greater for floating structures of larger extension.

4. IMPACT DEFORMATIONS OF SHIPS

Knowledge of the deformation characteristics of ships in collision is fundamental for a proper prediction of the maximum total load as well as the development of the contact area.

Several previous projects have dealt with the energy absorbing capacity of ships in major collisions. However, much of the work has been directed towards the safety of nuclear vessels. An empirial correlation between resistance to penetration and energy absorption of ships was derived by Minorski /11/.However, the formula does not assess the force development during indentation and analyses of low energy cases, such as corresponding to supply vessels in collision, showed a wide scatter. Generally more damage was created than indicated from the striking speeds reported.

A promising approach to this problem was reported by M. Rosenblatt & Co. Inc. /12/ who made a comprehensive study of the structural damage of tankers in minor collisions applying plastic analysis methods.

Adapting similar techniques Veritas has developed a computer programme capable of determining the relationships between the force and indentation of the ship side. The calculations are based on a static approach accounting for plastic deformations only. It is assumed that the hull is equally indented over the entire ship side by a infinitely stiff object. Thus all dynamic effects including possible flexural hull girder deflection are neglected. The impact load acting on the ship side is determined for various degrees of indentation according to the membrane tension force of the ship side, deck and bottom and the plastic buckling load of the deck, bottom and transverse frames.

Due to lack of data from real collisions the model has been compared with several scale tests with a vertical, infinitely stiff bow indenting the side of different ship models measuring the static relationship between load and deformation /13/14/. Example of a load-penetration curve recorded in these experiments together with the corresponding calculated curve is shown in Fig. 4. The point R indicates where rupture of the ship side occurs. Beyond this point, the impact load drops dramatically due to disappearance of the membrane stresses in the side. Comparisons of the calculated and recorded load-penetration curves reveal that the magnitude of the impact load can be reasonably well predicted by theoretical means. However, discrepancies exist at several points. These are due to various reasons. In particular there are uncertainties regarding some of the predominant parameters of the theoretical model, such as the collapse load of the transverse frames, the rupture criterion and the membrane tension forces in the side.

The model as outlined above has been applied in a study with the objective of obtaining a "catalogue" of the deformation behaviour of various ships representative of those operating on the oil fields in the North Sea. In this investigation tankers, supply vessels and barges of various sizes are assumed to be hit by a vertical, rigid cylindrical column. The three column diameters studied are D=1.5 m (typical for a jacket structure) D=10 m and 20 m (the latter representing towers of concrete gravity platforms). When interpreting the results one should be aware of the shortcomings of the model as stated above. The force assessments should be considered as indications on the order of magnitude. Fig. 5 displays the results of one such calculation. The force-indentation relationships for collision between the transverse frames are presented for a supply vessel of 3200 tons displacement and for a tanker of 128.000 dwt. Generally, at initial contact, the force depends heavily on the buckling capacity of deck, bottom and transverse frames in the contact zone. At further indentation the membrane tension forces become predominant in tankers, causing only minor deviations between the curves relating to the various column diameters. However, for the small column diameter of D=1.5 m rupture of the side occurs at an early stage of indentation as there is no direct contact between the column and nearby transverse frame resulting in smaller extension of the plastic deformation. On the other hand, the indenting column diameter becomes a more important parameter for supply vessels. Having a space frame in the range of 0.6-1.8 m, direct contact with several frames may occur. Hence, the contribution from the membrane tension forces in the side will be small compared with the plastic buckling load of frames.

Curves of the type above can be used as basis for analysing upper limits for the impact force in a selected collision situation, namely a drifting vessel in a sideways collision. The impact velocities are selected according to the criteria referred to previously, yielding a value of 2.2 m/s.

A simplifying assumption has been made that all energy is to be absorbed by the colliding vessel. Maximum impact forces versus ship displacement are shown in Fig. 6. A typical load that may be caused by a tanker is in the range 100-200 MN, whereas the maximum collision load associated with supply vessels is one order of magnitude lower (factor 1/10)

Evidently the estimates of maximum load depend on the uncertainties related to the model assumptions, material properties etc. If the distribution functions of all the parameters were known, the distribution functions of the maximum impact force could in principle be determined. However, the statistical properties can only be assessed with some uncertainty for some of the parameters. The values derived for the impact force have been based on available characteristic values of the parameters and on proper engineering judgement (Fig. 6). These limit for the forces should, however, not be interpreted as accurate upper and lower values, but only as bounds derived from the assumptions made concerning the parameters. Within these limitations it is, in fact, interesting to note that the scatter in impact force is relatively small compared to the great uncertainties.

The investigations have so far concentrated upon sideways collisions, which in many cases may impose the largest impact force on the structure. However, sometimes also the intensity of the forces, i.e. the force pr. unit area, may be of concern. This may be the case when considering the punching shear strength of a concrete tower. Situations with high localized forces may in particular occur during the early stages of sideways collision with contact at bilge or deck frame and in bow or stern collisions. These aspects will be emphasized in the further refinements to be made with the ship collision analysis model.

5. ENERGY ABSORPTION IN STEEL JACKETS

So far collision studies of steel platforms have introduced several simplifying assumptions. If the ability of resisting a possible maximum load has been of main concern, the total kinetic energy has often been assumed to be absorbed by the ship as discussed in section 4. On the other hand the energy absorption capability of the platform itself is an important aspect and has been analysed on its own. Another extreme situation is to assume that the platform will absorb all impact energy, however, this may lead to unduly conservative design. Indeed, the real behaviour of the platform is between these two extreme cases. As illustrated in Fig.7 the impact energy will be absorbed by the platform in different ways, depending on the relative stiffnesses. This means energy absorption due to local deformation of the cross-section of the member being hit, beam deformation between neighbouring joints and global bending of the entire structure. While the two first modes involve considerable plastic deformation the global response will be mainly elastic.

Local energy absorption

As a first step in the analysis of the impact resistance of steel structures it is natural to ask how much energy will be associated with deformation of the structure just beneath and in the proximate vicinity of the load. Except for a number of tests reported in /15/, the information existing in the field of large-deflection behaviour of steel tubes subjected to lateral load is rather sparse. Consequently a number of tests with small-scale models have recently been conducted by Veritas.

The test arrangement, shown in Fig. 9, consists of a tube specimen mounted to a stiff frame by means of four clamp at each end of the tube, providing vertical support and a small rotational restraint. The load is applied through a rigid beam across the tube and pushed by a hydraulic jack, while the deflections are monitored by electrial potensiometers. The main parameters of interest are the diameter to thickness ratio of the tube and the breadth of the beam indentor. The selected parameters of the test tubes are listed in Table 1.

The load-deformation relationships measured during the tests are summarized in Fig.8 . The form of the arrived curves appear to be quite similar regardless of the breadth of the loaded area and the physical properties of the tube. However, the bearing capacity increases somewhat with increasing breadth of the loading beam.

The load arises steeply in the initial stages of deformation, then the gradient decreases gradually until the net deflection approaches a value of about 0.7 times the radius of the tube. At this stage the tube starts deflecting like a beam. Due to development of high axial forces there is a small increase in the load. Beyond this limit the axial forces became so large that the bolts failed at the supports. Fig. 10 shows that the major part of deformation is localized to the area close to the load.

The experimental results above can be compared with a theoretical calculation procedure based on the theory of plasticity. Provided all effects are included in the model this will yield an upper bound prediction for the load. The plastic work is calculated for the deformed surface which is assumed bounded by a series of yield lines. The effects included are

- Rotation at the yield lines
- Flattening of the surface between yield lines
- Tension work due to elongation of generators.

A rigid plastic material is supposed so that strain hardening is neglected.
In general the load-deflection

relationships are estimated fairly well at small indentation whereas the deviations increase when the tube starts undergoing global deformations. The latter stage of deformation may also be accounted for in a plastic collapse analysis when assuming beam behaviour and allowing for the change of beam cross-sectional geometry.

Fig. 11 summarizes the strength properties of the tube as predicted by the theory. The forces are made non-dimensional by the factor

$$M_p \cdot \sqrt{(\frac{D}{t})} = f_y \; \frac{t^2}{4} \sqrt{(\frac{D}{t})}$$

where f_y is the yield stress, and t and D are the tube thickness and tube diameter, respectively. The experiments indicate that these curves can be applied for design purposes. A possible design curve is suggested in the figure. At present Veritas is carrying out similar tests with double skin grouted tubes.

Beam deformation behaviour

In the initial stages of loading the hit tube will deform locally until the load reaches a value at which the tube starts to deflect like a beam. In this phase a considerable amount of energy will be absorbed, depending mainly on the support conditions and the strength of the actual tubular joints. The simplest approach to the beam type of deformation is the three hinge mechanism in which hinges develop under the load and at the supports. If the ends of the beams are axially restrained the capacity of the beam will increase considerably as the beam undergoes finite deflections due to development of membrane tension forces. For centrally loaded tubular beam the load-carrying capacity is given by:

$$\frac{P}{P_o} = (1 - (\frac{\delta}{D}^2)^{\frac{1}{2}} + \frac{\delta}{D} \arcsin(\delta/D) \qquad \frac{\delta}{D} \leq 1$$

$$\frac{P}{P_o} = \frac{\pi}{2} \cdot \frac{\delta}{D} \qquad \frac{\delta}{D} \geq 1$$

where P_o is the plastic limit load in bending and δ is the plastic deformation of the tube at the load. The expression above assume that the ends have either zero or full axial restraint. In a typical jacket structure it is likely that the supports provide some intermediate degree of axial restraint. The post yield behaviour of tubes including the influence of in-plane displacements has been studied in /16/. Here the load is related to the stiffness of the supports against axial displacement represented by an equivalent spring constant K, which may be assessed by a frame analysis of the structure. In Fig. 12 curves relating p/p_o to the stiffness parameter $k = DK/\pi Ltfy$ are shown. It appears that it is very important to have a fair estimate of this stiffness parameter k.

The discussion above is based on the assumtion that the tube possesses enough rotational capacity to develop a fully plastic mechanism. It is well-known that the tube may fail at a lower load level due to local buckling, ovalization or fracture at the weld. From literature reviews /17-19/ it is found that for a D/t ratio less than 35 plastic design may be applied. Above this limit this procedure may not be reliable. Since the D/t ratio of actual jacket members is in the range of 20-50 it is concluded that this problem warrants clearification. The API rules prescribe D/t < 9000/fy (fy in MPA) to maintain full capacity through plastic deformation. For 9000/fy< D/t < 15200/fy only a limited plastic rotation capacity can be presumed. On the other hand, the capacity may not be exhausted if the plastic moment drops. Restrengthening may occur in plastic tension. Although the lower collapse load is associated with a load at midspan, another question is whether the joints are able to support the load when the location of impact is close to the joints. In other words, a shear failure may be possible. If the load transferred to the joints exceeds the capacity of the joints the amount of energy absorbed by the beam mechanism is greatly reduced. Although the stress effect at the joints is composed of both punching shear, shell bending and membrane stresses the simple concept of punching shear is widely adopted for characterizing the stress state. It is natural to apply codes developed by recognized institutions when investigating the capacity of the joints /20-22/. The normal control is to ensure that the nominal punching shear stress, deduced from the brace loads, does not exceed the allowable punching shear stress derived empirically from model tests. A survey shows that various load combinations are treated somewhat differently by the various codes.

Global deformation

When a jacket is hit by a floating vessel it will start to deflect globally like a girder, in addition to the displacements of the elements in direct contact with the impacting body and the surrounding elements. In section 3 the central impact was mentioned as being the worst case, in which all the impact energy has to be absorbed by the colliding bodies. However, some of the impact energy will be transferred into kinetic energy due to exitation of vibrations in the platform. Hence, a static approach may be insufficient in order to determine the energy absorbed in global bending of the platform.

In fact one is not only interested in the energy distribution. The ability of the jacket to sustain the load without collapsing is of main concern. Progressive collapse may be initiated by a number of elements failing due to instability,punching shear etc. Such situation should be investigated by removing failing elements and perform reanalysis of the collision load. The ability of the platform to develop plastic membrane in bracings should be verified by removing bracing exposed to collision and introduce plastic tension forces at the modes. Even if the platform is capable of surviving the direct collision load, subsequent environmental loads in severe weather conditions may represent a threat to the platform. The amount of collision damage allowed to the platform may be restricted by requirements to survival during the repair period. Hence, reanalysis of the platform with damaged members removed should also be conducted for the maximum credible storm condition during this period.

The dynamic response of the structure depends on the form and duration of the impact impulse relative to the natural periods of vibration. As an illustrative example a four-legged jacket at 70 m water depth has been studied. The structure has been analysed by an ordinary linear-elastic space frame computer programme. The load input to the calculation is that caused by a supply vessel in sideways collision, as described in section 4. The mass and impact velocity of the supply vessel is 3200 tons and 2.2 m/s. An added mass factor of 0.4 was applied. It is assumed that the vessel hits the structure at one corner leg joint, which is locally stiff due to grouting, so that the energy contribution from local - and beam deformation of the leg can be neglected.

The dynamic response is illustrated by a sketch of the corner leg, Fig. 13. It appears that the leg behaves like a girder partially supported at both ends in the initial stages of loading due to the heavy inertia represented by the deck module. At later stages the deck takes up kinetic energy, making the jacket act like a cantilever and resulting in an increased deflection at the deck level. It is evident that the deformation pattern, which deviates considerably from the static solution shown in Fig. 14 consists of several eigenmodes.

The distribution of energy during the impact is illustrated in Fig. 15. While the kinetic portion is significant during the intermediate phases, it only amounts to about 5% of the total energy at final stage. The analysis shows that yielding and instability failures will occur in the structural elements surrounding the contact zone. The model adopted is obviously not able to represent the true behaviour of the structure at all stages. When failure occurs the stiffness of the platform will change. Such effects can only be accounted for by performing non-linear analysis.

Energy absorption of platforms

It is not possible to give a general formula on how the energy will be distributed in the platform due to the complex variety of all possible situations of collisions.

While both the bracings and the legs may be hit by the bow and stern of the vessel, the legs are the more likely point of initial contact if the ship drifts sideways onto the platform. In the first case the contact zone will be limited. If the ship structure does not deform too much, the effect on the platform may be simulated by a concentrated load. In the latter case the contact zone may spread along the entire height of the ship side. It is, however, likely that the initial contact will be located to the deck corner or bilge due to roll motion and thence followed by contact along the entire side.

The amount of energy that will be absorbed locally by actual jacket members depends most of all on the wall thickness of the tube. For wall thicknesses in the region 20-50 mm this energy may be significant compared to the total collision energy. Below this level the wall thickness is so small that the contribution is negligible. On the other hand, excessive wall thickness provides a shell strength which exceeds the loads likely to be imposed by typical vessels.

Inspecting the typical dimensions of jackets, it is clear that the corner legs of medium size platforms will undergo considerable plastic bending. On the other hand, if a bracing is hit, the smaller dimensions cause a predominant portion of the energy to be absorbed by membrane tension. An indispensible condition for membrane tension forces to develop is that the tubular joints possess the strength required.

The energy contribution from global bending of medium size platforms is significant. For deep-water platforms the dynamic magnification are anticipated to increase due to increasing periods of vibration. On the other hand, the stiffness of the platform will increase so that the impact impulse from a vessel will only induce a small deflection.

6. IMPACT STRENGTH OF CONCRETE STRUCTURES

When considering concrete gravity structures subject to ship collisions, the impact analysis, energy considerations and aspects of ship deformations and collision forces remain essentially similar as for fixed steel platforms. However, concrete platforms are in general more stiff and rigid as compared to steel jackets in similar depths of water.

The strength analysis will be considered in two steps: -

i) local strength of the concrete wall in contact with the colliding ship

ii) global strength of the tower (platform) and residual strength in order to avoid progressive collapse in case of local damage

Item (i) above relates to punching shear strength of the concrete wall when subject to a local impact load and, if appropriate, local bending strength in conjunction with this. It is here of importance to realize that a ship collision, if not minor, will result in a deformation of the ship so that the area of contact will not remain constant in the course of the collision.
For sideways collisions, the ship will tend to bridge across an initially punched hole in the wall, thus possibly activating considerable reserves of local strength. In this way one must take account of the dynamic nature of the collision situation with changing area of contact, which will also make the analysis considerably more complex. Step (ii) entails an analysis of the global strength of the member (tower, platform etc.) when subject to a localized collision force that has to be determined as a function of the deformation occurring. If the collision force is large enough to create local damage in the zone hit by the ship, this has to be taken into account when analysing the global strength subsequently.
A further analysis to ensure that progressive collapse will not take place with the local damage endured, will also have to be carried out for defined storm situation until the situation can be fully restored by repair and structural strengthening.

As for the design of steel structures the energy absorbed by the deformation of the ship the fenders and the structure has to be considered. Offshore concrete shell structures with a thickness of 0.5 m or more are stiff compared with the ship's hull and this may lead to quite serious damage to the ship before the forces have reached a critical level with respect to the local strength of the concrete. Local spalling and chipping at the point of contact can hardly be avoided in an unfendered zone, but the punching shear strength should be checked using design forces obtained from the impact energy analysis.

The local shear resistance (punching shear) may be expressed as the sum of the following components:

$$V_r = V_{cr} + V_{pr} + V_{sr} \leq 0,25 \cdot f_{cr} \cdot b \cdot d$$

where

- V_{cr} is the shear resistance due to the concrete and the longitudinal reinforcement
- V_{pr} is the shear resistance due to prestress or axial force
- V_{sr} is the shear resistance provided by shear reinforcement
- f_{cr} is the design compressive strength of the concrete
- $b \cdot d$ is the width and thickness of the studied member

More detailed design formulae may be found in DnV's Rules /22/(Appendix D: Concrete Structures) or in other relevant design codes.

The punching shear strength of a number of concrete shaft designs have been estimated either by scaling experimental results or using the CEB-FIP Model Code for concrete structures /23/. To make a comparison possible the results have been scaled to a typical column with an internal diameter of 12 m and a wall thickness of 0,6 m using a load factor γ_f = 1,0 and material factors γ_m concrete = 1,5 and $\gamma_m$steel = 1,15.

The results have been plotted together with force contact zone curves for a typical supply-boat with 2500 tons displacement in Fig.16. It is seen that in the early stages of a collision, for a given equivalent radius of contact zone, the strength of concrete in punching shear is apparently greater than the force which the supply boat can apply.

As explained earlier, the capacity of the concrete column to absorb energy in a collision will not be limited by a possible punching shear failure, which may be due to underestimation of the local stiffness of the boat or inappropriate shear design. For a sideways collision, the impact force can be transferred to the undamaged part of the shaft due to the bridging of the ship structure.

If a punching shear failure can be prevented in the early stages of a collision it seems unlikely that such a failure will occur later because of spreading of the contact zone due to deformation of the ship and the rapid increase of punching shear strength with the area of contact.

However, elastic theory calculations may predict the stress in the reinforcement in the contact zone to reach yield or the concrete to crush. It is then necessary to allow for inelastic deformation of the concrete, in order to calculate the energy absorption. In the absence of a non-linear computer programme capable of analysing a concrete cylinder under radial load, estimates of the load required to cause a local bending failure of the column have been made using a form of yield-line or plastic theory. Where possible, conservative assumptions have been incorporated in the plastic theory, and the usual material factor γ_m = 1.5 has been included. The corresponding failure loads and contact chord lengths are plotted in Fig. 16. The concrete capacity appears to be much greater than the force which the ship can apply on the same contact area (using the entire ship's side).

From this analysis it appears that a typical supply boat is not strong enough to cause a local failure of a typical concrete column in a sideways collision, although it can cause local yielding and cracking. However, this conclusion is based on rather simplified calculations and needs experimental confirmation. Bow-on collisions have not been investigated in full detail, and of course if the boat were heavier or the column less substantial the conclusion would require amendment.

If a local failure does not occur, an overall bending failure of the platform leg will not occur either. Again, this relates to the particular study made here with sideways collision with a typical leg. The force which the ship can apply is limited in two ways: firstly the ship's inertia can cause a plastic flexural hinge in the ship in a heavy collision, limiting the sideways force on the column, and secondly, for heavy indentations the force from the ship's side will drop when the plating reaches its ultimate strain and begins to tear. Both these limits appear to be below the force necessary to cause an overall failure of the leg, unless it has been damaged fairly extensively locally.

For the majority of punching shear tests performed the loading has been static and only a few used dynamic loading. The reason for this is the quasi-static nature of the collision between a ship and a rigid or little deformable body. A study of these tests have been made by Veritas /24/, with the main objective to compare the punching shear strength of a curved cylindrical shell with the corresponding results from tests on flat slabs. This was performed for different loaded areas with varying form such as quadratic, circular and rectangular with the long axis parallell to or perpendicular to the generator of the cylinder. In addition to this the influence of prestressing and scale effects were investigated. The results show that the punching shear strength of cylindrical walls will increase compared with flat slabs of the same thickness. Although the various investigators tend to use their own formulae for punching strength, the formula proposed by Veritas above compares favourably and include all main effects to be considered.

7. SUMMARY AND CONCLUSIONS

1. Ship collisions with offshore platforms are being recognized as involving considerable risks which should be adequately designed for and protected against. When analyzing the probability of ship collisions, this is made difficult due to the various types of ship traffic and due to the fact that statistical data are lacking. It is therefore recommended that further work should be carried out in gathering collision data including situations of "near misses".

2. In the absence of sufficient data, Veritas has turned to simulation studies as a prospective method for analysing ship collision. This has been done within the framework of the general simulation programme GASP IV. This method has been used to simulate the ships path after critical failure and drifting towards neighbouring platforms, relating to an offtake tanker servicing an offshore field with a loading buoy. In this way statistical data have been generated and may further be calibrated against historical data. The further work intended in this area will incorporate interactive simulation whereby the ship pilot or crew can be allowed to influence the out-of-control tanker by any means they might be in control of.

3. As for the impact analysis this is based on the principle of conservation of energy and force equilibrium. This means that the initial collision energy has to be absorbed by ship, platform, fender system and that any remaining energy will be transformed to rotational energy in the ship and vibrations in the colliding structures. Whereas this method of analysis is quite simple impressible, further work is recommended to ensure that all major aspects are sufficiently well catered for. For instance, pressure loads and other effects in ships containing liquid, may set up considerable transient force effects during the course of the collision.

4. As a basis for any prudent analysis of ship collisions, a realistic analysis of collision forces on ships has to be carried out. In fact, major part of our work today has been concentrating on energy absorption, indentation and stiffness characteristics in colliding ships. Analysis methods and computer programmes which compare favourably with known model tests have been established for tankers and supply ships in sideways collisions. By this kind of analysis it is possible to arrive at quite reasonable upper and lower bounds for the forces exerted by various ships in sideways collision. The future work will be concentrating on bow and stern collisions and other hard spots which so far have not been included.

5. Steel platforms such as f.inst. steel jackets are vulnerable to collisions by ships out of control. Considerable work has been devoted to this aspect. The impact energy to be absorbed by the platform itself will be due to local damage of the hit member, major deformation of the hit member and adjacent joints as part of the adjoining frame and thirdly, by the overall deflection of the entire platform which in many cases may very well be elastic.

   Plasticity methods have been used in assessing local impact strength of steel tubular members. Tests have been carried out on steel tubes and the results can be fairly well predicted by this theory. Further work is now in progress regarding double skin, grouted tubular members which will have much more local impact resistance. Future work should concentrate on energy absorption in the entire member and the adjoining frame. In particular it is of interest to have large scale tests carried out on models of typical cylindrical steel platform legs with internal stiffening and subject to concentrated collision loads. It is hoped that the method of plasticity can also be adapted in order to predict impact strength of such stiffened structures properly.

6. Concrete platforms of the caisson tower type have also some vulnerability with regard to ship collisions. However, supply

ships of normal size does not at present seem to be a realistic threat as analysis shows that it hardly is strong enough to damage existing towers substantially. This does not preclude smaller local damages such as chipping and local yielding of steel, a situation that can be mastered by subsequent repair work. Another matter is collision with large ship such as a tanker or merchant vessel at full speed.
Such a situation will involve forces in excess of those being considered realistic to design for. Nevertheless it is important to know the limiting conditions and what forces would be required in order to produce a substantial damage to a given platform tower. Defining this accidental situation, further requirements would be that the platform shall not sustain progressive collaps in a subsequent and defined storm situation. As basis for analysis of impact strength of concrete walls punching shear formulae have been developed by various investigators based on several test programmes. It is believed that the punching shear formula in common use will predict the local strength conservatively in most cases. The tests performed so far will not cover the dynamic situation in that a colliding ship is likely to bridge across an initially punched hole and thus transfer the load to the undamaged parts of the wall as the collision proceeds. It is therefore recommended that further work in this area allows for the dynamic change of the contact area for a cylindrical concrete tower subject to a realistic ship collision.

7. It is the intention of Veritas to continue its already substantial work in this field. A continued project (phase II) is currently proposed to interested parties. This work, if it proceeds, will in fact cover all aspects mentioned above, and will proceed as soon as the funding has been sufficiently secured.

REFERENCES

(1) Amdahl, J., Furnes, O. et al: Impacts and Collisions Offshore. VERITAS Project Reports (1977-1980), Progress Reports 1-10.

(2) The Risk of Ship/Platform Encounters in U.K. Waters. NMI, England 1977

(3) Batchelor, Chalk, Lewison: Survey of Shipping in the Forties Field 1978. NMI, England, 1979.

(4) Thoft-Christensen, P.: Probabilistic Simulation of Offshore Collisions. Second Danish-Polish Matm. Progr. Seminar, Denmark 1979.

(5) Furnes, O., Amdahl, J.: Computer Simulation Study of Offshore Collisions and Analysis of Ship-Platform Impacts. Brazil Offshore -79, 1979.

(6) Norrbin, N.H.: Theory and Observations on the Use of a Mathematical Model for Ship Manoeuvering in Deep and Confined Waters. SSPA, Publ. 68, 1971.

(7) Heldor, E., Amdahl, J.: SAILSIM - A Simulator for Analysis and Risk Assessment of Ship Movements. ASSOPO 80, Trondheim, 1980.

(8) Costa, F. Vasco: The Berthing Ship. The Dock and Harbour Authority, Vol. XLV, 1964

(9) Larsen, C.M. Engseth, A.G.: Ship Collision and Fendering of Offshore Concrete Structures. EUROPEC, London, 1978.

(10) Thoresen, C.A., Torset, O.P.: Fenders for Offshore Structures. 24th Int. Navigation Congress, Leningrad, 1977.

(11) Minorski, V.U.: An analysis of Ship Collisions with Reference to Protection of Nuclear Power Plants. Journal of Ship Research, 1959.

(12) M. Rosenblatt & Son, Inc.: Tanker Structural Analysis for Minor Collisions. Dep. of Transp., U.S. Coast Guard, Washington, 1975.

(13) Studies on Collision Protective Structure of Nuclear Powered Ships. The Shipbuilding Research Assocication of Japan, Rep. No. 71, 1970.

(14) Jour. of Zosen Kioakai, The Society of Naval Architects of Japan, Vol. 118, 1965.

(15) Thomas, S.G. et al: Large Deformation of Thin-Walled Circular Tubes under Transverse Loading. Part I-II, Int. Journ. of Mech. Sciences, Vol. 18, 1976.

(16) Oliveira, J.G. de: Simple Methods of Estimating the Energy Absorption Capacity of Steel Tubular Members Used in Offshore Structures. Report SD/r50, Div. of Marine Structures, NTH, Norway, 1979.

(17) Sherman, D.B.: Tests of Circular Steel Tubes in Bending. ASCE Journ. of Struc. DiV., Vol. 102, No. St11, 1976.

(18) Dhalla, A.K.: Discussion to /17/ ASCE, Journ. of Struc. DiV., Vol. 103, No. ST8, 1977.

(19) Allen, D.: Discussion to /17/ ASCE, Journ. of Struc. DiV., Vol. 103, ST7, 1977.

(20) Recommended Practise for Planning, Designing and Constructing Fixed Offshore Platform. API, March, 1979.

(21) Regulations for the Structural Design of Fixed Offshore Structures on the Norwegian Continental Shelf. NPD 1977.

(22) Rules for the Design, Construction and Inspection of Offshore Structures. Det norske VERITAS, 1977.

(23) CEB-FIP: Model Code for Concrete Structures. FIP, London, 1978.

(24) Carlin, B., et al: Offshore Fender Systems. VERITAS Report No. 77-156, 1977.

Specimen No.	DIN	Diameter D (mm)	Thickness t (mm)	D/t	Length L (mm)	Yield stress f_y (N/mm)	Breadth of loading beam (mm)
0		298	6.6	45.2	1190	426	100
1	St 35	219.1	7.3	30.0	1340	328	100
2	"	"	6.2	35.3	"	"	100
3	"	"	"	"	"	"	50
4	"	"	"	"	"	"	195

TABLE 1: Principal data of test specimens

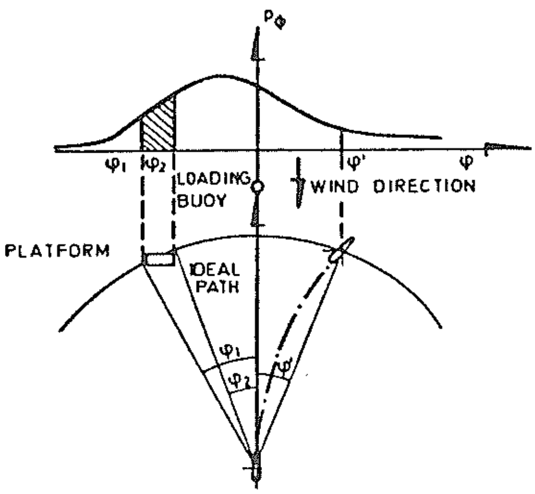

FIG. 1: Collision probability simulation model.

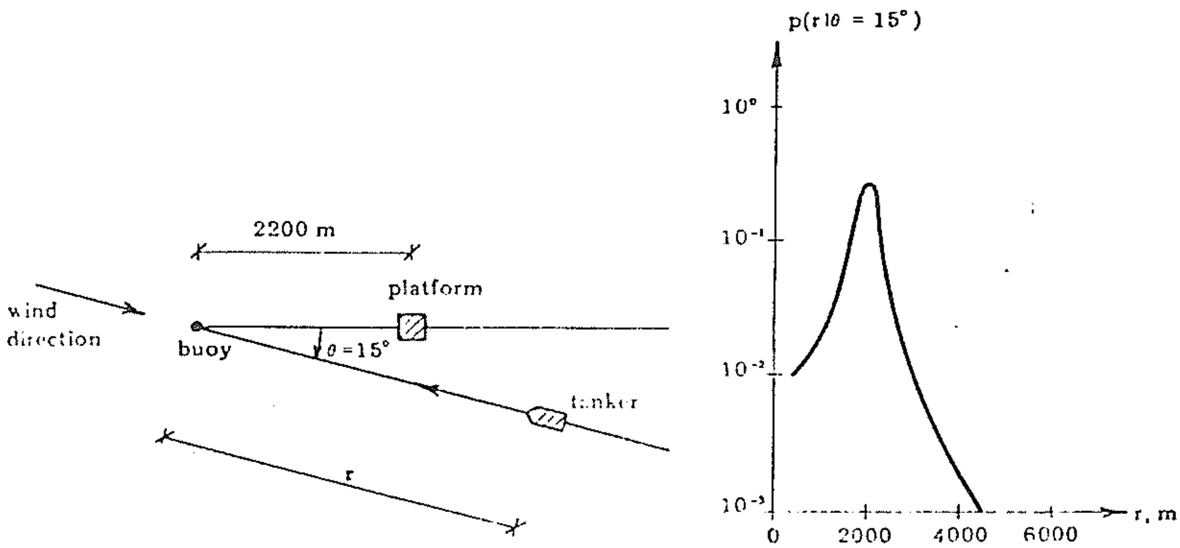

FIG. 2: Collision probability for a given approach direction

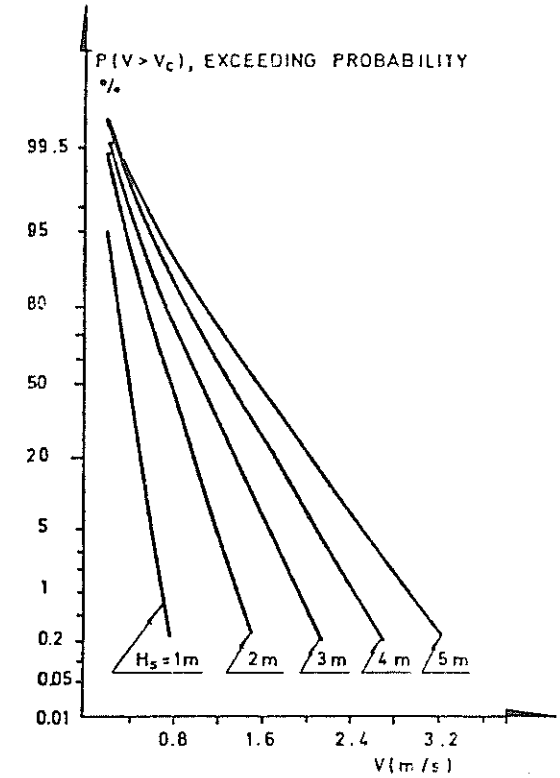

FIG. 3: Distribution of supply vessel impact velocity

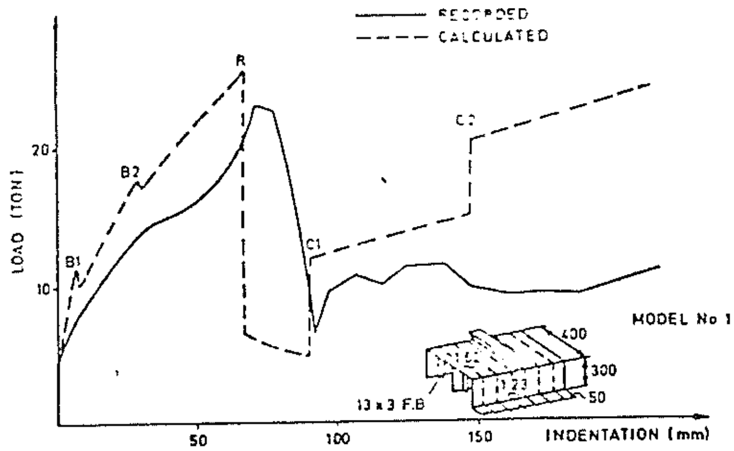

FIG. 4: Load-indentation relationship for a ship side model.

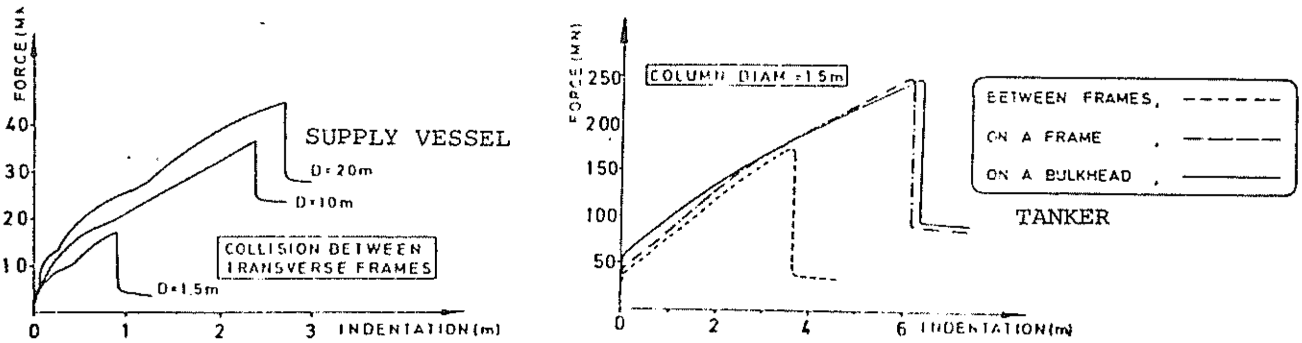

FIG.5: Force indentation curve for a supply vessel and a tanker.

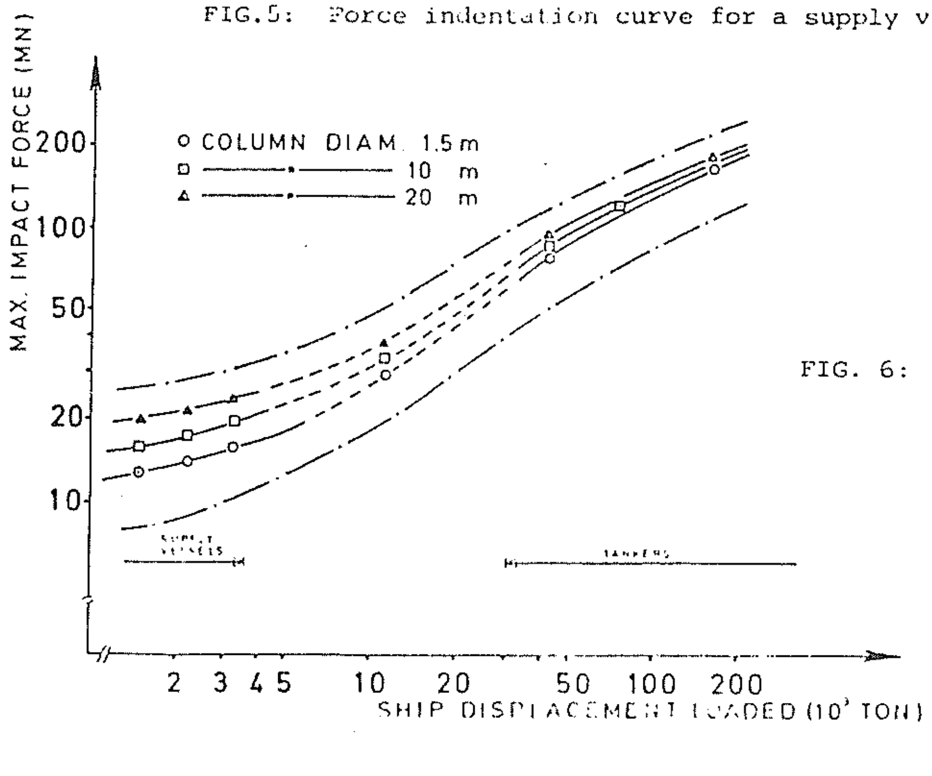

FIG. 6: Max. impact force versus ship displacement. All energy absorbed by the ship.

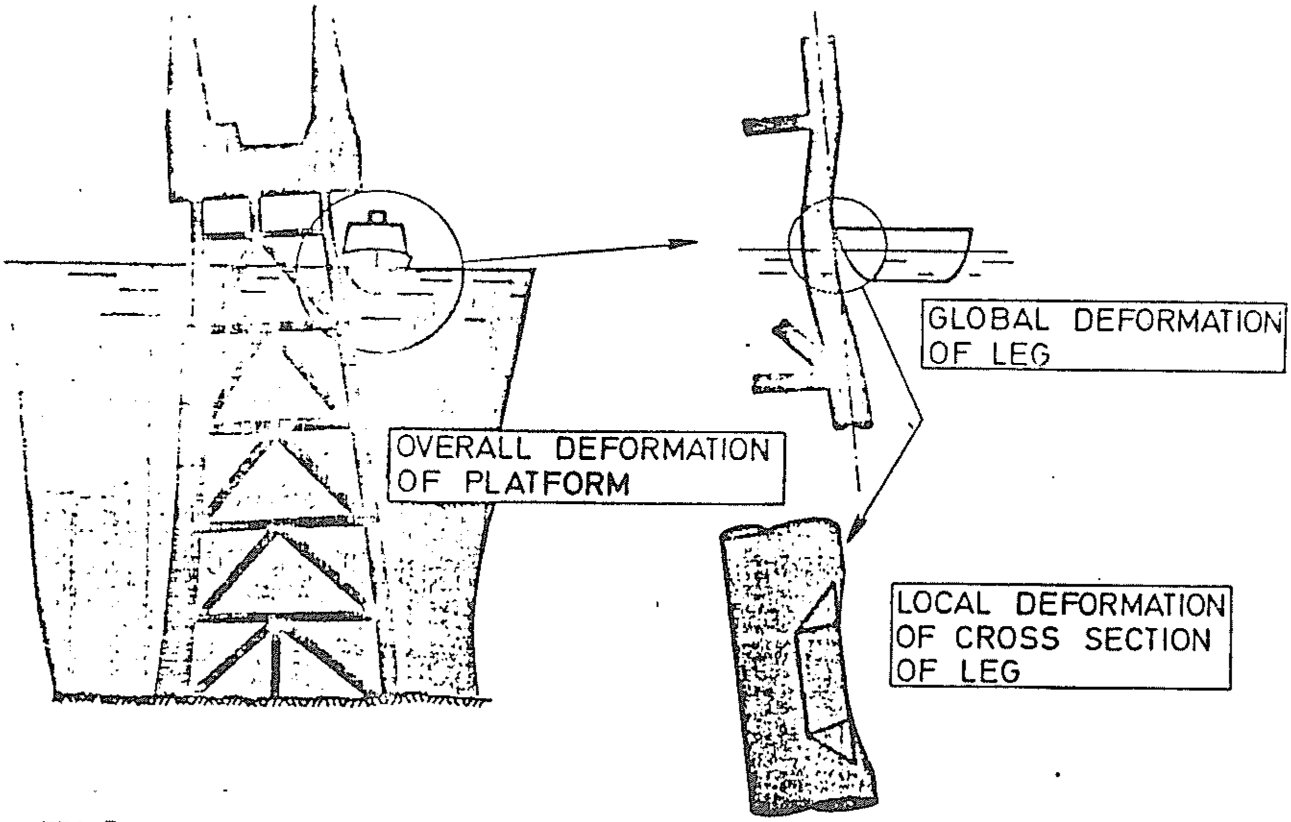

FIG 7: Energy absorption of steel jackets

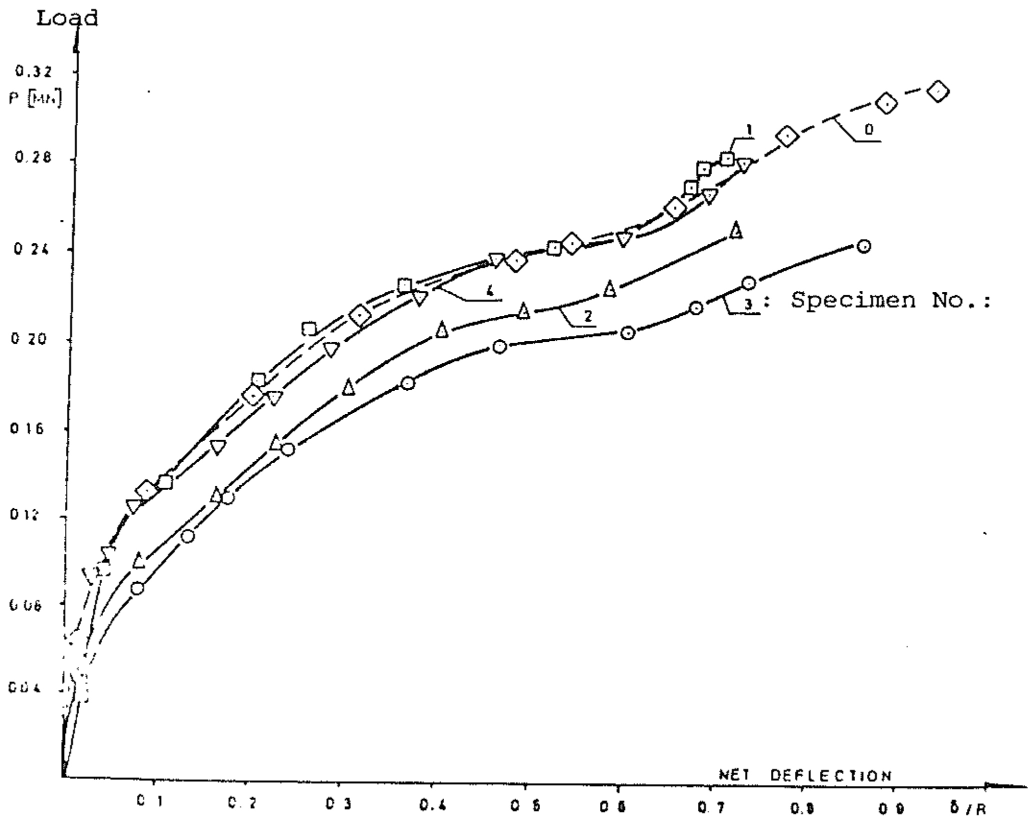

FIG. 8: Load versus net deflection for local denting of steel tubes.

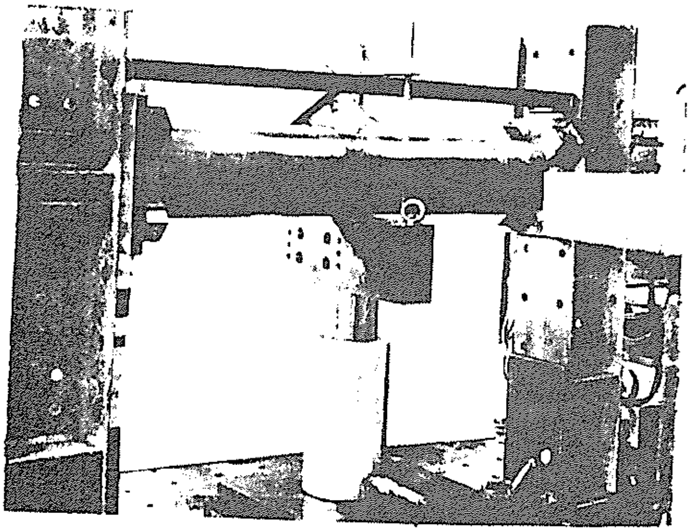

FIG. 9: Test arrangement

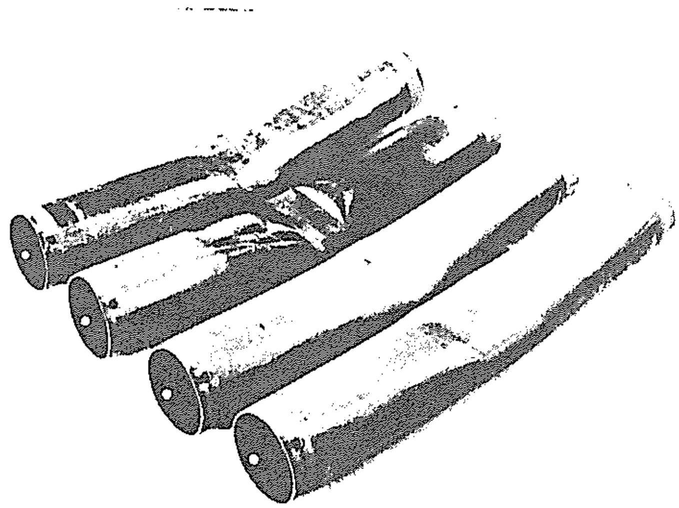

FIG. 10: View of tubes from the loaded side

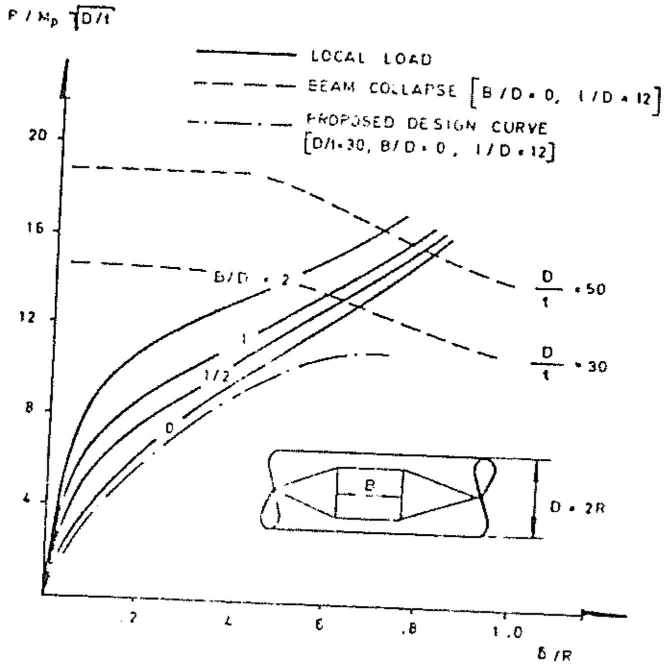

FIG. 11: Non-dimensional load-deformation diagram for transversly loaded tubes.

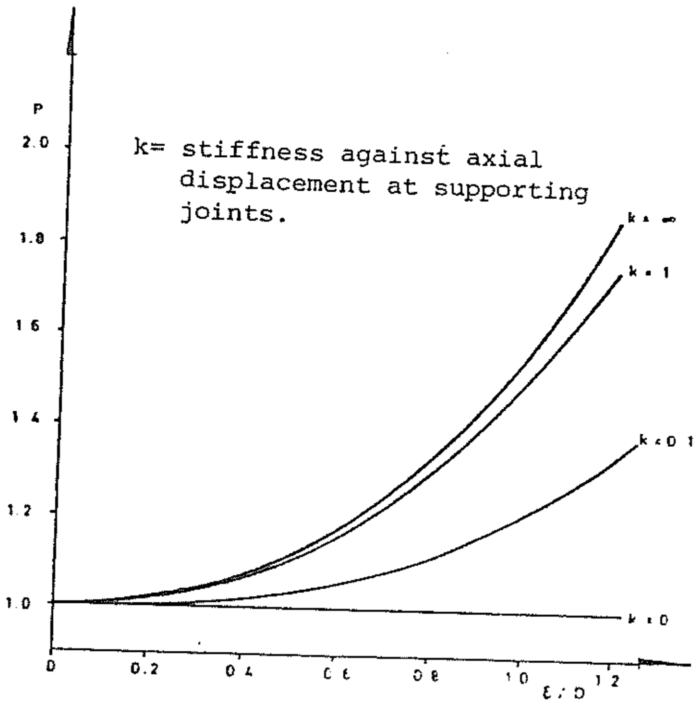

FIG. 12: Beam hinge load v.s. axial stiffness of joint.

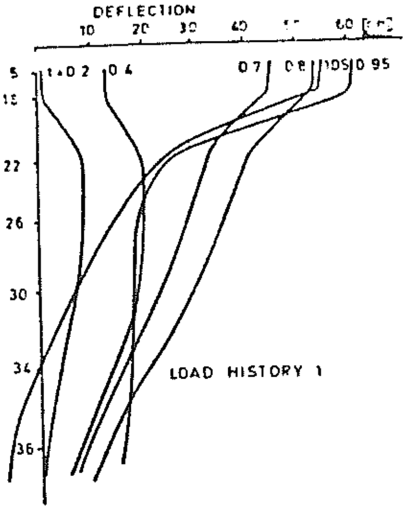

FIG. 13: Dynamic response of a jacket corner leg.

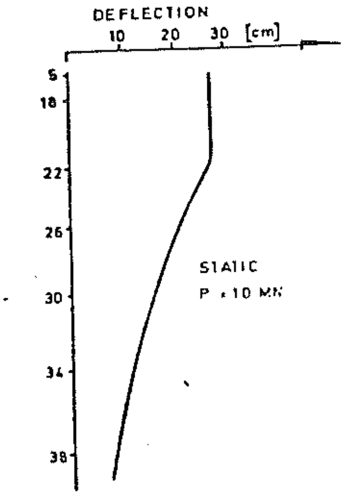

FIG. 14: Static response of a jacket corner leg.

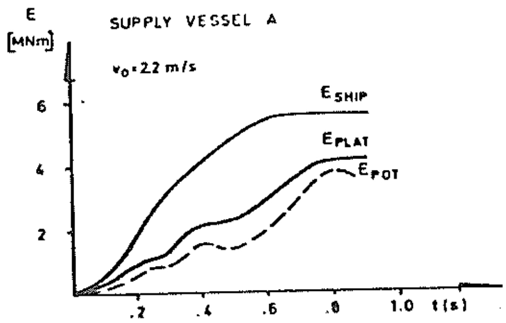

FIG. 15: Distribution of absorbed energy during impact.

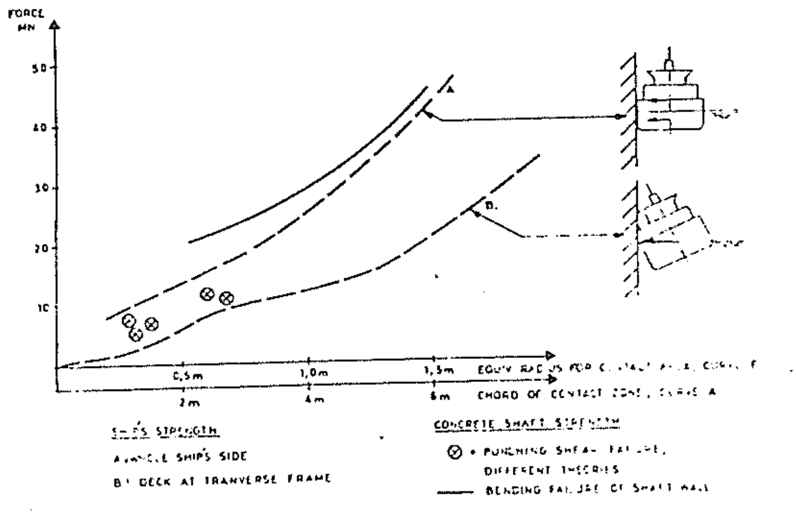

FIG. 16: Curves relating impact force and contact zone.