International Journal of Technology (2016) 6: 1107-1116
ISSN 2086-9614

THE EFFECT OF SYMMETRICAL AND ASYMMETRICAL CONFIGURATION SHAPES ON BUCKLING AND FATIGUE STRENGTH ANALYSIS OF FIXED OFFSHORE PLATFORMS

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(Received: September 2015 / Revised: July 2016 / Accepted: September 2016)

ABSTRACT

The fixed jacket is still the most common offshore structure used for drilling and oil production. The structure consists of tubular members interconnected to form a three-dimensional space frame, which can be categorized into a column structure. The structure usually has four to eight legs that are battered to achieve stability against axial compressive loads and toppling due to wave loads. The configuration of a typical member on the jacket structure has significant influence on buckling and fatigue strength. Horizontal and diagonal braces play an important role in resisting the axial compression and wave load on the global structure. This paper discusses the effect of symmetrical and asymmetrical configuration shapes in buckling and fatigue strength analysis on two types of fixed jacket offshore platforms. The axial compressive and lateral (wave) loads were considered and applied to both structures. The material and dimensions of the two structures were assumed to be constant and homogenous. Crack extension and corrosion were not considered. To assess the buckling and fatigue strength of these structures, due to the symmetrical and asymmetrical configuration shape, the finite element method (FEM) was adopted. Buckling analysis was performed on these structures by taking two-dimensional planes into consideration to obtain the critical buckling load for the local plane; fatigue life analysis was then calculated to produce the fatigue life of those structures. The result obtained by FEM was compared with the analytical solution for the critical buckling load. The stress-strain curve was also applied to show the difference between symmetrical and asymmetrical shapes. For fatigue life analysis, the procedure of the response amplitude operator was applied.

Keywords: Buckling analysis; Fatigue analysis; Finite element method; Fixed offshore platform; Symmetrical and asymmetrical shape

1. INTRODUCTION

A fixed jacket platform is a type of column structure that resists not only axial compression but also lateral load. Axial load is generally distributed to all jacket legs in a vertical direction. In contrast, the lateral load acts on the structural components, such as diagonal and horizontal braces, including jacket elements. The configuration of the braces or tubular members on the fixed jacket structure plays an important role toward the local and global structural behavior so the failure mode of the structure can occur in any situation. In this situation, structural degradation (i.e. buckling and fatigue) can suddenly take place. The buckling of offshore

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Permalink/DOI: https://doi.org/10.14716/ijtech.v7i6.877

structures has already been evaluated by Lee et al. (2015), and the irregular shapes of the structural members were evaluated by a design guide and by numerical methods. In addition, fatigue is a primary mode of failure for steel structures that are subjected to dynamic load. A practical method for a dynamic fatigue assessment of a jacket-type of offshore structure was investigated by Azarhoushang and Nikraz (2012). The buckling behavior of a column with a weakening hinge strengthened with a spring support was analyzed by Wang (2002). Equations were formulated for six different combinations of end conditions, which focused mainly on the influence of the bracing stiffness on the optimum location of the hinge. Normally, when structural members are in compression, the members do not have the capacity to receive any additional load. They will not fail except by crushing or exceeding their compressive yield strength, and fatigue does not occur for elements in compression. However, if the geometry of the member is such that it is a "column" then buckling can occur. Buckling is particularly dangerous because it is a "catastrophic failure" that gives no warning. That is, the structural system collapses, which often results in total destruction of the system, and, unlike yielding failures, there may be no signs that the collapse is about to occur. Design engineers must be constantly vigilant against buckling failure. Therefore, the effect of the braces' configuration on buckling and fatigue of the fixed jacket platform must be taken into account.

Many studies have been performed on the assessment of buckling strength and fatigue analysis. Geschwindner (2003) briefly reviewed a wide range of analytical approaches, including elastic buckling analysis, as well as first- and second-order elastic and inelastic analytical methods. The result of these approaches will be compared to those of an elastic stability analysis for simple frames, which have been found in the literature. Schuring and Bertram (2011) investigated the torsional buckling of a plastically deforming cruciform column under a compressive load. The problem was solved analytically, based on the von Karman shallow shell theory and the virtual work principle. Solutions found in the literature were extended for path-dependent incremental behavior as typically found in the vortex effect that is present in metallic polycrystals. Azarhoushang and Nikraz (2012) investigated a jacket-type offshore structure using a practical method for dynamic fatigue assessment. An accurate procedure for the random vibration computation of structure was developed using frequency domain techniques. Taier et al. (2013) evaluated the fatigue lives of four tubular joints of a fixed offshore platform using finite elements. The Stress Concentration Factor was also calculated and compared with the finite element. The results showed that the finite element analysis was recommended for joints whose type and/or behavior was not consistent with the computational model used. Khalifa et al. (2014) assessed the fatigue life for single-side welded tubular joints of the fixed platform. The analysis procedure was presented for numerical fatigue assessment methods based on S-N curve approach for the American Petroleum Institute standard utilizing the simplified method and the spectral (stochastic) method. The effects of the current, the jacket natural period, and the jacket stability on fatigue life assessment have been investigated.

In the present study, the effect of the symmetrical and asymmetrical configuration shape in buckling and fatigue analysis on fixed jacket offshore platforms was discussed. Two kinds of fixed jacket offshore structures were the object of the analysis. The axial compressive and lateral (wave) loads were considered and applied to both structures. The material and dimensions of the two structures were assumed to be constant and homogenous to ascertain the effect of the symmetric and asymmetric configuration shapes of both structures to the buckling and fatigue strength analysis. For simple calculations, and to reduce unassociated results regarding the target purposes, crack extension and corrosion were not considered. To assess the buckling and fatigue strength of these structures, due to the symmetrical and asymmetrical configuration shape, the finite element method (FEM) was used. As a fundamental case, a buckling analysis was performed on these structures by taking two-dimensional (2D) planes into consideration to obtain the critical buckling load for the local plane, followed by a fatigue life analysis calculation. The result obtained by FEM was compared with the analytical solution for the critical buckling load, and the stress-strain curve was applied to show the difference between the symmetrical and asymmetrical shape of two structures, including their fatigue life. The applicability of the FEM was further applied to investigate local and global structural deformation.

2. ANALYTICAL METHOD

The maximum load a column can carry is called the "ultimate load," which depends on the initial eccentricity of the column, the eccentricity of the load, the transverse load, the end condition, local or lateral buckling, inelastic action, and residual stress. Buckling failure can be calculated by the Euler approach. Euler buckling is defined by Young's modulus, the moment of inertia, and effective length. The Euler buckling load is determined using this expression:

$$P_E = \frac{\pi^2 EI}{L_e^2} \tag{1}$$

The Euler buckling load is the load for which an ideal structure will first become unstable and buckle if slightly disturbed from its equilibrium condition. Due to various factors (as explained above), the ultimate load will be less than the Euler buckling load. Generally, the ultimate load is the load concern, but the Euler buckling load is helpful information. The linear elastic buckling load is easily calculated and can give an idea of the type and pattern of ultimate failure (Hughes & Paik, 2010). For ideal columns, the buckling load will be less than the Euler buckling load if the compressive stress in the column exceeds the proportional limited stress; an effective weakening of the column is therefore indicated by the diminished slope of the stress-strain curve. The relationship between the Euler buckling load and the deflection shape for the ideal column can be defined as:

$$\frac{d^2w}{dx^2} + \frac{Pw}{EI} = 0 \tag{2}$$

Mathematically, it is the Eigen value in the solution to Euler's differential equation, as shown in Equation 2. The Euler buckling load is also called the "critical buckling load." Since Young's modulus depends on the critical buckling load, the calculation of that load is generally a trial and error approach. To calculate the critical buckling stress, this expression can be used:

$$\begin{aligned} \sigma_E &= \frac{P_E}{A} \\ \sigma_E &= \frac{\pi^2 E}{\left(\frac{L_e}{\rho}\right)^2} \end{aligned} \tag{3}$$

where ρ is the radius of the gyration, or can be expressed using these relationships:

$$\begin{aligned} I &= \rho^2 A \\ \lambda &= \frac{L_e}{\rho} \end{aligned} \tag{4}$$

λ is slenderness ratio of column.

In this study, the effect of wave load was also included in the analysis. Therefore, to calculate wave load, the Airy wave theory was used. This theory is selected depending on the characteristics of the environmental data. The structures are located in Indonesia, so the ratio of $\frac{h}{\lambda}$ and $\frac{H}{\lambda}$ corresponds with the Airy wave theory, where h = 48.83 m (water depth), H = 5.54 m (wave height), and λ = 132 m (wave length). From here, the calculation of wave load can be done by using the Morison equation, which is defined as :

$$f = \frac{1}{2}\rho C_D D|u|u + \rho C_I \frac{\pi D^2}{4} a \tag{5}$$

where ρ = 1025 kg/m^3, C_D = 1.0, C_I = 2.0, D, $|u|$, and a are fluid density, drag coefficient, inertia coefficient, pile diameter, horizontal water velocity, and horizontal water acceleration, respectively. These values were selected for extreme conditions. It should be noted that the pile diameter was different for each structural member. Horizontal water velocity $|u|$ and acceleration a are determined according to the following equations:

$$u = \frac{\omega H}{2} \frac{Cosh(ky)}{Sinh\ (ky)} Cos(kx - \omega t) \tag{6}$$

$$a = \frac{\omega^2 H}{2} \frac{Cosh(ky)}{Sinh\ (ky)} Sin(kx - \omega t) \tag{7}$$

ω, H, and k are angular velocity, wave height, and wave number, respectively. Angular velocity and wave height were expressed using these equations:

$$\omega = \frac{2\pi}{T} \tag{8}$$

$$k = \frac{2\pi}{\lambda} \tag{9}$$

The relationship between angular velocity and wave number was defined using this formula:

$$\omega^2 = g\,k \tanh kh \tag{10}$$

To determine fatigue life, the fatigue spectral method was performed. The following procedures were derived:

$$S(\omega) = \alpha\, g^2 \omega^{-5} \exp\left[-1{,}25\left(\frac{\omega}{\omega_0}\right)^{-4}\right] \gamma^{\exp\left[\frac{-(\omega-\omega_0)^2}{2\tau^2\omega_0^2}\right]} \tag{11}$$

The JONSWAP spectral was used because for the general wave in Asia especially in Indonesia, this wave spectral in some places most closely to the JONSWAP spectral compared to others.

The general equation of response amplitude operator (RAO) was determined by:

$$Re\,sponse\ (\omega) = RAO\ \ \eta\ (\omega) \tag{12}$$

Response spectra are defined as response energy density on the structure due to wave load; in this case it was the spectrum of energy density. For the linear system, the function of RAO is a quadratic function. A response spectrum is a multiple between wave spectrum and RAO quadratic function. Therefore, the response spectrum equation can be expressed by:

$$S_R(\omega) = [RAO(\omega)]^2 S(\omega) \tag{13}$$

To determine zero and second moment, a stress spectrum calculation was used:

$$m_0 = \int_0^m S_R(\omega) d(\omega)$$
$$m_2 = \int_0^m \omega^2 S_R(\omega) d(\omega) \tag{14}$$

The mean zero crossing periods for stress were calculated using the following equation:

$$T_{Z\sigma} = 2\pi \sqrt{\frac{m_0}{m_2}} \tag{15}$$

Stress significance was:

$$\sigma = \sqrt{4 m_0} \tag{16}$$

The stress range number and the number of cycles based on the S-N curve was written by:

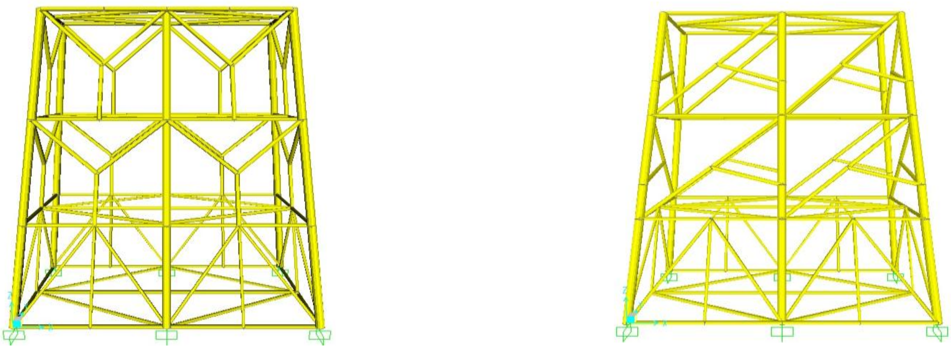
$$n = \frac{T}{T_{Z\sigma}} \tag{17}$$

Finally, fatigue life was determined by using Miner's formula:

$$D = \sum \frac{n}{N_i} \tag{18}$$

3. FINITE ELEMENT METHOD

To calculate buckling strength and wave load, FEM was carried out. Only the jacket structure was considered for analysis (deck structural components were not included). The wave load is always applied directly to the jacket structure, and does not work on the deck structure. This is why only the jacket structure was analyzed. Two kinds of fixed offshore platforms were chosen to be evaluated for critical buckling load and critical buckling stress. The number of elements for symmetric and asymmetric shape configuration were 127 and 140, respectively. The number of grid points were determined based on the 3D model for symmetric and asymmetric shape configuration in the FEM. Both shapes are shown in Figure 1.



(a) Symmetric (b) Asymmetric

Figure 1 Fixed offshore platforms

The boundary conditions were assumed to be fixed to both structures at the bottom sea level. The material and dimensions, including the breadth, depth, diameter, and thickness of members were set up to be constant. As a simple calculation to obtain the critical buckling load, the plane section was considered. In this case, the structures were symmetric at any plane. In the FEM model, the property modification factor for area was set at 100,000 and the property modification factor for shear area was set at 0. These modification factors were imposed on both structures. The self-weight multiplier was set at zero when the calculation was conducted using FEM. This was because the analytical method did not consider this effect (i.e. the analytical method performs a classic analysis). The geometries, loadings, and dimensions of the two structures are shown in Figures 2 and 3.

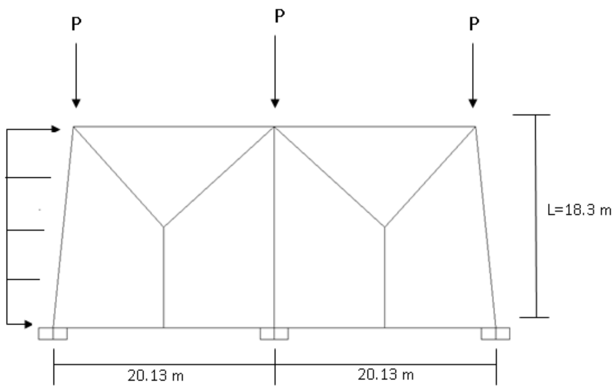


Figure 2 Axial and wave loads on the symmetrical column

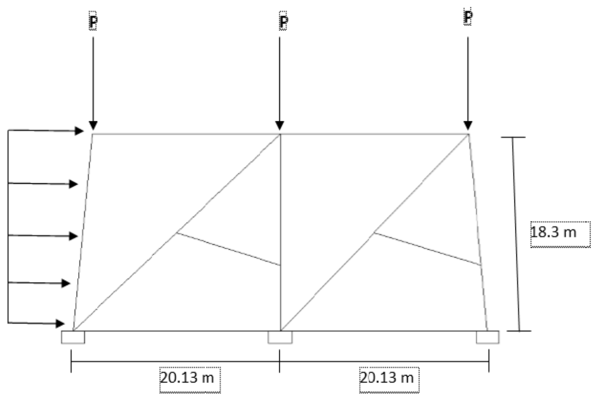


Figure 3 Axial and wave loads on the asymmetrical column

Figure 4 shows the FEM that was to analyze the structure for buckling assessment.

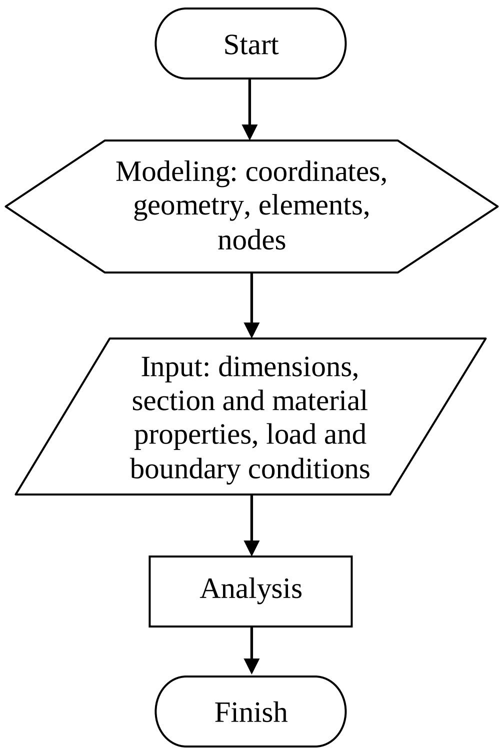


Figure 4 The finite element method (FEM)

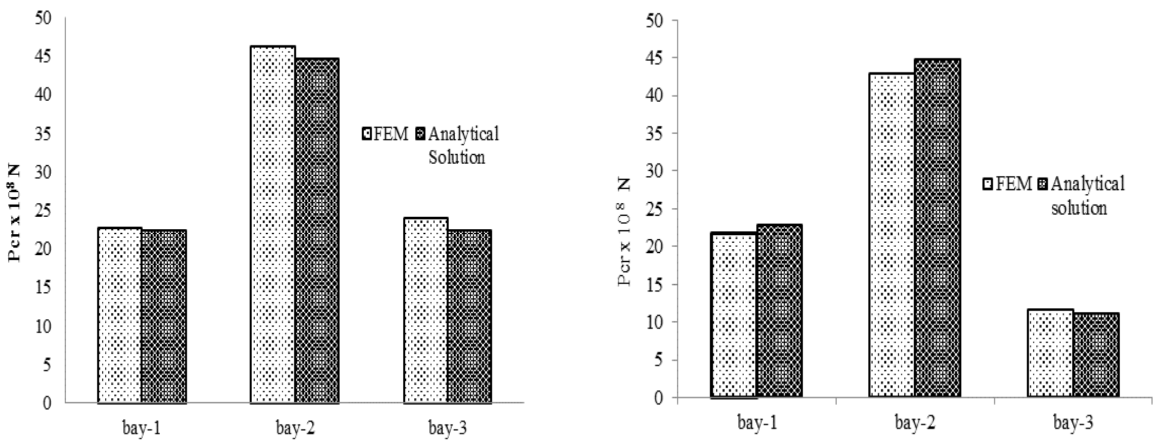
The buckling strength of the irregular shaped members of the offshore structures was evaluated by a design guide and by numerical methods (Lee et al., 2015) and calculated by DNV-RP-C201, which was established for idealized plate structures. The result was compared with the buckling strength by the classical finite element software ABAQUS. Also, an efficient method, the Idealized Structural Unit Method, which evaluates the ultimate strength of structures, was described by Ueda (1991). Its application to offshore frame structures was presented taking into account the nonlinear behavior of the structure as a whole, plus the members and joints.

4. RESULTS AND DISCUSSION

Buckling stresses can be referred to a process in which a structure is not able to retain its original shape. The consequences of buckling is essentially geometric problem where the large deflection may occur and make the structure becomes deformed. The bending or buckling phenomenon can occur in a column, a plate, or a frame. Buckling strength analysis for a simple rigid frame structure was performed and analyzed by Timoshenko and Gere (1985). The structure was also verified by Computers and Structures Inc. (CSI, 2014) using FEM code SAP 2000. The critical buckling load was evaluated by FEM analysis using SAP; the result was in agreement with the analytical solution derived by Timoshenko and Gere (1985).

Therefore, from this viewpoint, two fixed jacket structures were also calculated using FEM code SAP 2000 to evaluate the critical buckling load including load-end shortening of the stress-strain curve. Only the jacket structure was analyzed; deck structural components were not included. The axial compressive load was distributed vertically downward to all jacket legs. The lateral loads (wave loads) were calculated based on the Airy wave theory and placed on the braces, including the elements of the jacket legs. This also can be done using FEM (CSI, 2014).

The critical buckling load calculated by FEM by taking bay-1, bay-2, and bay-3 into consideration for symmetrical and asymmetrical shapes. In this case, only one bay was selected and the other was calculated using a similar procedure. For example, one bay at the top of the jacket structure was selected as shown in Figures 2 and 3. As for this purpose, the bottom supports were assumed to be fixed condition. The critical buckling load obtained by FEM was compared with the analytical solution for symmetrical and asymmetrical shapes. The results are summarized in Figure 5.



(a) Symmetric (b) Asymmetric

Figure 5 Comparison of the critical buckling load

The critical buckling load obtained by FEM for the symmetrical shape was greater than that of the analytical solution. However, the critical buckling for the asymmetrical shape was smaller than the analytical solution. The difference in these results may have been caused by the configurations of the structural members and the ratio of column breadth. It should be noted that the column breadth for each bay was different from the top to the bottom of the structure. Figure 5 shows the comparison of the critical buckling load obtained by FEM and the analytical method. The result was the same for both methods.

The critical buckling load was probably caused by the effect of batter or the slope of the structure, which are not identical if the structure is slightly perpendicular. This is explained when the rigid frame structure considers the axial compressive load, and when the critical buckling is calculated. The rigid frame structure calculated by Timoshenko and Gere (1985) and validated by CSI (2014) was a typical column structure that had no diagonal member. Also, the structure did not have a horizontal brace at the bottom part between the two vertical members. In this case, buckling occurred only in the horizontal direction due to the constraint at the bottom part. However, the critical buckling load and deformation was influenced by instability of the column behavior, so that the reaction of end support gives reasonable estimated between calculation by Timoshenko and Gere (1985) and CSI (2014).

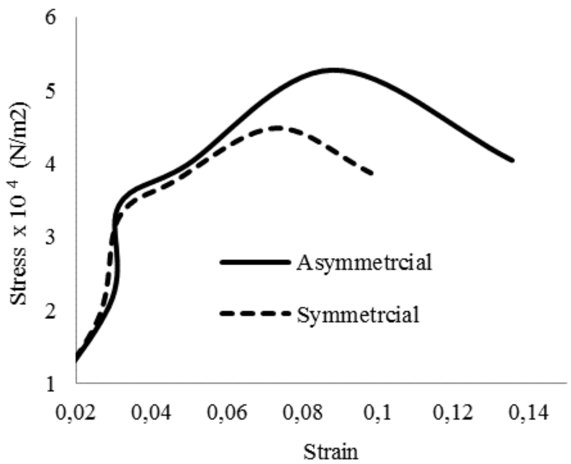


Figure 6 Stress-strain relationship obtained by FEM

The comparison of the stress-strain curves for symmetrical and asymmetrical obtained by FEM is shown in Figure 6. The critical buckling load for the symmetric and asymmetric structures of fixed offshore platforms has been discussed (Muis Alie, 2015). The paper focused on the critical buckling load for symmetric and asymmetric structures obtained by FEM and the analytical solution, and the stress-strain relationship was compared.

These frames were selected based on bay-1, bay-2, and bay-3 of the symmetrical and asymmetrical structures. These elements were not similar because the number of symmetrical and asymmetrical shape elements were not identic. Figure 6 describes the stress-strain relationship obtained by FEM between the symmetrical and asymmetrical shapes of fixed offshore platforms. The stress-strain relationship for the asymmetrical shape was greater than the symmetrical shape. The number of elements and the configuration of the structural components may have caused this. The effect of lateral load also has a significant influence, not only on the critical buckling load but also on the deformation and stress concentration. This effect was influenced by the configuration shape of the structure, because the structures had an identical shape at bay-1 (at the bottom level). However, bay-2 and bay-3 were completely different. The results for the elastic area were almost identical except for the difference in ultimate strength.

Jacket structure must be able to withstand a wide range of loading that works against static and dynamic loadings, including some seismic loads. All of these must be considered, otherwise the structure will be in a dangerous situation because, like buckling, structural failure is unpredictable. Environmental loads and/or periodic loads degrade the structure due to stress fluctuations; as a result buckling may occur, which can lead to collapse.

Offshore structures are deliberately constructed to withstand continual wave loading and other types of loadings, such as severe storms, corrosion, fire, explosions etc. These may lead to significant fatigue damage on individual structural members. Fatigue life is one of the major concerns for offshore structure installations since the utilization of tubular members gives rise to significantly high stress concentrations in the joints. Fatigue is structural system caused by cyclic loading. In accordance with this, fatigue limit is defined as stress against the cyclic loading is indefinite number. The fatigue strength of the structure is the maximum stress against it without collapse on a certain load frequency. In general, fatigue assessment may be calculated by several methods. As a simple calculation, fatigue life procedure analysis can be simplified by using the formulas shown in Table 1.

Table 1 Fatigue life analysis results between the symmetrical and asymmetrical shapes of offshore structures

No.	Items	Formula	Comparison result	
			Symmetrical	Asymmetrical
1	Zero moment	$m_0 = \int_0^m S_R(\omega)d\omega$	30.08013 $[N/mm^2]^2$	28.572973 $[N/mm^2]^2$
2	Second moment	$m_2 = \omega^2 \int_0^m S_R(\omega)d\omega$	1.353793 $[N/mm^2]^2$	1.17009 $[N/mm^2]^2$
3	Mean zero crossing period ($T_{Z\sigma}$)	$T_{Z\sigma} = 2\pi\sqrt{\frac{m_0}{m_2}}$	139.60707 second	153.43205 second
4	Stress significance (Ss)	$Ss = \sqrt{4m_0}$	10.969072 $[N/mm^2]^2$	10.690739 $[N/mm^2]^2$
5	Number of cycles (n)	$n = \frac{T}{T_{Z\sigma}}$	14193158.858	12914285.99
6	Number of cycle failures (N)	$N = 2.10^6\left(\frac{\Delta_\sigma}{\Delta_{\sigma eff}}\right)$	241028154.5	265347066.6
7	Fatigue per year (D)	$D = \sum_{i=1}^{n}\frac{n_i}{N_i}$	0.05888	0.04867
8	Fatigue life	$\frac{1}{D}$	16.981995	20.54679

According to Table 1, the fatigue life for symmetric structures is less than that for asymmetric structures. This may be caused by stress response spectra. The stress response spectrum is one of the significant parameters in determining fatigue life. This can be regarded as a multiple of wave spectrum and RAO square.

From this viewpoint, it can be concluded that critical buckling load and fatigue life analysis are very important aspects of the design of offshore platforms. In this regard, the structure particularly the configuration of elements such as brace and/or diagonal members of fixed offshore platforms plays an important role in supporting not only axial compression but also lateral pressure due to environmental loading and structural deck components. It is clear that local and global deformation for asymmetrical structures is always larger than that for symmetrical columns, which is caused by the configuration of braces. Therefore, the influence of the element configuration of fixed offshore jacket platforms must be taken into account.

5. CONCLUSION

The critical buckling load obtained by FEM analysis for both symmetrical and asymmetrical shapes is in agreement with the analytical method. The largest deformation takes place in the asymmetrical shape. The number of elements and the configuration of the structural components which are completely different may cause this effect.

The stress-strain curve of the asymmetrical shape was greater than the symmetrical shape due to the configuration of the structural members. The effect of lateral load also had a significant influence, not only on the critical buckling load but also on the deformation and stress concentration.

The fatigue life analysis revealed that the symmetrical column structure was less than that of the asymmetrical column. This may have been caused by the stress response spectra, which is a significant parameter in determining fatigue life.

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