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DYNAMIC ANALYSIS OF OFFSHORE TRICERATOPS UNDER FORCES DUE TO ICE CRUSHING IN ULTRA-DEEP WATERS

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ABSTRACT

Offshore triceratops are the new generation compliant platforms showing good adaptability to ultra-deep water conditions. In recent years, oil exploration is also heading towards ultra-deep cold regions with ice covered waters. Under such conditions, ice-structure interaction under different environmental conditions leads to the transformation of ice forces to the offshore structures by different failure modes. The maximum ice force occurs due to crushing failure, which is a very complicated process. In order to assess the performance of triceratops in cold regions, the dynamic analysis of the structure under the action of ice load becomes crucial. This study aims at investigating the response of offshore triceratops under dynamic ice forces, developed due to crushing of ice sheet against the buoyant legs of triceratops. The dynamic ice force time history is obtained from the spectral model for forces due to continuous ice crushing, by neglecting the feed-back effect due to structural displacements. The developed force time history is highly dependent on ice velocity. The numerical analyses of triceratops are then carried out from the force time history. It is followed by fatigue analysis of tethers to assess the service life of triceratops in ice-infested waters.

Keywords: *Offshore triceratops, dynamic analysis, ice crushing, ultra-deep waters, fatigue analysis*

1.0 INTRODUCTION

Offshore oil and gas production is heading towards ultra-deep waters in the Arctic region of water depth greater than 2000m, where even compliant offshore platforms are not adaptable. Thus, there is a need for a suitable platform compatible with the harsh cold regions. The geometric form of the platform should be highly capable of alleviating the ice loads acting on the structure, which is a major consideration in ice infested waters. The ice load on the structure from drifting ice mainly depends up on the type of ice failure. There are different modes of ice failure such as bending, crushing, cracking and spalling. Previous studies reported that the crushing ice failure tends to cause maximum ice force on offshore structures, where the ice failure occurs under three different modes such as ductile, ductile-brittle transition and brittle mode. The brittle ice failure causes

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random ice forces under very high ice velocity which leads to ice induced vibration on the structure. The analysis of structures under such dynamic ice forces is necessary to design them suitably for ice covered regions in ultra-deep waters [12]. Several ice structure interaction models are developed to assess the performance of the structure under different ice failure modes. But, developing analytical model for continuous crushing process is cumbersome [15]. However, the dynamic analysis under this type of failure can be carried through the spectral models developed based on real time data. One such spectra model was developed by Karna et al for continuous ice crushing which can be conveniently applied for both narrow and wide offshore structures [9].

The main aim of this study is to assess the suitability of offshore triceratops under ice infested waters at water depth greater than 2000m. Offshore triceratops are one of the new generation platforms, capable of alleviating the wind, wave and current loads efficiently in ultra-deep waters [4, 5]. The triceratops consists of the deck connected to three buoyant legs by ball joints. The buoyant legs are deep draft structures usually designed as orthogonally stiffened cylindrical shells. The buoyant legs ensures positive buoyancy to the platform. The buoyant legs are position restrained by a set of taut moored tethers under high initial pretension. Thus, the platform remains stiff in the vertical plane and compliant in the horizontal plane. The geometric form of triceratops has the advantages of spar platforms and the structural action is similar to that of Tension Leg Platform (TLP) due to taut mooring. Thus, triceratops acquires the advantages of both spar and TLP. However, the major component which enhances the advantage of triceratops compared to other compliant platforms is the ball joints. The ball joints restrains the transfer of rotational motion and transfers only the translational motion between the buoyant legs and deck. This reduces the deck response considerably and provides a suitable working area for oil drilling and production [7]. Previous studies reported that the response in deck is lower than that of buoyant legs even under the combined action of wind, wave and current loads. Neither the yaw response nor the pitch response due to wind load gets transferred from the deck to the buoyant legs [1]. Reduced pitch response was reported on deck of triceratops even under the seismic load, which makes the platform highly suitable for areas with high probability of earthquakes [6]. Studies carried out on stiffened triceratops, where each buoyant leg is suitably stiffened with intermediate stiffeners reported the high stability of platforms [2].

So far, the intrinsic studies carried out triceratops focussed only on the common environmental loads in offshore location such as wave load, wind load, current load and seismic load up to a water depth of 900m. As the platform is highly effective with respect to its innovative structural form, this study aims at assessing the dynamic response of triceratops under ice loads due to continuous ice crushing. Numerical analysis of triceratops is carried out under dynamic ice load at a water depth of 2400m for different ice sea states with varying ice thickness and ice crushing strength using Ansys Aqwa. It is followed by fatigue analysis of tethers to calculate the service life of tethers under the action of ice load. This study is a prima facie to understand the behaviour of triceratops in ice-infested waters and detailed finite element analysis is required to assess the stresses and deformation in buoyant legs under ice load action.

2.0 NUMERICAL MODEL OF TRICERATOPS

Since triceratops are one of the new generation platforms which are under developmental stage, the geometric details of the model suitable for ultra-deep waters are developed from Perdido Spar platform commissioned at the Gulf of Mexico at a water depth of 2348m [10]. The height of the platform is maintained same as that of spar and the buoyancy of hull is distributed to three legs. The geometric details are provided in Table 1. The deck of the platform is designed as an integrated truss deck system with three deck levels: cellar deck, main deck and the top deck. The deck is also provided with diagonal members to resist the wind load acting on it. The buoyant legs are designed as orthogonally stiffened cylindrical shells with stringers and ring frames and checked for bucking as per DNV standards [14]. Based on the developed geometry, triceratops is modelled in Ansys

Aqwa design modeller. The deck is modelled with solid elements and the buoyant legs are modelled as tube elements. The mass and centre of gravity are given as inputs for deck and the buoyant legs separately. The buoyant legs and deck are connected using ball joints. The buoyant legs are position restrained by a set of taut moored tethers, which are modelled as linear cables. The stiffness value of the tethers is also defined in the modeller, which is used for the calculation of initial pretension. The meshing of the model is then carried out with triangular and quadrilateral panels based on optimum meshing standards in Aqwa. The deck of the platform is meshed with 8079 elements and 8220 nodes. The developed numerical model is shown in Figure 1.

Table 1: Details of Triceratops

Description	**Unit**	**Quantity**
Water depth	m	2400
Unit weight of material	kg/m^3	7850
Unit weight of sea water	kg/m^3	1025
Geometric Details		
Diameter of Leg	m	15
c/c distance between the legs	m	61.77
Freeboard	m	20.24
Draft	m	154
Tether length	m	2246
Diameter of tether	m	1.00
Vertical Centre of gravity of buoyant leg	m	-112.74
Metacentric Height	m	35.83
Load Details		
Self-weight + payload	MN	562.42
Buoyancy force	MN	820.93
Total Tether force	MN	258.49
Structural properties		
Area of deck	m^2	3933
Stiffness of tethers	GN/m	0.22

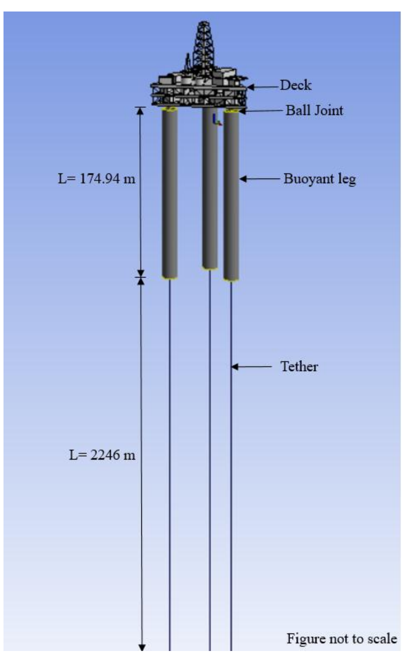


Figure 1: Numerical Model of Triceratops

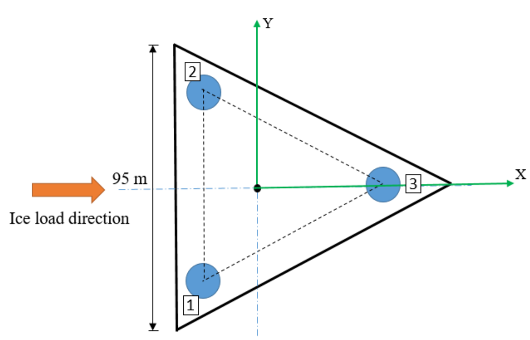


Figure 2: Plan of Triceratops

Free oscillation studies are then carried out by applying suitable displacement at different degrees of freedom to find the natural period of the structure in all six degrees of freedom. Then, the damping ratio in respective degrees are calculated by logarithmic decrement method. The natural period and damping ratio of triceratops in six degrees are freedom are listed in Table 2. The platform has higher natural period in surge, sway and yaw degrees of freedom ensuring its compliancy in horizontal plane. The lower natural period in heave, roll and pitch degrees of freedom shows that the platform is stiff in vertical plane.

Table 2: Natural period and damping ratio of tethered triceratops

Degree of freedom	Natural period (seconds)	Damping ratio (%)
Surge	215.00	5.84
Sway	215.40	5.87
Heave	4.30	0.94
Roll	6.20	6.11
Pitch	6.10	6.10
Yaw	215.90	6.23

3.0 NUMERICAL MODEL OF TRICERATOPS

The major criteria that limits the maximum ice load acting on the structure is the ice failure mechanism of drifting ice. Ice failure depends upon several factors such as shape and width of the structure, ice velocity, ice crushing strength and the relative velocity between ice and structure. Different ice failures are reposted during ice structure interaction such as bending, crushing, splitting and combination of modes [13]. Previous studies on ice failure mechanisms reported that the crushing failure causes maximum ice force on offshore structures [15]. Crushing failure occurs when a thick sheet of drifting ice hits the vertical structure. During interaction with complaint structures, the ice fails by ductile and brittle modes under low and high ice velocities respectively. Continuous crushing occurs at high ice velocities inducing random vibrations on structure. This particular failure process is considered in this study for the analysis of triceratops. The ice force time history under continuous crushing will have randomly distributed periods and amplitudes similar to random waves. Thus, it can be assumed as a stochastic process and conveniently represented in terms of spectral model. The spectrum developed by Karna et al based on the real time data is used in this study [9]. The autospectral density function for continuous crushing is represented by:

$$G_n(f) = \frac{{\sigma_n}^2 \bar{G}_n(f)}{f} \quad (1)$$

$$\bar{G}_n(f) = \frac{af}{1 + k_s a^{1.5} f^2} \quad (2)$$

where, $a = bv^{-0.6}$, v is the ice velocity in m/s, b and k_s are the experimental parameters, f is the frequency in Hertz and ${\sigma_n}^2$ is the variance of the local force. The variance of the local force is calculated from maximum ice force and intensity parameter by the following equations.

$$\sigma_n = \frac{I_n}{1 + kI_n} {F_n}^{max} \quad (3)$$

$${F_n}^{mean} = \frac{{F_n}^{max}}{1 + kI_n} \quad (4)$$

The maximum ice force highly depends upon the mechanical properties of ice and the shape and width of the structure. Several expressions are available to calculate the maximum ice force on fixed and compliant structures. In this study, Korzhavin's equation is used for calculating the maximum ice force under continuous crushing on the buoyant legs. It is given by:

$$F = a_1 a_2 a_3 hw\ \sigma_c \quad (5)$$

where, a_1 is the shape factor (0.9 for circular members), a_2 is the contact factor (0.5 for moving ice), a_3 is the aspect ratio factor, σ_c is the crushing strength of ice in MPa, h is the thickness of ice in m and w is the projected width of the structure in m. The crushing strength of ice mainly depends upon temperature. The maximum ice crushing strength in the coldest time of the year as recorded in Beaufort Sea is 3MPa, which can be considered as an extreme value [11]. Under spring conditions with the temperature close to the melting point, the ice crushing strength is 1.5 MPa. Based on this, two ice sea states are developed to assess the response of triceratops as shown Table 3. As the spectral model is valid for the ice velocity range of 0.04m/s to 0.35m/s, the ice velocity for both the ice sea states are maintained same as 0.2m/s. The spectral density plots under different sea states are shown in Figure 3. The ice load time history is then obtained by inverse fast fourier transform using MATLAB.

Table 3: Ice sea states

Ice sea state	Ice thickness (m)	Crushing strength (MPa)	Ice velocity (m/s)	Maximum ice load (kN)
Normal	0.5	1.5	0.2	5468.10
Extreme	1	3	0.2	23382.70

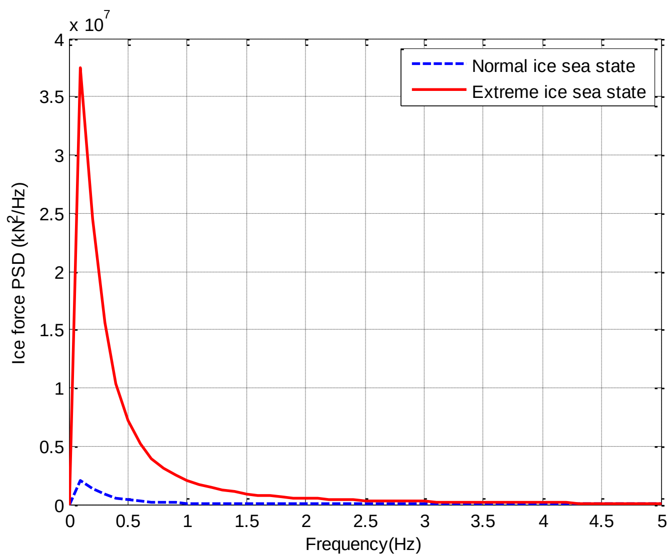


Figure 3: Ice force spectrum for continuous ice crushing under different sea states

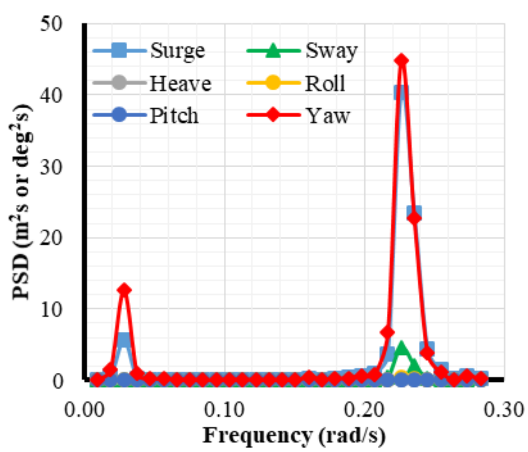
4.0 DYNAMIC RESPONSE OF TRICERATOPS UNDER CONTINUOUS ICE CRUSHING

Since triceratops is a three legged structure, it will be subjected to maximum ice force when ice acts on two legs simultaneously. Thus, the obtained ice load time history under both ice sea states is applied as structure force in Ansys Aqwa on two buoyant legs (Buoyant leg 1 and 2) as shown in Figure 2. The ice load action on buoyant legs causes significant response in all degrees of freedom in the deck unlike the response of deck under the action of waves [3]. The responses are found to be periodic in nature. The statistical quantities of the deck response are given in Table 4. As seen from the table, the ice load causes a shift in the mean surge position of deck and the platform starts oscillating in a new mean position. As surge and heave degree are coupled in compliant platforms like triceratops, the mean shift in surge degree also causes a setback in heave degree of freedom. The total surge response in extreme sea state is only about 10% of draft of the structure and the total heave response in 18% of the surge response. This shows the adequacy of the platform even under extreme ice sea state conditions. Though the ice load is applied along x-axis, it also induces sway response in the deck. However, the total sway response in normal and extreme sea states are only 24% and 29% of the total surge response respectively. The mean shift in the sway response is also comparatively less than that of surge response. Responses are also observed in roll and pitch degrees of freedom with very less magnitude. The response in surge and sway degrees induces response in the yaw degree of freedom with the mean shift in both normal and extreme sea states.

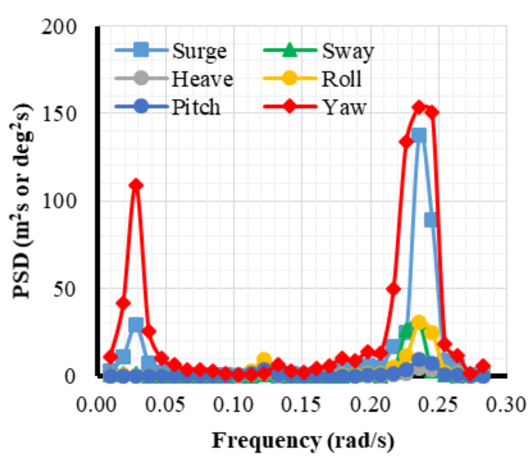
Table 4: Deck response under different sea states

Sea state	Statistics	Surge (m)	Sway (m)	Heave (m)	Roll (degree)	Pitch (degree)	Yaw (degree)
Normal	Maximum	4.54	0.48	0	0.46	0.05	6.47
	Minimum	0	-0.59	-0.18	-0.003	-0.24	0
	Mean	2.49	-0.06	-0.06	0.15	-0.08	3.62
	SD	0.90	0.28	0.04	0.10	0.05	0.98
Extreme	Maximum	14.88	1.27	0	6.96	0.04	24
	Minimum	0	-3.09	-2.70	0	-3.93	0
	Mean	10.27	-1.02	-0.97	2.45	-1.34	16.70
	SD	1.91	0.83	0.39	1.01	0.58	2.84

The power spectral density plots of response of deck and buoyant legs under normal ice sea state is shown in Figure 4(a). Maximum deck response in surge and yaw degrees of freedom are observed at surge natural frequency and at the neighbourhood of one-fourth of pitch natural frequency. Similarly, sway response is also significant at one-fourth of pitch natural frequency. The responses in other degrees of freedom are comparatively less. The deck shows prominent responses only in the horizontal plane i.e., in surge, sway and yaw degrees of freedom under normal ice sea state. The PSD plot of deck response in extreme ice sea state is shown in Figure 4(b). The responses in surge and yaw degrees of freedom are significant at surge natural frequency and at the neighbourhood of one-fourth of pitch natural frequency. A shift in the second peak is observed from normal to extreme ice sea states. Heave response in both the sea states is very less due to high initial pretension in tethers. The reduced response in roll and pitch degrees of freedom shows the effectiveness of ball joints in restraining the rotational degrees of freedom from buoyant legs to deck.



(a) Normal ice sea state



(b) Extreme ice state

Figure 4: PSD plots of deck response

5.0 FATIGUE ANALYSIS OF TETHERS

The response of buoyant legs in different degrees of freedom under ice load action causes dynamic tether tension variation which is periodic in nature. This may lead to fatigue failure of tethers. The statistics of tension variation in buoyant legs are shown in Table 5 for normal and extreme ice sea states. Under normal ice sea state, the tether tension variation in buoyant legs 1, 2 and 3 are 1.4%, 1.2% and 1.4% respectively. In extreme ice sea state, the maximum tether tension is observed in buoyant leg1 with the tether tension variation of about 5.5%. From normal to extreme ice sea states, the mean shift in the tether tension also increases in all buoyant legs. The maximum stress developed in the steel wires of buoyant leg 1 are 11.5 N/mm^2 and 12.5 N/mm^2 in normal and extreme ice sea states respectively. Though the stress developed is only about 3% of the yield stress of the material, the large number of cycles with reversal of stresses may cause fatigue failure.

Table 5: Tether tension statistics

Sea state	Statistics	Buoyant leg 1 (MN)	Buoyant leg 2 (MN)	Buoyant leg 3 (MN)
Normal	Maximum	28.13	28.02	28.13
	Minimum	27.38	27.38	27.27
	Mean	27.73	27.69	27.69
	SD	0.12	0.09	0.12
Extreme	Maximum	30.55	28.77	28.56
	Minimum	27.43	27.27	27.38
	Mean	28.64	27.92	27.94
	SD	0.33	0.21	0.15

In order to carry out a fatigue analysis of tethers, the stress histogram is plotted using rain-flow counting method. Then the allowable number of cycles are calculated by S-N curve approach [8]. The fatigue damage of tethers are calculated by Palmgren Miner's rule. The design fatigue factor is taken as unity and the S-N equation parameters are chosen for the seawater environment. The service life of tethers is then estimated from the fatigue damage. Maximum fatigue damage is observed in buoyant leg 1. The fatigue damage under normal and extreme ice sea states are 2.65e-06 and 3.12e-06 respectively. The service life decreases form 24 years under normal ice sea state to 20 years under extreme ice sea state.

3.0 CONCLUSIONS

Triceratops is one of the new generation offshore compliant platforms which is seen as an effective structural form for ultra-deep water applications. This study is carried out to check the dynamic response of triceratops in ice infested ultra-deep waters. Since crushing failure caused maximum ice force on offshore structures, the triceratops model developed in Ansys is analysed under the action of continuous crushing ice load developed from ice spectrum model. The study shows that the ice load action induces response in all degrees of freedom. The response of the deck is found to be periodic in nature with the shift in the mean position. The response and the mean shift increases from normal to extreme ice sea states. However, the heave response in deck is very less compared to surge response ensuring the suitability of the platform in ultra-deep waters even under extreme ice sea state. The response in roll and pitch degrees of freedom are less in deck, showing the advantage of ball joints. The fatigue analysis is also carried out to evaluate the fatigue damage and service life of tethers. This study reveals that the maximum stress developed in the steel wires is only about 3% of the yield stress of material and the service life of tethers decreases from normal to extreme ice sea states.

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