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ASSESSMENT OF STRUCTURE STRENGTH AND PRIMARY PARAMETER ANALYSIS FOR JACK-UP/SHIP COLLISION

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ABSTRACT

It's commonly known that there are high collision risks between vessels and jack-ups in work condition. When such an unfortunate incident happens, not only would the jack-up be damaged but also drilling activities might get suspended and economic losses would occur. Comparing with other offshore installations, jack-ups are much more flexible and have a much lower degree of redundancy, but its collision danger has not been paid sufficient attention. As a matter of fact, there is little research on this subject in our country. Based on non-liner finite element analysis methods, taking a 300ft jack-up designed by Shanghai CIMC Offshore R&D Center as an illustrative example, one approach of assessing structural strength for collision between jack-up and vessel considering the initial state of the jack-up and residual strength is put forwarded. Furthermore, the influence of impact parameters on structure damage and dynamic response is considered. The conclusion of this analysis may be helpful to structural design against collision loads for jack-ups.

Keywords: *Jack-Up, Collision Strength, Impact Parameters*

1. INTRODUCTION

Nowadays, there are about 506 jack-ups in the world, more than other types of offshore installations. And its utilization is as high as 75%, compared with other platforms. However, the risk of collision between jack-ups in work condition and ships is very high. According to the WOAD database[1], the mean incident frequency of jack-up is 0.1413, lower only to semi-submersibles, and more than one third of incidents result in moderate or severe damage. Therefore, it's necessary to take collision loads in consideration in basic structural design of jack-ups.

Compared with other offshore installations, jack-ups are much more flexible and have a much lower degree of redundancy. When a collision happens, the structure only provides limited resistance to severe damage. The collision between offshore platforms and ships is generally a very complex problem, and current researches focus on structure strength assessment and dynamic response analysis. In the past [2], it was generally assumed that the local structure deformation was independent of overall deformation when a collision happened, and the contribution of elastic deformation can be ignored. Therefore, more simplified techniques were applied normally. However, in this way key aspects such as dynamic effects are often ignored, sometimes to the detriment of the final calculated energy absorption capacity of the jack-up. To make things worse, the influence of initial state and residual strength of the structure of jack-ups could also get lost in the simplified process.

There is few research on jack-up/ship collision in our country as of now. Based on the non-linear finite element analysis approach, one approach of assessing structural strength for collision between jack-up and ship considering the initial state and residual strength of the jack-up is put forwarded in this paper. Furthermore, taking a 300ft jack-up designed by Shanghai CIMC Offshore R&D Center as an illustrative example, the influence of primary parameters on collision dynamic response and structure damage are analyzed.

2. MECHANICS OF JACK-UP/SHIP COLLISION

The collision scenarios between jack-ups and ships are quite complicated because a lot are involved, for example, the operational condition of ships, the ocean environment and the sea bed conditions. Pedersen and Zhang had studied

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offshore installation collision with analytic methods [2]-[3]. With the help of advanced computers, some researchers made a research on this type of problem with a simplified numerical method [4]. Based on the non-linear finite element method, one approach of assessing structural strength for collision between jack-up and vessel considering the initial state of the jack-up and residual strength is put forwarded in this paper.

2.1 Collision Mechanics

The analysis of the collision mechanics is generally based upon the solution of the differential equation of dynamic equilibrium such as conservation of momentum (formula 1) and conservation of energy (formula 2). The problem is simplified if the initial collision duration is considerably smaller than the natural period of the considered motion.

When determining the impact energy from a collision, the relative motion between the ship and jack-up must be considered. Normally the translation motions (sway, surge) in the horizontal plane are accounted for. In this way, the determination of impact kinematics and energy transfer during collision can be decoupled from the analysis of strain energy dissipation in the colliding objects.

For typical jack-up platforms, the ratio between the collision duration (t) and the natural period of vibration for leg impacts (T) may be such that dynamic effects should be involved. Normally, a static analysis is considered appropriate provided a suitable dynamic magnification factor (usually 1 to 2) is incorporated.

$$m_s v_s + m_p v_p = (m_s + m_p) v_c \quad (1)$$

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

Where m_s is the mass of ship including added mass, m_p the mass of platform including added mass, v_c the common velocity of ship and platform after initial impact, v_s the velocity of ship immediately before collision, v_p the velocity of platform immediately before collision(e.g. Wave induced), E_s the strain energy (elastic or plastic) dissipated by the ship, and E_p the strain energy dissipated by the platform.

This method is used in Refs [5] now, but the energy to be dissipated as strain energy is determined considering translation motions only, that is, the force vector is assumed to act through the center of gravity. Therefore, it is always conservative to use the formulas above.

2.2 Character Of Jack-Up Collision

Compared with ship/ship collision, the character of jack-up/ship collision is different. The legs of jack-ups around the waterline are easy to be impacted, not only the local structure damage but also the global integrity need to be considered. Besides, the influence of added mass and strain-rate sensitivity of material can't be ignored.

2.2.1 added mass

It is necessary to consider fluid-structure coupling in the collision analysis, which is normally accounted for by the added mass now. The added mass coefficient of ship for the surge motion is usually considered to be 0.1. The added mass coefficient of jack-up is calculated to be 0.711 in accordance with formulas 3 and 4 in Refs [6].

$$C_{Mei} = \left[1 + \left(\sin^2\beta_i + \cos^2\beta_i \sin^2\alpha_i\right)\left(C_{Mi} - 1\right)\right]\frac{A_i l_i}{A_e s} \quad (3)$$

$$C_{Ae} = \sum C_{Ai} = \sum C_{Mei} - 1 \quad (4)$$

Where C_{Mi} is the inertia coefficient of an individual member, C_{Ai} the added mass coefficient of an individual member, C_{Ae} the equivalent added mass coefficient per unit height, A_e the equivalent area of leg per unit height, and A_i the equivalent area of an individual member.

2.2.2 material model of steel

Jack-up/ship collision is a dynamic process, so the strain-rate sensitivity of steel can't be ignored. In this paper, the Cowper-Symonds model is used as material model of steel.

$$\sigma_0' / \sigma_0 = 1 + (\dot{\varepsilon} / D)^{1/q} \quad (5)$$

Where σ_0' is the dynamic yield stress when plastic strain-rate is $\dot{\varepsilon}$, σ_0 the static yield stress, D and q the parameter of stain-rate sensitivity attained from material experiment.

The accuracy of analysis result depend on the failure criterion of steel, which is the key point in the collision analysis. When collision happens, the plastic deformation of structure become larger and larger until it is totally destroyed. The maximum plastic strain ε_r when structure is destroyed is normally defined as failure criterion. The material

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of members used in legs are different, so the ε_r is chosen in accordance with Refs [5] which shows in Table 1.

Table1. Material Of Legs

Structure	Steel grade	ε_r
Chord	S690	10%
Horizontal brace	S355	15%
Diagonal brace	S355	15%
Span breaker	S235	20%

3. NUMERICAL SIMULATION APPROACH OF COLLISION

When numerical simulation approach is applied to analyze jack-up/ship collision, it is necessary to consider the initial state of the jack-up in the ocean environment before collision, the energy absorption in the collision and the residual strength after collision. In this paper, one approach of assessing structure strength for jack-up/ship collision is put forward. The analyses included:

STEP 1: Initial state analysis. Pre-impact analyses caused by ocean environment in accordance with historical database.

STEP 2: Free vibration analyses. Mode analyses of jack-up prepared for calculating a suitable dynamic magnification factor.

STEP 3: Impact analyses. Non-linear dynamic numerical simulation.

STEP 4: Post-impact analyses. Damage condition assessment caused by the environmental loading with a return period of at least 1 year.

3.1 Fe Model

The target platform in this paper is a 300FT Jack-up Unit designed by CIMC Ocean Engineering D&R Institute Co.(ORIC) which is to be constructed, fitted and furnished to meet the requirements of American Bureau of Shipping, IMO MODU 2008 Code.

The vessel consists of a modified triangular hull with three triangular truss work legs, each fitted with a spud can as its lower end. The maximum drilling depth can be 30000ft and its maximum variable loads can be reached 2500 tons under the survival environment in 300ft drilling water depth.

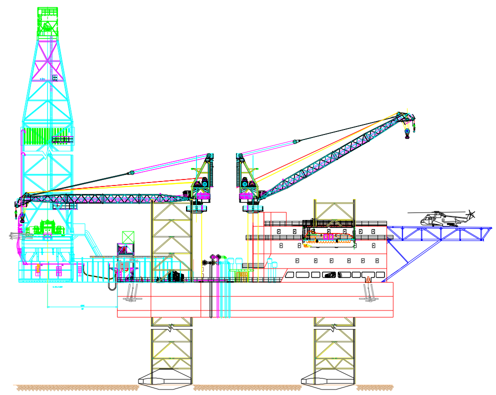

Fig.1 Outboard Profile Of Jack-Up

Studying the incident records, the jack-up status, in which incidents happen, could be divided into four categories: jacked-up, going on location, moving-off and in transit. The majority (75%) of the incidents reported had occurred when the rig was jacked-up in accordance with Refs [7]. Besides, the majority (63.4%) of the incidents to jacked-up rigs seem to have been caused by supply ship. Therefore, the typical status mentioned above is studied in this paper.

Normally, the striking boat is much stronger than jack-up, so it could be assumed that all strain energy would be dissipated by jack-up structure only, corresponding to indentation by an infinitely rigid boat [5]. In this paper, the striking boat is defined as a rigid body during collision. The structure deformation happens in the collision area locally, meanwhile, the structure far away from collision area doesn't deform at all. The global shell model is too time consuming, so the shell-beam embedded model is applied in this paper (Figure 2), and only the collision area is modeled by shell element. Besides, the leg is defined pin-ended at least 3 m (10 ft) below the sea bed [8], the hull is considered rigid.

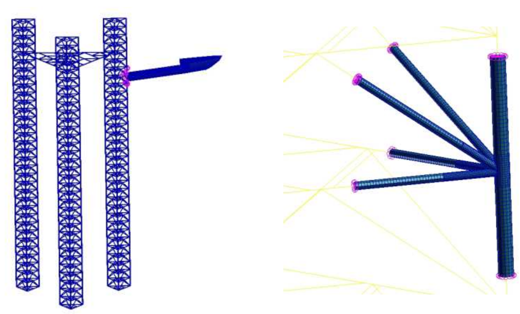

Fig.2 FE Model Of Jack-Up Collision

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3.2 Collision Scenarios

3.2.1 vessel size

The size of supply vessels for all the recorded incidents is typically 1200~11500 tonnes displacement. The average displacement of these vessels is about 3300 tonnes with 95% of the vessels having displacements up to 5000 tonnes which coincide with the vessel size recommended by DNV. As a result, a ship with displacement of 5000 tonnes has been taken as representative of the typical size of vessel involved in collisions with a jacked-up rig.

3.2.2 vessel orientation

Vessels are likely to impact chord of platform with head-on, sideways-on and stern-on, and brace only with head-on and stern-on. The most probable collision orientation for supply vessels is stern-on, accounting for about 70% of all known cases, although in about one fifth of the incidents where the orientation was known sideways-on collision occurred [9]. So stern-on is chosen to be the primary orientation studied in this paper.

A distinction should be made between a central impact where the force vector is through the center of gravity and a non-central impact. In non-central impact, some of the initial translational energy will be transferred into rotational energy for which a secondary impact could result. Therefore, the central impact (Figure 3) is assumed to be the most critical collision and hence is recommended for design.

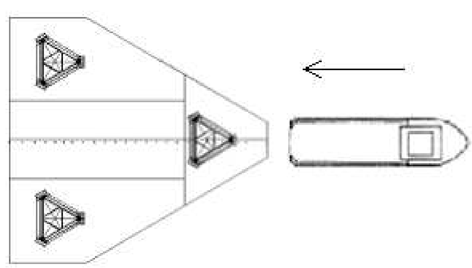

Fig.3 Vessel Orientation

3.2.3 impact velocity

From a review of North Sea collision incidents, it is found that 74% of the incidents were occurred in sea states experiencing wave heights between 1 and 4m. A typical collision scenario is assumed that a ship losing its power on approach and colliding with the rig due to wave induced motion. In this case, the velocity of the vessel is dependent on the wave height and can be expressed as formula 6 [10]:

$$v_s = 0.5 \times H_s \tag{6}$$

Where v_s is the impact velocity and H_s the maximum significant wave height for operation close to the platform.

According to the historical database and formula 6, the representative impact speed is given as 4m/s, which is as the same as recommended speed by DNV and HSE.

3.2.4 impact location

Normally, the representative vertical impact location is chosen as chord or brace of jack-ups. Comparing with brace, chord is not permitted to be destroyed for hull support. So it is reasonable to take the chord as the impact location for use in collision analysis.

3.3 FE Analysis

3.3.1 initial state analysis

Structure initial displacement and stress exists before collision subjected to environment loading for jack-ups. It is necessary to analyze initial state of jack-up before collision analysis for its influence on calculation result [11].

74% of incidents were found to have occurred in sea states experiencing wave heights between 1m and 4m as mentioned above. Therefore, the maximum permissible significant wave height is taken as 4m.The 95 percentile value of wind speed recorded during collision incidents is about 20m/s. During the simulation of the collision scenario, the environmental loading is assumed to be acting on the jack-up in the same direction as the ship impact. Therefore, the worst loading situation for jack-up is simulated.

Analysis result are shown in Figure 4, the initial stress in collision area is about 30MPa, which is much smaller than steel yield stress. The initial stress of hull is only 40MPa, so it is appropriate to deal with hull into rigid beam in the collision analysis.

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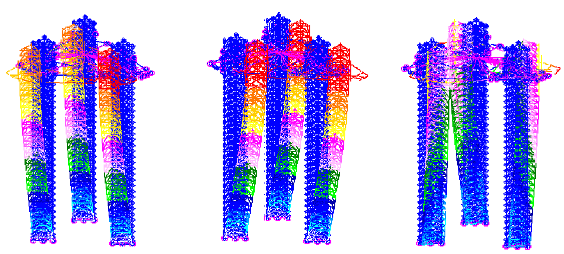
Fig.4 Initial State Of Jack-Up

3.3.2 free vibration analysis

For typical jack-up collision, collision force as an excitation will lead to dynamic effect. It is can't be ignored in the collision analysis and residual strength assessment of platform. The ratio between the collision duration (t) and the natural period of vibration for leg impacts (T) may be such that dynamic effects are involved. Normally, a static analysis is considered appropriate provided a suitable dynamic magnification factor is incorporated.

The mode analysis result for jack-up and added mass is acquired at first based on a static analysis [12]. The simplified beam model is applied in the analysis considering first three modes. The natural period of vibration is 8.77s according to the first mode calculation result for 300ft jack-up studied in this paper.



First Mode 0.114 Hz *Second Mode 0.116 Hz* *Third Mode 0.216 Hz*

Fig.5 Mode Analysis Of Jack-Up

3.3.3 impact analysis

Impact analysis is the key point of collision research of jack-ups. Tie result of initial state analysis is used as pre-impact analyses for collision model, and then impact analysis is applied based on the assumption mentioned above.

(1) Structure Damage

Figure 6 and 7 shows the integral and local deformation of jack-up/ship collision. Some of impact energy transfers into rotary energy of sway motion for jack-up. Because the chord structure is strong enough, there is no large deformation occurring in the collision area. The impact energy transfers into the joint between chord and brace, which lead to some plastic deformation. So the importance of structure strength for tubular joint can be attained in impact analysis.

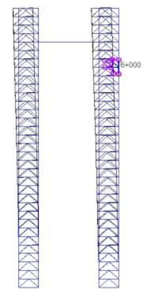


Fig.6 Global Deformation

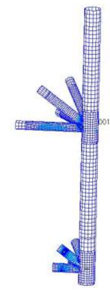


Fig.7 Local Deformation

(2) Energy Transfer

When jack-up is collided by vessels, the energy absorption is as follows: the local deformation of tube (dent), the elastic/plastic bending and extending of members, the integral deformation (sway) of jack-ups and deformation of vessels. In this paper, the vessel is assumed to be rigid, which means no deformation happens. The energy transfer in the collision is shown in Figure 8, and the impact energy of striking ship are transferred to the kinetic energy of hull, the kinetic and strain energy of legs.

Because the chord structures are much stronger than braces, the energy dissipated due to the deformation of the chord is relatively small at 2MJ only, about 18% of the ship's initial kinetic energy. The total energy dissipated by braces deformation, which are more slender than chords, is nearly three times that by chords.

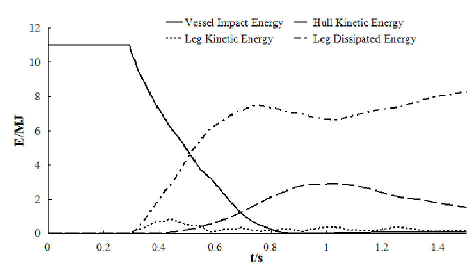


Fig.8 Collision Energy Exchange

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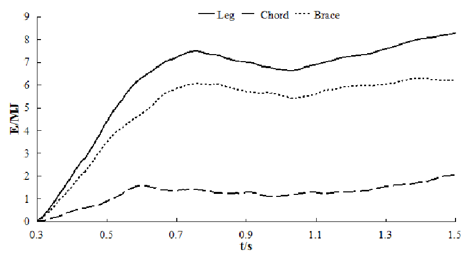

Fig.9 Energy Absorption Of Leg

(3) Collision Force

Collision force is an important index to assess the severity of collisions. The damaged leg experiences a maximum collision force about 24.5MN. It is interesting that twice impacts between the ship and the leg are observed in a collision. The second impact occurs due to the rebound of the jack-up and the subsequent catching up with the ship, which is also the characteristic for jack-up/ship collision.

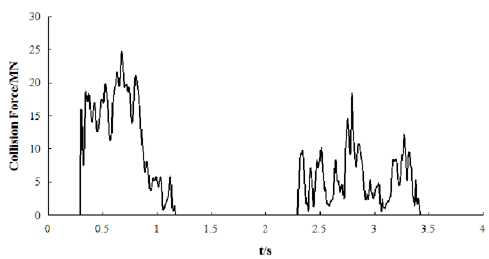

Fig.10 Collision Force

(4) Motion

Twice impact occurs for the structure characteristic of jack-ups. The initial collision duration (t) is 0.86s, and the ratio between it and the natural period of vibration for leg impacts (T) is about 0.098. So it's obvious that the dynamic effect is not need to be considered.

The maximum hull horizontal displacement is about 0.88m, and the ratio between it and the working height of jack-up $\Delta / H < 1/100$, which would not lead to the global overturning. The Maximum deck acceleration is about $1.7\, m/s^2$, which is not sufficient to cause discomfort to persons and damage to equipment and their mountings.

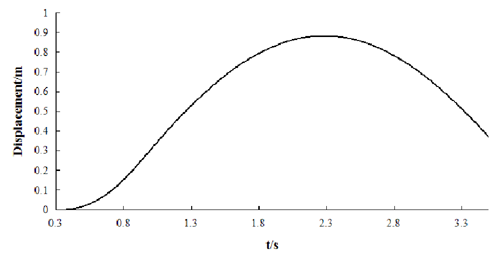

Fig.11 Displacement Of Jack-Up

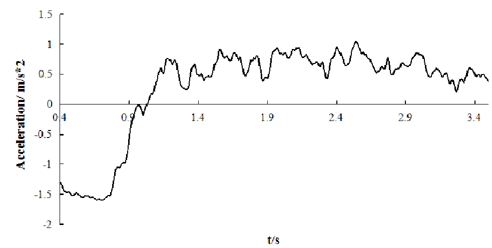

Fig.12 Acceleration Of Jack-Up

3.3.4 Post-impact Analysis

It states that ship impact is most likely to cause local damage on one of the legs only, but the possibility of progressive collapse and overturning should also be considered. The damaged legs would lose their capability of resisting the environment loading partly or completely. This would endanger the safety of global integrity. Therefore, a one year environmental loading condition provided by owner would be used to assess the residual strength of jack-ups, together with the self-weight and operational loading.

The damaged structure during the collision is used as initial state in post-impact analysis in order to ensure the rationality of result. According to the historical database, the environmental loading is applied in the direction of striking vessel.

Compared with the environmental loading applied in the initial state analysis, the 1 year environmental loading condition is relatively small. Some structure damage in tubular joint would introduce high stress in these areas, but the global stress level is acceptable. It means the residual strength of jack-up is sufficient to resist the loading.

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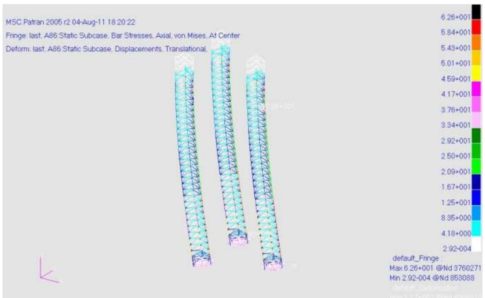


Fig.13 Residual Structure Stress

4. PARAMETER ANALYSES

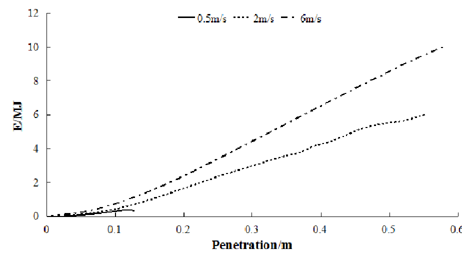
Impact parameters of striking ship and jack-up are studied in this paper. Impact parameters of striking ship include impact speed, vessel orientation and bow type, while of jack-up include water depth, impact location and sea bed condition. During the actual impact event, the parameters can be combined in many ways, which means hard to review the dynamic response and structure damage considering all the combination. In this paper only the effect of each parameter on collision response will be assessed respectively [13].

4.1 Parameter Of Striking Vessel

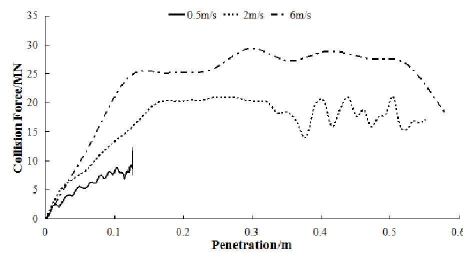
4.1.1 impact speed

The velocity of striking vessel may be different duo to wave induced in different working marine condition. Three representative impact speed would be considered: (a) operational impact 0.5m/s; (b) accidental impact 2m/s; (c) passing vessel collision 6m/s.

With the increase of impact speed, the collision become more and more severe. The maximum collision force reaches to 30MN in passing vessel collision scenarios, 2.5 times of operational impact scenarios. The increase of impact speed will lead to more deformation in collision area, together with more impact energy. The absorbed plastic energy is only 0.3MJ in operational impact scenarios, while larger deformation of structures and longer collision process will be caused in passing vessel collision scenarios.



(A) Energy Dissipated



(B) Collision Force

Fig.14 Effect Of Impact Speed On Dynamic Response

4.1.2 vessel orientation

The possible collision situations for a jack-up platform leg are head-on, stern-on and sideways-on collisions for the chords, and head-on and stern-on collisions for bracing. Accounting for the waves, tidal elevation and draught of the vessel, the impact should be assumed to occur any place in the collision area. The most probable collision orientation for supply vessels is stern-on, and nearly all passing vessel collisions are head-on. So the three vessel orientations are considered as representative scenarios.

Sideways-on collision leads to most severe damage shown in Figure 15, and then is stern-on and head-on. Sideways-on collision brings more added mass, which means maximum impact energy. Compared with head-on collision, stern-on collision results in larger collision area and more severe structure damage.

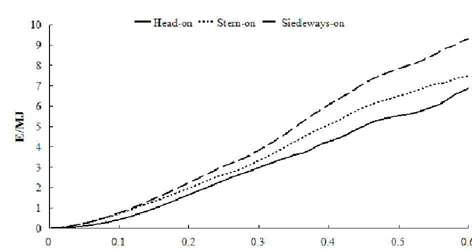


Fig.15 Effect Of Vessel Orientation On Energy Absorption

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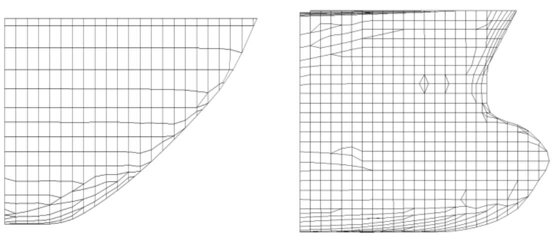
4.1.3 bow type

For the typical working area of jack-ups, the mean frequency of shuttle tanker is just less than supply vessel, which implies the high probability of collision. However, the bow type of shuttle tanker is different from supply vessel, and the structure damage is also different. So it is necessary to research the difference caused by bow type.

The chord size and structure strength is relatively small compared with bow, so the contact area with ship bow is nearly the same. The bow of supply vessel is sharper than shuttle tanker, which will result in more severe structure damage in the same penetration shown in Figure 17.



(A) Supply Vessel (B) Shuttle Tanker

Fig.16 Bow Type

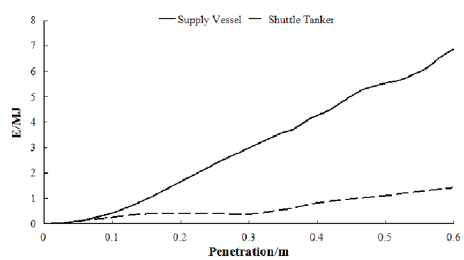


Fig.17 Effect Of Bow Type On Energy Absorption

4.2 Parameter Of Jack-Up

4.2.1 water depth

The water depth of jack-up varies greatly for its self-elevating characteristic. It is required by vessel owner that jack-ups need excellent working capability in several representable water depths. The jack-up designed by Shanghai CIMC Offshore R&D Center is required to drill in water depth of 250ft, 275ft and 300ft, so these scenarios has to be researched.

The increase of water depth means that impact location is far away from spudcan-soil interaction. The same collision force will cause larger bending moment of legs, which result in the structure damage earlier and the larger energy dissipated.

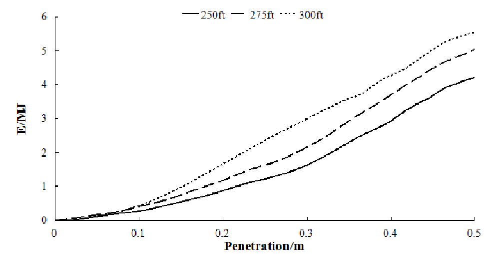


Fig.18 Effect Of Water Depth On Energy Absorption

4.2.2 impact location

For typical collision between jack-ups and vessels, the impact location is normally around the water line of legs. Seven representative impact locations (Figure 19) are chosen to analyze the energy dissipated in order to assess the collision strength in the collision area in this paper.

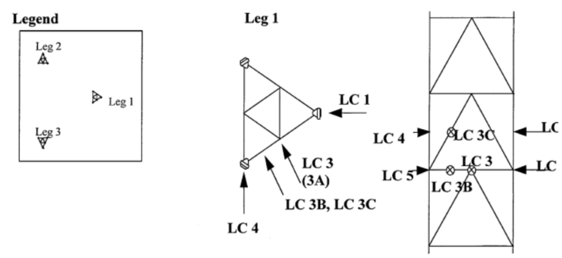


Fig.19 Impact Location

The more energy dissipated in the same penetration, the more capability of structures to resist the ship impact. The sequence of structure strength is as follows, LC2>LC1>LC5>LC4> LC3A>LC3B>LC3C. Where the strength of chord is much stronger than brace, LC1 is stronger than LC4. And LC2 is stronger than LC1 because it is in the joint of structures. Besides, the strength of brace joint is stronger than the center of horizontal and diagonal brace.

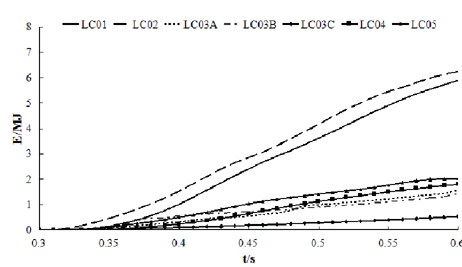


Fig.20 Effect Of Impact Location On Energy Absorption

4.2.3 sea bed condition

When jack-up is in working condition, its legs may penetrate the sea bed and its rotational stiffness is between pinned and fixed. The rotational stiffness from the interaction is limited to a maximum value

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based on the equations provided in Ref 8. The Owner may select individual values of the rotational stiffness from zero (representing the pinned condition) to the maximum as the basis of the conditions that are reviewed in the unit's classification and listed in the Operating Manual. So the three scenarios as pinned flexible and fixed stiffness are considered in this paper.

The result imply that the influence of sea bed condition on energy dissipated is little. Sea bed condition may influence on the distribution of structure bending moment in static analyses, but hard to on the dynamic impact analysis result whose stress is much larger than yield stress. So it implies us that assuming pinned condition is sufficient to analyze the collision between jack-ups and vessels accurately.

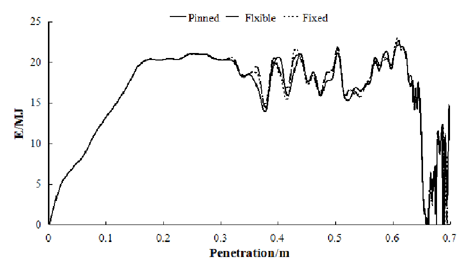

Fig.21 Effect Of Sea Bed Condition On Energy Absorption

5. CONCLUSIONS

Taking a 300ft jack-up designed by Shanghai CIMC Offshore R&D Center as an illustrative example, one approach of assessing structural strength for collision between jack-up and vessel considering the initial state of the jack-up and residual strength is put forwarded. Furthermore, the influence of impact parameters on structure damage and dynamic response is considered.The primary conclusion is as follows,

(1) Jack-up/vessel collision is a complex dynamic process, which can be simulated accurately by non-linear finite element method. The approach provided in this paper takes into consideration the initial state and residual strength of the jack-up. The author believes it has a certain level of applicability in actual collision cases.

(2) Global deformation and local damage happens in the assumption provided in this paper. The jack-up doesn't overturn in a one year environmental loading condition provided by vessel owner, which implies that the residual strength is sufficient.

(3) The effect of collision parameters is complicated. The increase of impact speed brings larger impact energy and more severe structure damage. The sideways-on impact is the most dangerous impact orientation which leads to largest structure damage. The vessel without bulb stem and the increase of water depth will result in larger deformation of legs. The strength of impact location decides the severity of collision and the influence of sea bed condition is not obvious.

(4) In actual impact events, there is many combinations of parameters, so it is necessary to assess the dynamic response of jack-up collision by reliability approach in the further research.

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