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NUMERICAL ANALYSIS OF STEEL TUBULAR MEMBER RESPONSE TO SHIP BOW IMPACTS

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ABSTRACT

Offshore platforms and ship traffic can be close in proximity in some areas. Although incidents involving collisions between these two structures have a low chance of occurrence, the effects of a ship impact, when occurs, can result in hazardous scenarios regarding the integrity of the platform.

Current risk analysis of jacket installations is very limited when it comes to jacket legs being head-on impacted by vessels. Bow forces have always been estimated by assuming rigid offshore structures, which may not lead to accurate predictions of the contact force between ship and platform as the structural deformation of the platform also absorbs a significant amount of impact energy. On the other hand, deformations in the platform members have always been studied under the assumption that the ship hulls were strong enough to be treated as rigid.

The present paper describes a detailed finite element model developed for impact analysis of merchant vessel bows against tubular members, representative of offshore jacket legs. The model comprises a general supply vessel in the range of 2000ton to 5000ton displacement and a vertical steel pipe representative of a jacket leg. The verified model is used to perform parametric simulations. Different geometrical parameters such as member length, wall thickness and diameter of the tubulars, as well as boundary conditions, axial preloading and dynamic aspects such as the impact velocity and the strain rate effects are considered in the analyses to examine the performance of the platform under vessel impact. Based on intensive numerical results, discussions are made with respect to the accuracy of the current code of practice in offshore platform design to resist possible vessel impact.

Keywords: Ship impacts, bow collisions, shared energy dissipation, tube deformations

1. INTRODUCTION

Offshore platforms are in most of the cases constituted by tubular steel members. In this paper, the response of tubular members to ship bow impacts is analyzed by means of FEM calculations. The FEM simulations focus on the damage that can be provoked on jacket legs as the collapse of such

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members would affect the integrity of the platform. The classical way the collision problem has been being handled is through quasi-static analyses, where the collision effects are assessed by following the laws of conservation of momentum and conservation of energy. In most previous studies, to simplify the problem, many researchers consider only one impact structure is deformable and assume the other one is rigid. As a result, the impact loads are related to only the damage of the 'deformable' structure. However, it is commonly agreed that neglecting the deformation and damage of the other structure, usually platform, which may absorb significant amount of impact energy and hence affect the ship-platform structure interaction, may lead to inaccurate predictions of impact loads and ship-platform interaction and structural responses. Since head-on collisions from a ship can represent the most harmful case for the integrity of the steel platform, it is of interest to assess with a certain level of detail how platforms are locally affected, and more precisely the hit tubular members by ship bows by considering deformation and damage of both ship bow and platform structure.

2. DESCRIPTION OF FINITE ELEMENT MODEL

2.1. Ship

In the present, the Norwegian Petroleum Directorate requires platforms to be designed for impacts from supply vessels of 5000 ton of displacement with a speed of 2 m/s (added mass effects are included). This yields a kinetic energy of 11 MJ (added mass estimated in 10% for surge) for bow/stern impacts when specified values for hydrodynamic added mass are taken into account. Amdahl and Johansen (2001) obtained force deformation relationships that could be used for strength design of jacket legs against bow collisions of vessels with displacements between 2000-5000 tons and the kinetic energy up to approximately 50-55 MJ (velocities up to 6m/s for displacement of 3000 tons). In this study, the model of the ship employed for numerical experiments is developed to give a good characterization of loading, deformation behavior and energy distribution that could be expected in a real impact scenario. Therefore, it is essential that the bow structure has a reasonable level of detail. The finite element model of the bow is shown in Figure 1 which replicates to some extent the model by Amdahl and Johansen (2001). Since any possible kinetic energy to be absorbed by the ship is dissipated through the deformation of the very front part, the rest of the body has just been given the real outer shape in order to keep the ship dimensions and respective inertia properties. The bow is defined by a set of shell elements. Thickness of 11 mm/14 mm and 9 mm are assumed for the shell plating and deck plating (average thickness) respectively. The mechanical properties of the steel that makes up the deformable zone used in the present study are given in Table 1.

Table 1: Steel mechanical properties of vessel bow

ρ (kg/m^3)	E (GPa)	σ_y (MPa)	σ_u (MPa)	ν	ε_u
7800	200	275	400	0.3	0.2

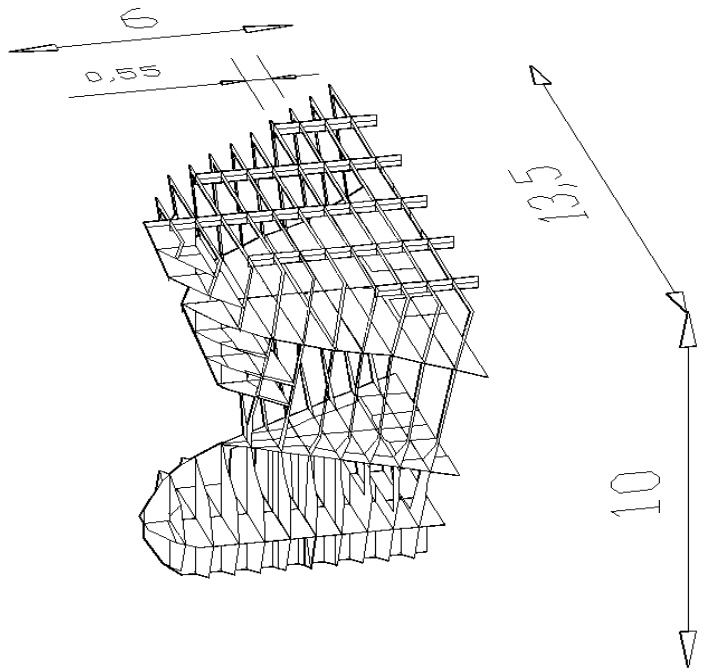

Figure 1: Bow internal structure (dimensions in meters).

The bow has been discretized with (64620) shell elements and with the application of mass scaling, so that the selected mesh size after mesh convergence tests could reasonably reduce the calculation time and capture the plastic deformations of the structure.

The strain rate effects are also taken into account, which are modeled in accordance with Cowper-Symonds (1967):

$$\frac{\sigma_0^d}{\sigma_0} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P} \tag{1}$$

where σ_0^d is the dynamic flow stress, σ_0 is the static flow stress and C and P are constants in the strain rate hardening law. The coefficients C and P are usually set as 40.4 s^{-1} and 5, respectively. These values are better suitable for uniaxial tensions with small strains. Several authors have conducted many research works about the estimation of the strain rate. Abramowicz and Jones (1984) suggested the values of C = 6844 s^{-1} and P = 3.91 to be used for dynamic crushing of mild steel square tubes, whereas Yang and Caldwell (1988) defined C = 500 s^{-1} and P = 4 to assess the energy absorption of ship bow structures. The bow deformation response is simulated for collision with a rigid wall and a rigid leg with 2m of diameter. The results are compared in Figure 2 with the cross sections method of Amdahl (1983) and the current design curve of the DnV code (2010) for bow impacts on a rigid wall. As shown the current numerical model developed in LS-DYNA gives reasonable predictions of responses of ship collision with a rigid wall.

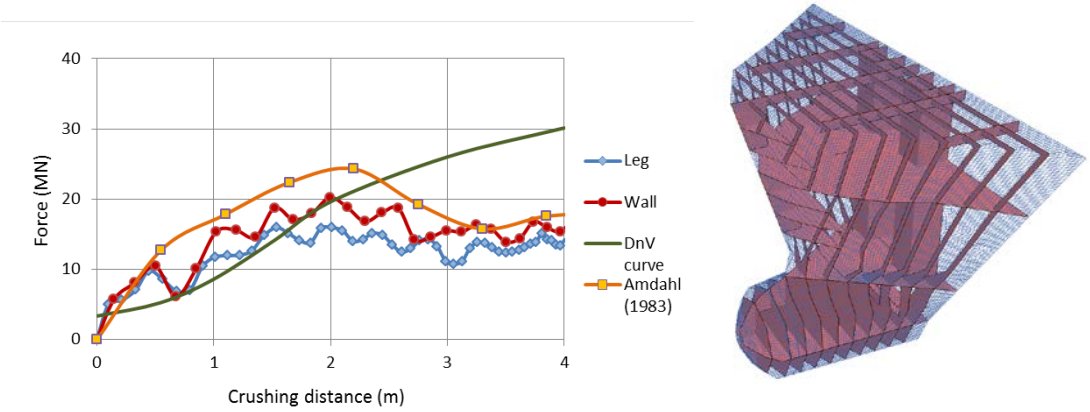

Figure 2: Ship bow crushing response

2.2. Tubular members

Tubular members used in offshore steel structures have their response to lateral loading influenced by their geometrical and mechanical properties and external conditions such as axial pre-loading and stiffness of the adjacent members and connections. Their response to lateral impacts also depends on the type of the indenter they are subjected to during penetration. For tubular members, deformation of the cross section can contribute to energy dissipation. For large deformations, the global bending response of the hit member has normally been estimated using the three hinge mechanism (Oliveira, 1981), which is based on the principle of virtual works. The load is modeled as a concentrated load and the method is best applied to braces due to their oblique position and thus an only single zone of contact. This assumption is also acceptable for stern impacts or early stages of broadside impacts where the contact with the platform happens at the ship deck or bilge due to rolling. The plastic collapse load of a circular tube with wall thickness t in pure bending is given by:

$$P_u = \frac{8M_u}{l} = \frac{8\sigma_u D^2 t}{l} \tag{2}$$

whereas for local denting of the tube walls, force/energy-deformation relationships are mainly dependent of the plastic moment of the tube wall:

$$m_p = (t^2 \cdot \sigma_Y)/4 \tag{3}$$

The steel pipe models used for numerical calculations have been modeled with shell elements of 0.1m edge, and with the material properties set as σ_y = 250 MPa, ε_u = 0.15 and the same values as in Table 1 for the remaining parameters. Since the ship impact is likely to happen while the offshore platforms are carrying their design loads, it is of significance to test how the tube response is affected when subjected to axial stress. The combination between the axial prestress and the lateral impact load may increase the chance of failure due to buckling of the tubular member and

consequently the global strength of the whole platform. The levels of preloading that have been introduced to the tested tubes correspond to 50% of the allowable axial compressive stress, F_a, obtained from the API (2010). The tubes geometry and external conditions that have been accounted for the numerical tests in this study are shown in Table 2:

Table 2: Geometric dimensions and external conditions of the tested tubes

D (m)	*t* (mm)	*L* (m)	Axial preloading	Boundary conditions	Strain rate effects [*C* (s^{-1}),*P*]
1.5, 2	40, 50, 60, 80	15, 18, 18.5, 21, 22, 24, 26, 37, 30	No preloading, 50% *Fa*	Fixed ends, Pinned ends	[0,0], [40.4,5], [500, 4], [6844, 3.91]

3. NUMERICAL INVESTIGATION

The way how the energy is absorbed through the tubes depends on the nature of the deformation they are subjected to. Local denting and global bending of a tubular member can interfere with one another during the deformation process. While the damage caused by the local deformation of the tube wall is influenced by the cross section geometry, the global bending deformation not only depends on the cross section, but also the boundary conditions and the tube element length. As a criterion, it has been considered that cross sections undergoing deformations of less than 2% of their diameter should be assumed as fully effective with negligible local denting deformation, equivalent to a rigid cross section. Depending on tube element conditions, either local denting or global bending deformation can absorb more impact energy although usually bending response would absorb more energy than local denting. However, for shorter members with thin walls, local denting also contributes with significant amounts of energy absorption. Nonetheless, large values of energy absorption come from the combination of the two deformation modes, especially when the tube is slender with large bending deformation and the wall is thin with considerable denting deformation. The energy absorption by plastic deformation of the platform steel member therefore depends on both plastic hinge formations due to bending and plastic wall deformation owing to local denting. For the structure integrity, it is important that denting and bending deformation should be minimized. Figure 3 relates the tubes dimensions with the dominant deformation response for different tubes with fixed ends, in which the non-dimensional displacement (*X/D*) represents the ratio of horizontal displacement of the tube membranes *X* to the tube diameter *D*. As shown, when the tube member is short and tube wall thickness is thin, the deformation is primarily local denting. When the tube element is long and tube wall is thick, the deformation and energy absorption are governed by the global bending deformation.

By increasing the shell thickness of the bow structure from 11 mm to 14 mm, the stiffer structure generates a larger impact force but shorter loading duration owing to less structural deformation.

As for the pinned tubes (additionally plotted in Figure 3), although the ultimate plastic load corresponding to the bending capacity of a beam with pinned ends is expected to be reduced to half as compared to the fixed end tubes, the loads corresponding to the collapse of the jacket leg do not reduce by the same amount. This is because of the interaction between ship bow and tube structure. The impact force also depends on the deformations of the ship bow. The recorded peak impact force is slightly higher for the tubes with stiffer constraints. Likewise, the duration of the impact is shorter for the clamped tubes and it reaches the peak earlier. The tube elements with pinned and fixed boundary conditions also result in different energy absorptions owing to the different flexural capacities of the elements with different boundary conditions.

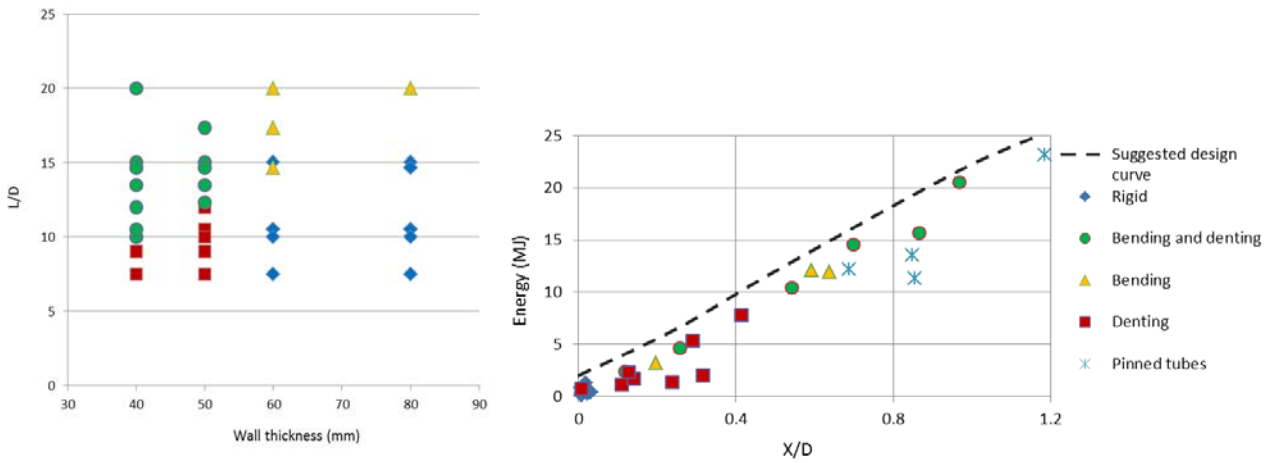

Figure 3: Deformation response of tubes.

Another external condition that must be taken into account and that can be responsible for increasing the chance of failure due to buckling is the axial preloading. Ship impacts are likely to happen while the offshore platforms are carrying their design loads. The numerical tests carried out indicate that despite axial preloading reduces the lateral load-carrying capacity, it has little influence on the peak impact loads on the tube from ship impact. This can be attributed to the short impact duration. In other words, the peak of impact load is reached before the tube experiences significant deformation and failure. Therefore the axial preloading has little effect.

For comparison, the quasi-static solutions that are employed to assess the deformation response of bow structures are also derived. They seem acceptable as the local inertia effects of the structures are very low owing to the relatively low ship impact velocity. Although the greater bow crushing distance is observed for higher impact speeds, the deformation of the bow is not significantly affected by the increase of the impact speed except the maximum penetration depth of the tube increases. The pair of values (40.4 s^{-1}; 5) adopted by many authors to include the strain rate effects in numerical simulations look questionable as it estimates contact forces with higher peaks and shorter impact duration, implying these values result in stiffer interaction between ship bow and tube structures.

4. DISCUSSIONS AND CONCLUSIONS

This paper presents parametric analysis results of ship bow impacts on tubular members of offshore platform structures. The results give a general idea of what to expect of a jacket leg, and to some extent a jacket platform, when subjected to ship collisions. Based on parametric simulations, the conditions under which the tubular structure can be assumed as rigid, or experiences primarily bending deformation, local denting deformation, or both under ship impact are defined. The influences of ship bow shell thickness and ship-platform interaction have also been considered in the study. Compared to most previous studies of ship impacts on offshore structures that assumed mainly the low velocity broadside impacts during berthing and neglected ship-platform structure interaction by assuming either ship or platform structure as rigid, the present study considered ship and platform structure interaction. It is found that both ship bow structure and platform tube structure might experience large plastic deformation during impact. Neglecting their interaction and plastic deformation of either structure might lead to inaccurate predictions of impact loads, deformation, failure modes of the tube, and energy absorption. As shown in Figure 4, the current practice based on assumption of either rigid ship or tubular structure in analysis of ship-platform structure interaction does not necessarily lead to accurate predictions.

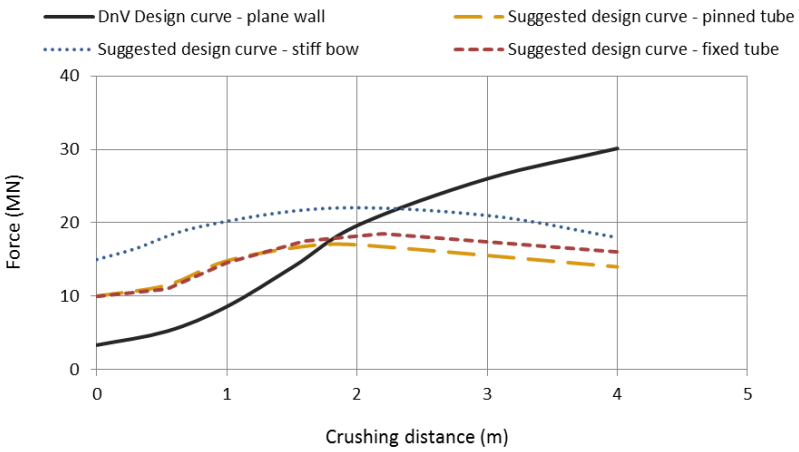

Figure 4: Force-deformation relationships for bulbous bow

In regards to the different deformation modes and their interaction, it has been demonstrated that the absorbed energy increases nearly linearly with the increase of the maximum deformation of the tube membrane, irrespective of the predominant response mode of the structure and its boundary conditions. This, however, does not necessarily well correlates with the maximum load-carrying capacity of the structure and the member steel fracture since the deformation mechanisms are complex and combined with the local denting and global bending deformations.

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