Spectral-Based Fatigue Analysis of a Semi-submersible Platform

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Abstract Offshore structures are exposed to wide range of cyclic loadings which causes fatigue damage and hence it is an important design consideration which determines the durability of the structure. Due to the complexity of the random loading conditions, determination of fatigue life is a tedious task. Therefore, it is important to develop a reasonable loading spectrum for fatigue assessment using cumulative fatigue damage (CFD) theory. There are few methods by which we can predict fatigue life of a structure which include fatigue crack propagation (FCP) model, by using conventional empirical relations and by developing fatigue stress response spectrum. In this paper, fatigue life of a semi-submersible platform is determined by analyzing critical joints which are exposed to cyclic loading and also by considering random numbers of short-term wave conditions which follow Rayleigh distribution. Structure considered for the study is a sixth-generation semi-submersible platform known as COSL Prospector made in CIMC Yantai Raffles shipyard in China designed for North Sea. Firstly, a hydrodynamic diffraction analysis is carried out in order to understand the response of the structure under various wave directions and frequencies. Wave-induced pressure on the column-bracing connections are determined and these joints are considered as critical locations for fatigue analysis. Suitable wave spectrum is then developed for each sea state conditions. In order to determine the stress concentration factor of the column-bracing joint, a local geometrical model of the connection is created followed by generating a fatigue stress energy spectrum and complex fatigue stress transfer function which is later described to the model. The minimum fatigue life of the local model is determined, and the results are compared with the specification required.

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1 Introduction

An offshore structure can be defined as those structures which are constructed on deep ocean mainly for oil exploration, and are able to withstand wide range of complex marine environment. Offshore structures are generally classified into three types: fixed structures which are designed to withstand lateral forces without any considerable displacement, compliant structures can undergo substantial displacement without damaging the integrity of the structure and are hinged to seabed and floating structures which are capable of moving from one field to another and can be used for larger water depths. Semisubmersibles are the most common floating structures which consist of a deck supported on columns which are attached to pontoons. Diagonal cross bracings are provided to resist the prying and racking loads by waves. Floating structures are flexible in nature which resist the lateral forces by global displacement. A semisubmersible offers better response to motion and also equal resistance to wave, current and wind from any direction. It also has the ability to support a mooring system and a large deck area, and better stability due to reduced response in roll and pitch motion.

In this paper, fatigue problems of semi-submersible structure are taken into consideration which is an important factor in offshore and wind power industry. Fatigue analysis should be performed during the design stage in order to ensure that the structure has adequate fatigue life. In addition, regular maintenance, carefully planned inspection and repairs are required from time to time to ensure the safety and operability of the floating structure during its design life.

2 Hydrodynamic Diffraction

2.1 Semisubmersible

In this paper, a four-column semisubmersible based on GG5000 design is used. Also known as COSL Prospector, it is sixth-generation semi-submersible platform designed for work in cold temperature with class notation ICE-T and Winterized Basic with covers of working areas and lifeboat stations. The unit is designed for North Sea and is developed in CIMC Yantai Raffles shipyard in China. Station keeping of the structure is maintained by dynamic positioning of variable speed thrusters or by catenary mooring system. Figure 1 shows the meshed geometric model of the structure.
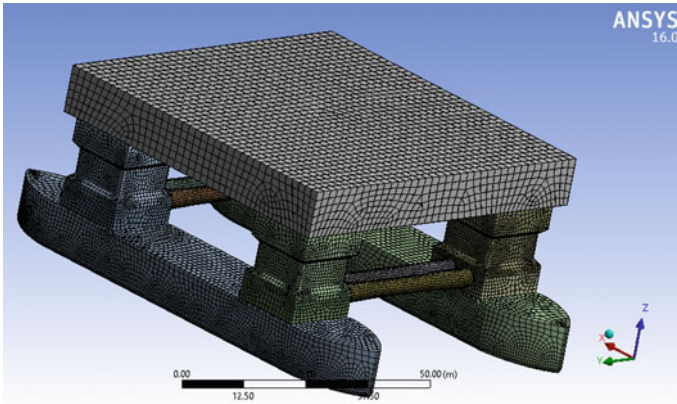
Fig. 1 COSL prospector

2.2 Modelling

Main dimensions of the structure [1] are given in Table 1. Solidworks Premium has been used to make the model geometry due to its simple user interface. Both modelling and analysis is done in Intel(R) Core™ i5-5200U CPU @ 2.20 GHz, having a RAM 8 GB and 64-bit operating Microsoft Windows OS. For neutrally buoyant structures, the effect of mooring lines on the structure is relatively less for larger units but high for smaller units. Current velocity has not been considered and the interaction of wave and current has been ignored. The effect of wind on the structure is not considered since it is negligible with respect to the impact produced by the wave. The model is exported into Ansys-Aqwa in parasolid format. Total mass of the structure is provided as point mass in centroid of the structure.

Since hydrodynamic diffraction follows finite element method of analysis, response of the structure is sensitive to mesh element size. Finer the mesh, more accurate will be the result. Hence, finer mesh cannot be used for large structures. Element size should be selected in such a way that it offers integrity of the structures, i.e. meshing will be continuous so that load acting on the structures should be transferred effectively through the mesh element boundaries. In this study, the whole unit is meshed, even though only the diffracting elements (below water surface) are used in hydrodynamic runs. Overall structure is divided into upper portion and lower submerged portion by slicing tool corresponding to the draft provided. Default wave range of − 180° to 180° is given; in addition to that a reasonable range of 0° to 180° with an interval of 15° is used because of the symmetry of the structure. However, only head sea (0°) will be regarded in this assessment as this heading will offer the highest response.

Table 1 Main dimensions and input parameters

Parameter	Dimension
Length of pontoon	104.50 m
Height of pontoon	10.05 m
Width of pontoon	70.50 m
Height (box bottom)	29.50 m
Draft	14.50 m
Weight	36141 t
Metacentric height	
GM_T	2.8 m
GM_L	3.96 m
Water plane area	1249.595 m^2
Water depth	300 m
Radii of gyration	
r_{xx}	30.20 m
r_{yy}	31.80 m
r_{zz}	34.80 m

Wave-induced pressure on the structure for various directions are calculated and the most critical condition is selected as is shown in Fig. 2. It is observed that stress concentrations occur at brace-column connection and is susceptible to fatigue damage. These locations are considered as the main case for the fatigue analysis in the following sections.
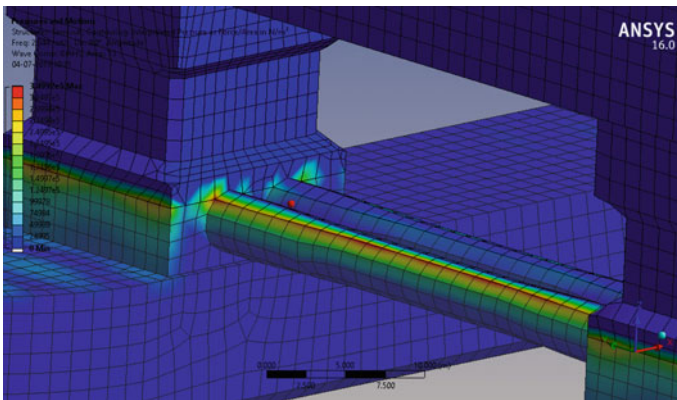
Fig. 2 Stress concentration

Fig. 3 Critical locations
considered around the joint
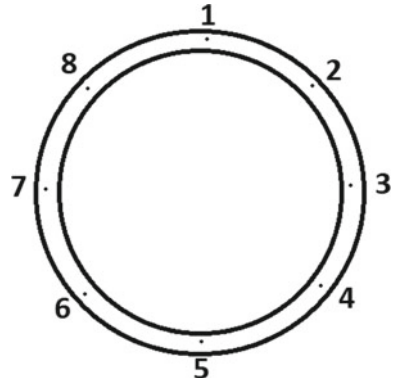
3 Stress Concentration Factor

Hot-spot stress includes all the stress concentrating features of a welded joint except that due to the local weld toe geometry. The hot-spot stress method has been widely used in the design of steel tubular structures. Since offshore structures are exposed to different types of loading environment, stress variations especially in joints are high when compared with other parts of the structure.

Fatigue lives of joint is estimated by determining the hot-spot stress range (HSSR) for the different locations considered around the joint. Stress concentration factor at a location can be defined as the ratio of HSSR at a particular location to nominal stress acting on the joint. The hot-spot locations considered in the analysis are shown in Fig. 3. Minimum eight locations around the welded joint [2] section should be considered in order to cover all the relevant hot-spot stress areas.

4 Fatigue Analysis

In this study, the brace-column link is considered as the critical point. Even though the actual structure is situated in North Sea, the effect of waves on the structure if it is placed on Indian Ocean is actually discussed in this paper. Wave data of Indian Ocean is obtained from the official website of European Centre for Medium-Range Weather Forecasts. The sea scatter diagram is shown in Table 2.

Different sea spectrums are used for different locations. Most commonly used spectrum in Asia & Gulf of Mexico is the P-M spectrum, this spectrum assumes that wind is blown steadily for a long time which covers a large area; thus, the waves would come to equilibrium and the state is known as fully developed sea state. P-M spectrum is used in this paper as the wave spectrum for further analysis, since this spectrum is widely used in Indian Ocean. Using Eq. 1 and the sea scatter diagram, spectrum is plotted for each sea state. A total of 13 sea states are used in this work for the fatigue analysis.

Table 2 Sea scatter diagram

H_s(m)/ T_z(Sec)	0–2	2–4	4–6	6–8	8–10	10–12	Probability of occurrences (%)
0–0.5	0	0	0	0.068	0	0	0.069
0.5–1	0	0	2.47	26.78	16.92	0.41	46.58
1–1.5	0	0	0.48	14.59	10.41	0.48	25.96
1.5–2	0	0	0	4.73	15.21	0.07	20
2–2.5	0	0	0	1.10	6.03	0.07	7.19
2.5–3	0	0	0	0.21	0	0	0.21
Total	0	0	2.95	47.47	48.56	1.03	**100**

$$S_\eta(\omega|H_s, T_z) = (H_s^2/4\pi)(2\pi/T_z)^4 \omega^{-5} e^{\left(\frac{\omega^{-4}}{\pi}\left(\frac{2\pi}{T_z}\right)^4\right)} \tag{1}$$

where H_s denotes the significant wave height, T_z denotes zeroth up-crossing period and ω represents the wave frequency.

A local model of a brace-column connection is constructed as per the guidelines described in DNV recommended practice. Stress concentration factor (SCF) is determined by considering unit axial loads, in-plane (IP) and out-of-plane (OOP) bending moments. Shell plating and inner strengthening members of the brace-column connection are considered in the local geometry model [3]. While doing the finite element analysis, mesh is refined around the region of interest and stresses at the corresponding locations are determined. Mesh refinement provided at the local model is shown in Fig. 4.
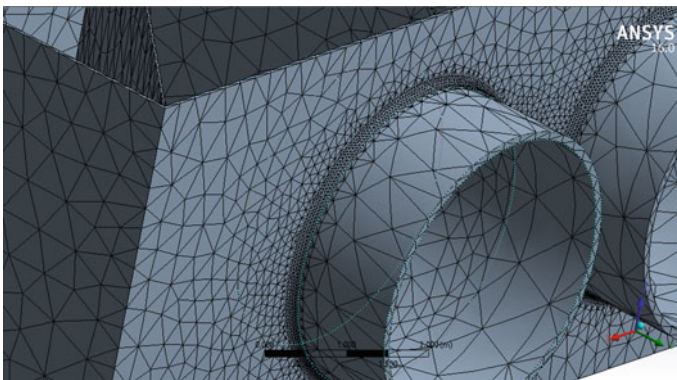
Fig. 4 Mesh refinement for local geometrical model

5 Stress Transfer Function

According to *ABS Guidelines on Spectral-Based Fatigue Analysis for Floating Offshore Structures,* stress transfer function denotes the relation between stress at structural locations and the unit amplitude incident wave of frequency (ω) and wave heading (θ). Usually, the frequency range is specified within 0.2–1.8 rad/s with an increment not greater than 0.1 rad/s. However, depending on the characteristics of the response, it will be convenient to use different frequency range. Using the axial forces and moments obtained from the analysis of global model of the brace-column connection together with the SCFs at location under consideration, hot-spot stresses in MPa/m (since they are estimated for a wave having unit amplitude) can be evaluated at each position as follows [4]:

$$X(\omega) = \text{SCF}_{\text{AX}}.\frac{N(\omega)}{A} - \text{SCF}_{\text{IPB}}.\frac{M\text{ipb}(\omega)}{I}.z' - \text{SCF}_{\text{OOB}}.\frac{M\text{oob}(\omega)}{I}.y' \quad (2)$$

The hot-spot response spectrum $S_\sigma(\omega)$ for a stress random process $X(\omega)$ is calculated by multiplying the square of hot-spot stress transfer function obtained from above equation with the wave spectrum. In this paper, only short-term sea state is considered and waves are uni-directional so that spreading function is neglected. Equation for hot-spot stress response spectrum is given by Eq. 3.

$$S_\sigma(\omega) = S_\eta(\omega|H_{\text{s}}, T_{\text{z}}).|X(\omega)|^2 \quad (3)$$

After getting the stress response spectrum, spectral moments are calculated which is used to define the probability density function (*pdf*) for a sea state. Same procedure is repeated to find *pdf* for the entire sea state and finally, fatigue damage is then calculated and corresponding fatigue life is estimated of each critical location which are considered.

6 Spectrum Based Fatigue Assessment

The stress range developed on the structure is usually expressed in terms of probability density functions for different short-term sea states corresponding to the wave scatter diagram. After determining the stress energy spectrum, spectral moments are calculated [5] and are given by Eq. 4.

$$m_n = \int_0^\infty \omega^n.S_\sigma(\omega|H_{\text{s}}, T_{\text{z}})\text{d}\omega \quad (4)$$

Since it is assumed that the wave conditions follow Rayleigh probability density function ($g(s)$) which denotes the short-term stress range distribution [6], the zero up-crossing frequency (f) of the stress response is calculated and is given by Eqs. 5 and 6.

$$g(s) = \frac{S}{4\sigma^2} \cdot e^{\left(-\left(\frac{S}{2\sqrt{2}\sigma}\right)^2\right)} \tag{5}$$

where S is the stress range, i.e. twice the stress amplitude, σ is the square root of zeroth spectral moments.

$$f = \frac{1}{2\pi} \sqrt{\frac{m_2}{m_0}} \tag{6}$$

where m_0, m_2 are the zeroth and second spectral moments.

After determining the short-term damage, the total fatigue damage is calculated using Palmgren Miner rule which assumes cumulative fatigue damage (D) as a group of variable amplitude stress cycles which is the sum of the damage induced by each stress cycle (d_i). Failure is predicted to occur when the cumulative damage (D) over N loading cycles exceeds the critical value. Summing D_i over all the sea states given in the wave scatter diagram will give the total cumulative damage D.

$$D = \left(\frac{f_0 T}{A}\right) \int_0^\infty S^m \left(\sum f_{0i} \frac{p_i g_i}{f_0}\right) ds \tag{7}$$

where f_0 average frequency of S over the lifetime.

7 Results and Discussion

The results on fatigue life of different critical locations which are prone to high fatigue damage is determined and is given in Table 3. The fatigue damage of location 3 is the lowest and fatigue life of location 6 is the shortest. The stress concentration is more evident in this sea state. However, it meets the specification requirement since minimum design life for a floating offshore structure as per the *ABS rules for Building and Classing Mobile Offshore Drilling Unit* is 25 years. The locations having significant stress concentration needs to reinforce when it is designed for ensuring sufficient fatigue strength in service.

Table 3 Fatigue life of critical locations

Location	Fatigue damage	Fatigue life (Yrs)
1	0.01974	50.66
2	0.01739	57.51
3	0.01464	68.32
4	0.01779	56.21
5	0.01590	62.91
6	0.01986	50.36
7	0.01833	54.57
8	0.01755	56.98

8   Conclusions

Semisubmersibles are susceptible to fatigue action due repeated application of wave loads, and hence should be adequately assessed while designing the structure. A spectral-based fatigue analysis will provide an effective and reliable technique for performing fatigue evaluation of offshore structures considering the distribution of wave energy across the entire frequency range and incorporating representative structural dynamics in the analysis. The fatigue life of the brace-column attachment meets the specifications. The locations considered are susceptible to fatigue damage and must be reinforced when it is designed for ensuring enough fatigue strength in service.

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