



CONSEQUENCES OF SHIP COLLISIONS

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Abstract

The analysis of the response of offshore platforms subjected to ship collision is discussed. Both simplified methods based on plastic theory as well as nonlinear finite element analysis are considered. Some results related to impacts with a jacket, semi-submersible and a concrete platform are presented.

1. Introduction

In Norway the design against ship collision is carried out in the limit state of progressive collapse (PLS) /1/. This is a two-step procedure:

- first, the platform is analyzed for the design collision load. Local failures in the form of yielding and buckling are allowed but the structure shall remain essentially intact.
- second, the damaged structure subjected to the design environmental loads shall comply with the conventional ultimate limit state criterion. In this case, however, the partial safety coefficients can all be set equal to unity.

In most cases the design event considered is a 5000 tons displacement supply vessel with a velocity of 2.0 m/s, yielding a collision energy of 14 MJ for beam impact and 11 MJ for bow/stern impact /1,2/. The different energy levels correspond to the assumption of a hydrodynamic mass coefficient of 0.4 and 0.1 for beam and longitudinal impacts, respectively.

This scenario is related to maloperation during manoeuvring or drifting due to black-out of machinery. The collision energy associated with a big tanker ramming a platform at full speed can be several orders of magnitude greater. To design a structure to resist such collisions may be very costly. So far it has mostly been assumed that the risk of collision with large merchant vessels is acceptable by keeping the probability of occurrence sufficiently low.

Various studies have suggested a wide range for the probability of collision with merchant vessels. In the COLLIDE project an improved model has been developed which contributes to reducing the uncertainties. Although the most "pessimistic" assessments are not confirmed using this model, the probability of collision can be such that special actions need to be taken

for platforms located close to typical shipping routes. Either the probability may be reduced by implementation of various preventive and protective measures or the design collision energy must be increased.

Probably, several well-proportioned structures can resist higher collision loads than those used in design because this is often based upon the use of simplified methods, sometimes with unduly conservative assumptions. However, documentation of these strength reserves puts heavy demands on the calculation tools.

The purpose of the present paper is to give a brief overview of present practice with respect to analysis of the structural response to collision. Further details may be found in /3/. Advances in nonlinear finite element analysis of ship-platform collisions are also presented.

2. Impact mechanics.

The analysis of collision response should in principle be based upon the solution of the differential equations of dynamic equilibrium. Since the collision force as well as the structural response are nonlinear an incremental-iterative technique is required.

The problem is significantly simplified if the collision duration is considerably smaller than the natural period of the governing motion. This is often valid for relevant rigid body motions of floating and articulated platforms. Applying the principles of conservation of momentum and energy the determination of impact mechanics and energy transfer can be decoupled from the analysis of dissipation of strain energy in the colliding objects. For example, the following expression emerges for the total kinetic energy to be dissipated as strain energy in the platform and the vessel for the case illustrated in Figure 1,

$$E_s + E_p = \frac{1}{2} m_s v_s^2 \frac{(1 - \frac{v_p}{v_s})^2}{1 + \frac{m_s}{m_p}}$$

where E is energy, m is mass including hydrodynamic mass and v is velocity. The suffices s and p relate to ship and platform, respectively. Corresponding expressions for impacts with an articulated platform and a jack-up can be found in /3/.

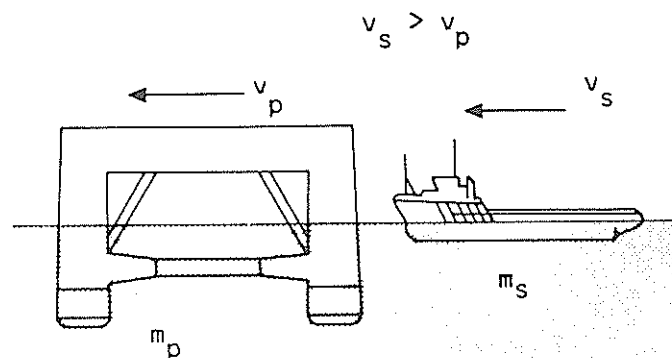


Figure 1. Collision between a supply vessel and a semi-submersible platform

For jackets the force rise time and the collision duration relative to the period of vibration may be such that significant dynamic effects are involved. This has been investigated to a very little extent. Normally static analysis is considered appropriate, but possible dynamic effects should be evaluated.

The dissipation of strain energy is a matter of structural analysis where the force displacement relationships for the hit and striking object must be established. For a given load level the area under each curve represents the absorption of energy. The distribution and extent of damage result from the condition

$$E_s + E_p = \int_0^{\delta_s} P_s(\delta) d\delta + \int_0^{\delta_p} P_p(\delta) d\delta$$

where P and δ denotes force and corresponding deformation.

Normally the two curves are established individually assuming a simplified shape of the contact area and no interaction between the two deformation processes.

Standard force deformation curves representative for a 5000 tons displacement supply vessel recommended by Veritas /4/ are shown in Figure 2. It is especially noticed that the curve for bow deformation relates to impacts against a large diameter column. For impacts against jacket members the bow is normally assumed infinitely stiff.

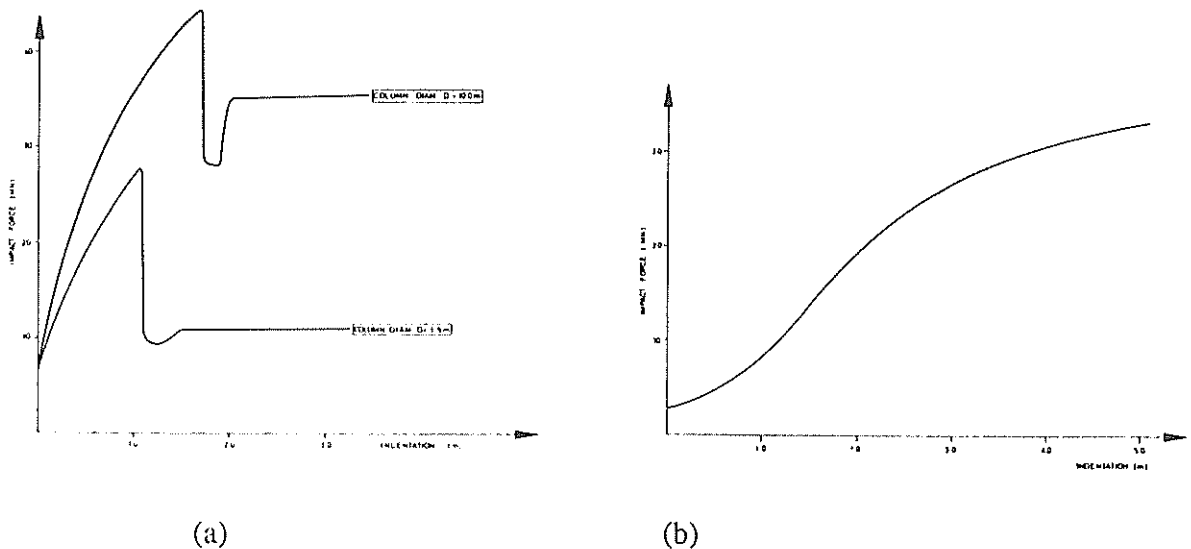


Figure 2. Recommended force-indentation curves for beam (a) and bow (b) impact. Boat displacement 5000 tons

Load deformation relationships for tankers drifting sideways have been calculated in /5/. No standard curves exist for high energy bow collisions. A possible approach is to use methods for analysis of ship-ship. An example is described in Section 3.

3. Response of jacket type structures.

The collision response of jackets is often split into three contributions, namely

- Local deformation of the tube wall at the point of impact
- Beam deformation of the brace element
- Overall frame deformation

The first two modes involve considerable plastic energy dissipation while the global response for typical design energies is mainly elastic, possibly with some dynamic effects involved. It is often difficult to distinguish between the different modes in practice since there may be significant interaction.

For the beam mode of deformation plastic methods yield very simple estimates of load-deformation characteristics as shown in Figure 3.

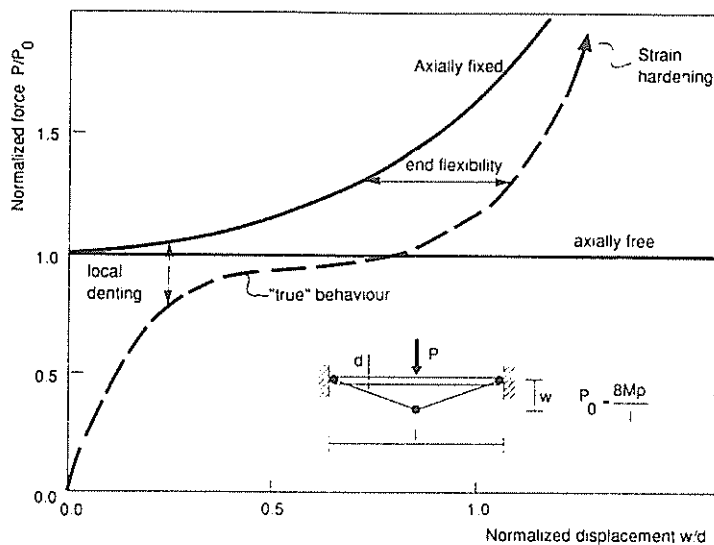


Figure 3. Load-displacement characteristics for tubular beams.

These methods should be used with caution since several effects may contribute to limit the validity of the approach:

- The curves have been established for ideal boundary conditions - either clamped or free. In practice the support of a brace will be more or less flexible, in the case of which no closed form solutions exist. Axial end conditions are especially important since small amounts of flexibility tend to delay the growth of membrane forces which are so essential to energy dissipation.
- Allowance should be made for any reduction in the plastic bending capacity due to local denting or local buckling caused by limited rotational capacity of thin-walled members.
- The behaviour is also affected if the joints at the ends of the member fail. In [3] it is recommended that the capacity of the joints as given by code requirements be greater than the interaction function for plastic capacities of the brace cross-section. For typical design collisions this is considered to be beneficial because the damage is limited to the hit member

only. For high energy collision it may not be advantageous to limit the zone of plastic deformation because the structure may act in a more brittle manner globally.

iv). If the adjacent structure fails to carry the end forces from the member due to yielding or buckling plastic deformations will spread to adjacent members and it becomes considerably more difficult to construct simple calculation models.

v). Due to combined bending and axial loads large strains will develop in a hit member. Hence, if the capacity of the joints and the adjacent structure is sufficient as such, rupture of the chord or brace wall governs the maximum energy dissipation. It is generally very difficult to establish simple calculation models for the strains and especially in the chord wall. In the early stages of PLS evaluations unrealistically high strains were allowed (up to 20-30 % on average over the entire tube). For typical brace dimensions there was never a problem to comply with the design criterion.

In reality the strains concentrate to the brace under the contact point and at brace ends. A more realistic calculation model which takes this strain concentration into account underlies the criterion proposed in /3/. To illustrate the energy level in question: A brace with diameter 0.75 m, thickness 0.025 m, length 25 m, yield stress 360 MPa undergoes rupture at a lateral deformation of 1.55 m in the case of full axial restraint and 3.12 m in the case no axial restraint. The corresponding energy dissipation is 4.6 MJ and 5.0 MJ. It is presupposed that no local buckling and denting takes place. This shows that two braces of such dimensions will have to be assumed damaged in the design collision.

Almost all analyses have been carried out statically. However, it is shown in /6/ that inertia forces may play a significant role for typical design collisions and this may be increasingly important for high-energy collisions.

An important effect of including inertia forces is that the braces at and above the contact point are more susceptible to failure due to the large forces transferred to the deck because of its large mass of inertia. In the static case the collision force is transferred to the ground which makes the lower stories more heavily loaded.

4. Nonlinear finite element analysis

For high energy collisions where the plastic zones will spread to several members it is necessary to resort to nonlinear finite element analysis to have a credible assessment of the collision resistance. Several general systems are available but the use of such systems is often costly and complicated. This has inspired the development of simplified special purpose programs. The fundamental principles behind one such program - USFOS - are shown in Figure 4.

The basic idea is to use one finite element per structural element which allows the use of the FE mesh from linear analysis. The elastic stiffness matrices contains the influence of large lateral deformations (in the form of the so-called Livesly's stability functions) and material nonlinearity is modelled by means of plastic hinges. No numerical integration is required in order to obtain incremental and total equilibrium equations.

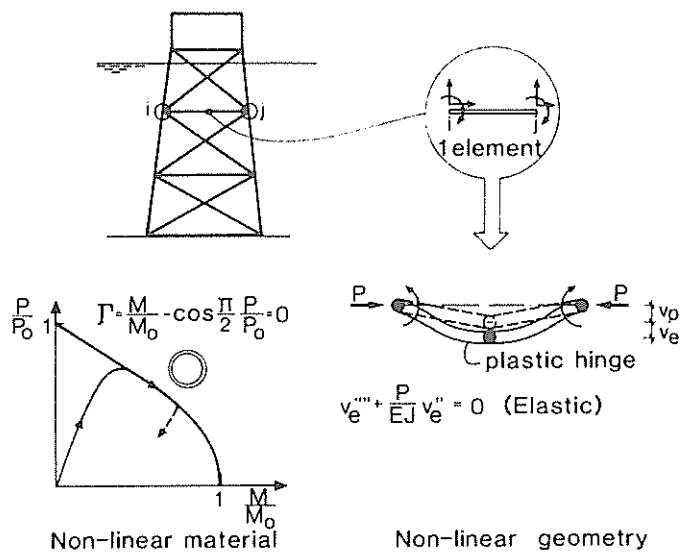


Figure 4. USFOS - basic concepts

Several special features are implemented. Elastic and plastic flexibility of joints may be taken into account; the latter in the form of interaction functions for joint capacity as e.g. specified in the API code. Interaction between local denting/buckling and beam bending is incorporated; the dent reduces the plastic capacities while the axial force influences the resistance to local denting as described in /8/. The strains at member ends and at midspan are surveyed. Once the critical level is exceeded, which is determined on the basis of a CTOD fracture mechanics level 3 approach /9/, rupture is assumed to occur and the member forces are removed before proceeding with the analysis.

For the purpose of illustration the jacket shown in Figure 5 has been analyzed for two impact situations: i) Contact point on the leg midway between two levels, the force acting in the diagonal direction. ii) Impact in the negative global x-direction on a diagonal brace.

Figure 5 shows the platform in the final deformed state for collision on the leg using the graphics module XFOS. The displacements are shown in true scale. It appears that the deformation mechanism is fairly local with large displacement under the contact point. It is found that the leg is allowed to unload completely and even become tensile. In this process the upper K-braces supporting the deck structure play an important role since they transfer the deck weight from the hit leg and the opposite leg to the two other legs.

The collision resistance is limited by tensile yielding of the horizontal braces just below the deck. This shows that members of little importance in the traditional design may be of significant importance in connection with redistribution of forces in the case of accidental loads.

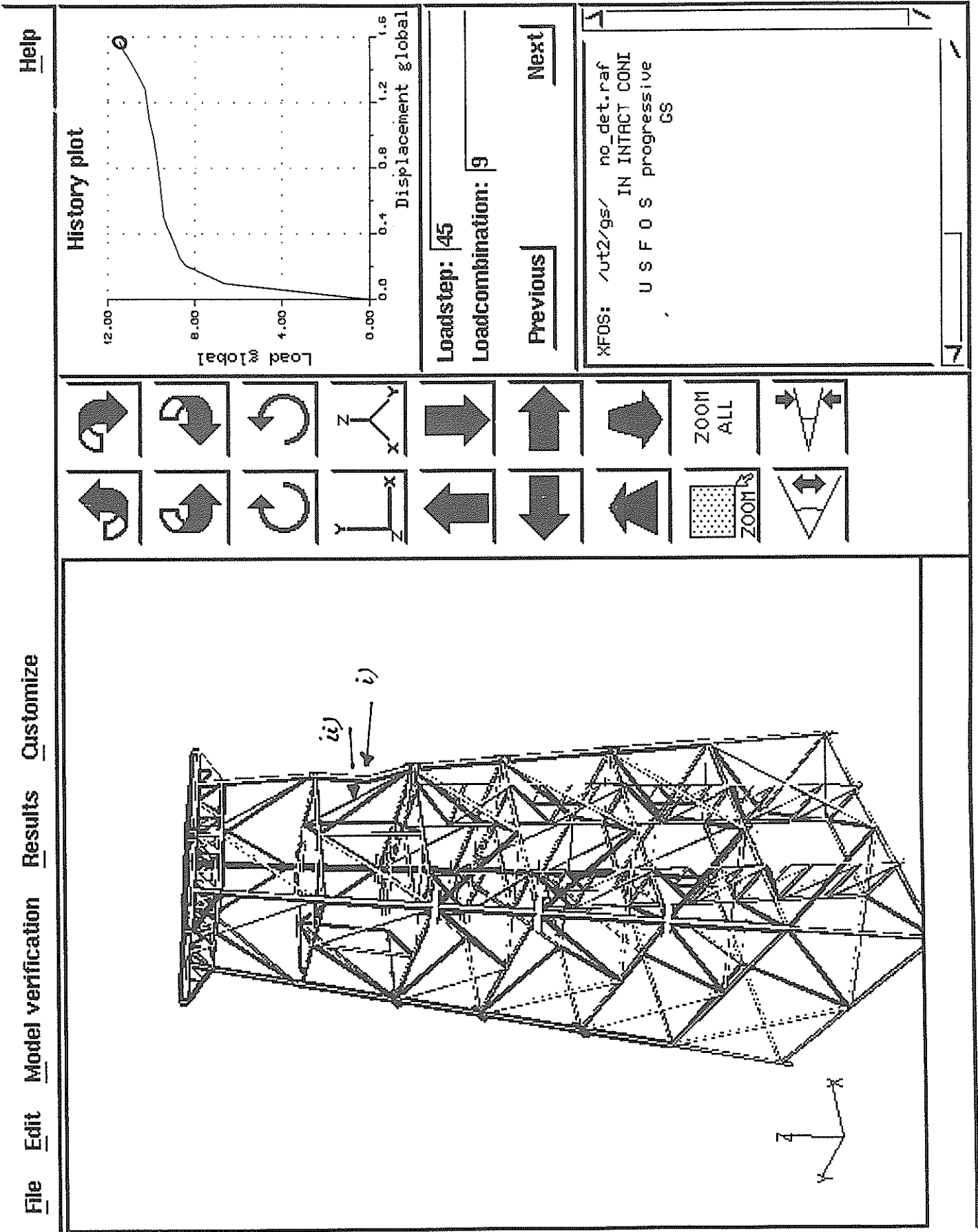


Figure 5. Jacket subjected to ship collision

Figure 6 displays the plastic interaction between axial force and bending moment at the point of impact normalized versus plastic axial force, N_p , and plastic bending moment, M_p . It is seen that the force state is never allowed to reach the fully plastic interaction curve for the original cross-section due to the detrimental effect of the dent.

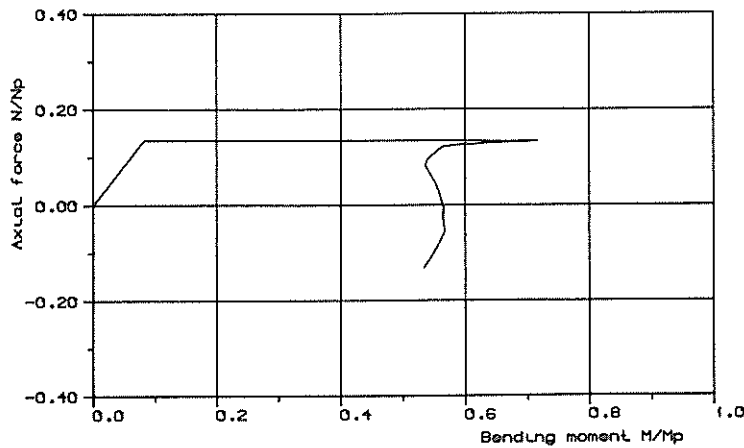


Figure 6. Bending moment - axial force interaction at damaged cross-section

The total energy absorption in the platform is about 16.8 MJ including a contribution of 2.7 MJ from local denting at the point of impact. Using the standard curve for supply vessel beam impact, Fig. 2, the energy dissipation in the ship will be 1.9 MJ. Hence, assuming ductile behaviour it is concluded that the sample platform can survive beam collisions with energies considerably higher than the typical design value of 14 MJ.

To study the influence of ductility another analysis is performed where fracture is assumed to occur when the maximum strain in the leg exceeds 0.15 (excluding strains in the dent). Fracture is then predicted at a lateral displacement of approximately 0.6 m with a total energy dissipation of 6.8 MJ. The corresponding energy dissipation in the ship is 0.9 MJ.

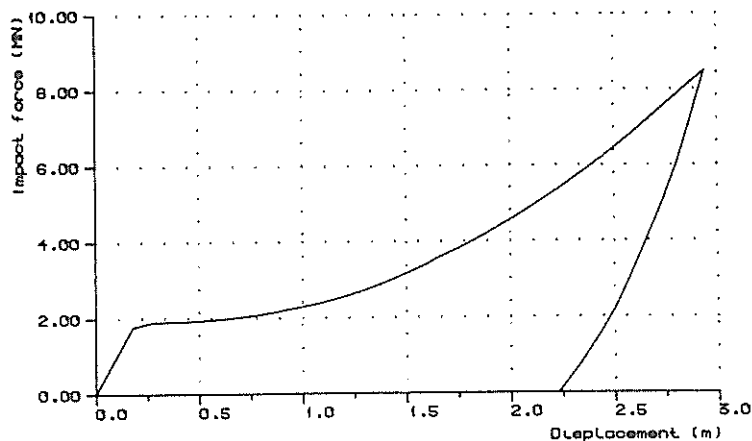


Figure 7. Load-displacement curve for impact on diagonal brace

The load-displacement curve for impact against the diagonal brace is shown in Figure 7. The entire collision energy of 11 MJ is dissipated at a displacement at the contact point of 2.9 m. The contribution from local denting is negligible. No limits to the strains are implied by this calculation. Using the same fracture criterion as above rupture is predicted at a deformation of 1.7 m and a corresponding energy dissipation of 3.9 MJ. In this case it would be natural to consider a secondary impact on another brace if an energy dissipation of 11 MJ is required.

The influence of the ductility should only be taken as indicative because the results are very sensitive to the choice of material parameters (strain hardening, critical CTOD etc.). However, this issue deserves further investigation.

Analyses show that the residual strength of the platform is little influenced by collision damages because the critical members with respect to environmental loads are the braces close to the sea floor where the global shear force becomes large.

5. Floating platforms.

An important aspect of the safety of floating platforms is hydrodynamic stability. Due to flooding of buoyancy compartments, either due to puncturing or as a result of maloperation during corrective action, the stability may be lost before the strength as such is exhausted. This is not dealt with, only strength aspects are addressed.

Platforms of the column stabilized type do often contain a bracing system. The energy dissipation mechanisms are similar to those described for jacket braces. Some important differences do exist: The diameter to thickness ratio is often very high (e.g 80-120 as opposed to 25-40 in jackets). This makes the braces highly susceptible to local buckling which reduces the energy absorption capability considerably. The joints have normally a complex internal stiffening system so that the nonlinear behaviour and ultimate capacity are often not known. More often, however, the limiting factor for the development of bending moments and membrane forces is the ability of the adjacent structure to support the brace end forces.

The columns have dimensions comparable to supply vessel width and are typically fitted with axial stiffeners, circumferential frames and internal bulkheads and decks. Very few analytical methods are available for determining the resistance to penetration of such columns. A very crude formula is proposed in /3/.

The collision resistance of the diagonal braces and the columns of an Aker H3 platform is investigated in /10/. It is found that the energy dissipation in the braces is likely to be strongly reduced by local buckling (brace dimensions: diameter 1.5 m, thickness 0.03 m, length 17.3 m and yield stress 300 MPa); the energy dissipated at the onset of local buckling is assessed to 2.9 MJ while the energy dissipated in the post-buckling regime is estimated to 1.8 MJ yielding a total energy of 4.7 MJ. Thus, in spite of larger dimensions the energy dissipation comes out to be in the same range as that of the jacket brace above. It is, however, emphasized that the calculations are very uncertain.

The loss of one bracing may not be disastrous for the platform but this was not pursued in /10/.

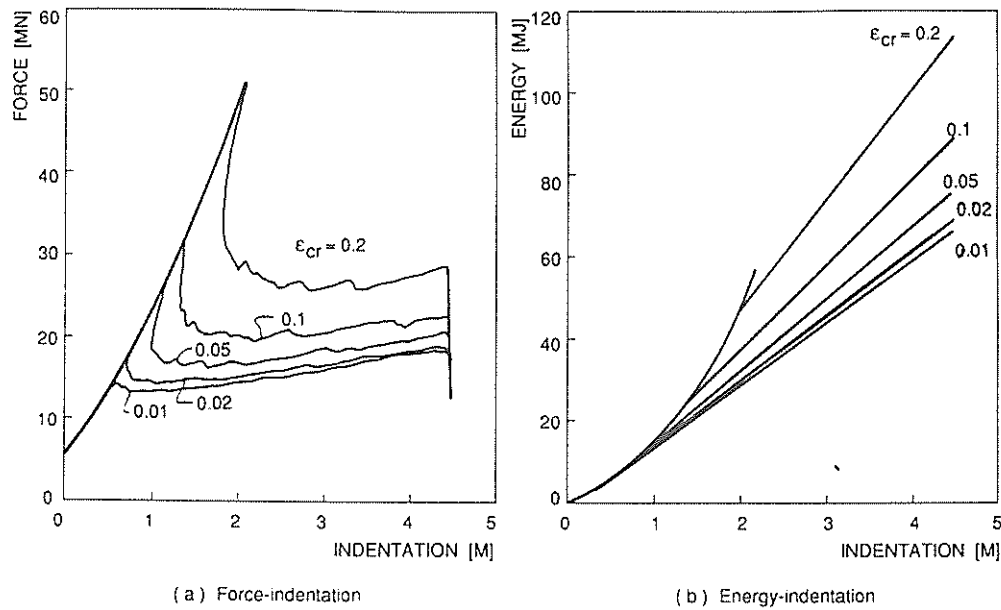


Figure 8. Load and energy dissipation versus indentation for large column of Aker H3.

The columns tolerate significantly larger collision energies. Figure 8 shows the force and energy dissipation versus lateral penetration of the large column obtained from a simple mechanism model of the stiffened shell. The energy dissipation depends very much on the strain assumed at fracture, ϵ_{cr} . With a critical strain in the range of 0.01-0.05 it is found that the energy dissipation in the large column is in the range of 65-70 MJ and in the small column 35-40 MJ. Recognizing the considerable physical and model uncertainties a probabilistic calculation was performed in /10/.

6. Concrete platforms.

While steel platforms can be designed for ductility and energy dissipation concrete structures have to be designed for strength, i.e. the energy has to be dissipated by deformation of the ship.

Experience has shown that if local punching failure of the chord wall can be avoided in the early stages of collision this will not take place at a later stage because the contact area increases rapidly. With respect to overall bending typical columns seem to have sufficient capacity to resist the maximum collision force.

Most concrete platforms are bottom supported. In this case local punching of the chord wall will seldom put the global integrity in jeopardy, although the economic consequences of flooding can be severe. For floating structures such as TLP's flooding can be disastrous if the compartementarization is not sufficient.

Various formulas are available for calculating the punching shear capacity /11,12/. For typical column geometries and shear reinforcement they predict a capacity in the range of 10 MN for a contact area of 1 m².

For bow collisions with supply vessels there is hardly any danger for punching shear failure. However, the stern is often heavily reinforced. For a given supply vessel the force at a contact

area of 1 m^2 is assessed to be $6 \text{ MN} / 13/$. Taking into account the considerable uncertainties associated with these calculations the possibility of a punching shear failure is not negligible.

A matter of concern as considering possible collisions with merchant vessels are bulbous bows. The bulbs are heavily stiffened and have often a cylindrical shape. In a collision they hit the structure below sea level and may act like a ram.

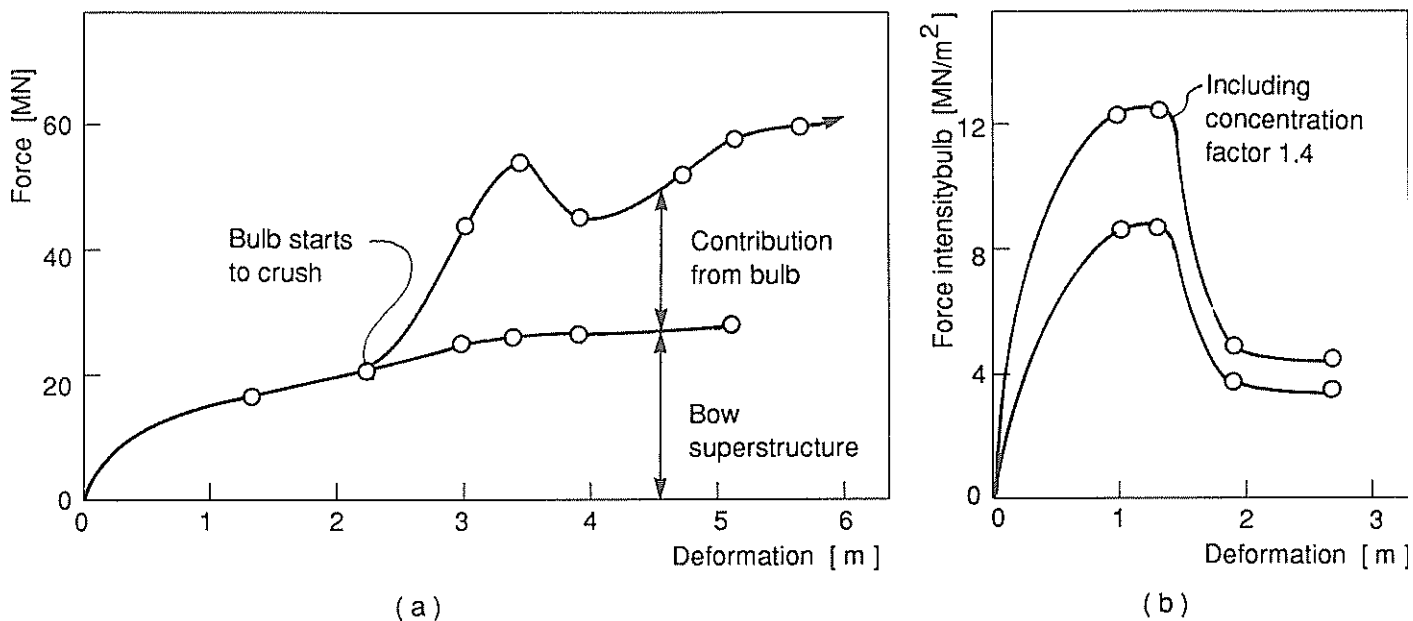


Figure 9. Total force (a) and force intensity (b) for collision with a bulbous bow. Boat displacement 18000 tons.

Figure 9a shows the force deformation relationship for crushing of the bow of an 18000 tons displacement vessel. Because the bow superstructure is very blunt the contact area is large and the intensity is moderate. On the contrary, the small bulb cross-section creates very high intensities as shown in Figure 9b. Again, punching shear failure of a typical concrete wall can not be disregarded in the early stages of crushing, especially if a concentration factor of 1.4 is used. This is intended to account for uneven force distribution and local peaks during deformation.

The bow deformation characteristics are predicted by means of a simple calculation model /13/ where the entire structure is assumed to consist of an assembly of basic subelements for which the plastic deformation mechanisms are known. The simplicity of the model makes the results very uncertain. With the present computational capabilities it should be possible to improve the confidence level by simulating bow crushing with an advanced nonlinear FE code.

7. Conclusions

Simple methods based upon plastic theory yield often reasonable estimates of the energy dissipation in steel platforms during ship collision. The major uncertainty is related to modelling of boundary conditions and estimation of strains.

Recent development of nonlinear finite element codes makes more accurate simulations of the collision process feasible. Calculations show that several structures may dissipate energy considerably in excess of typical design levels provided that rupture does not occur. Emphasis should therefore be placed on further development and verification rupture criteria.

Refinements in methods for calculation of platform response should be balanced by similar achievements in prediction of load-deformation characteristics of ship structures. This is especially important for collisions against concrete shafts where high load intensities may cause punching shear failure of the wall.

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