Deterministic and Spectral Fatigue Analysis of Tubular Joints of a Jacket Platform

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Abstract— Offshore jacket platforms are mostly constructed as truss framework with welded tubular member as structural elements and have been extensively employed in the offshore oil and gas exploration in complicated ocean environments. The surrounding ocean environment is affected by various environmental loads such as the wind, wave, currents and ice. Out of the environmental loads, wave loads, which are cyclic in nature, causes very high stress concentrations especially at critical locations like the welded tubular joints, which leads to significant fatigue damage of the structure. In addition, jacket platforms are subjected to other types of loads, including severe storms, corrosion, fire, explosions, etc., during their service life. As structures reach their design service lives, the fatigue life should be reassessed. This paper is centered on the study of fatigue behaviour of different tubular joints of an offshore jacket platform by using deterministic and spectral fatigue methods. A typical offshore jacket platform situated in Bombay High is modelled and the fatigue analysis is performed by using Structural Analysis Computer System (SACS) software for the wave conditions of Bombay High south field. The fatigue behaviour of K, T, X and KT joints are investigated in this work. To validate the model, Stress Concentration Factors (SCF) are manually calculated using the Efthymiou parametric equations in API RP 2A-WSD code and compared with the SCFs obtained from SACS software. The Hot Spot Stresses and the effect of weld improvement technique are also compared for different joints. Both methods predict fatigue life reasonably well for most of the joints. It is also evident that the fatigue analysis gives realistic values of fatigue life for joints located in the upper region of water depth where the wave action is predominant. In the case of joints, weld improvements shows an increasing trend in fatigue life.

Index Terms— Deterministic Fatigue Analysis, Jacket Platform, Hop Spot Stress, Spectral Fatigue Analysis, Stress Concentration Factor, Tubular Joint, Weld Improvement Technique.

1 Introduction

Offshore platforms have been extensively employed in the offshore oil and gas exploration in complicated ocean environments. Offshore platforms are existing in various configuration types, and are mostly constructed as truss framework with tubular member as structural elements. A structure constructed in this manner is known as Jacket Structure and is the most common structure used for drilling and production. Structures to be built in such environments are imposed on wind, wave, current, ice and earthquake loads. Among them, waves play a major role in fatigue failure due to their continuity in time in random sequences, as being tiny, moderate, and sometimes catastrophic, causes very high stress concentrations especially at critical locations like the welded tubular joints, which leads to significant fatigue damage of the structure. In addition, jacket platforms are subjected to other types of loads, including severe storms, corrosion, fire, explosions, etc., during their service life. As structures reach their design service lives, the fatigue life should be reassessed.

In general, there are two methods used for performing the fatigue analysis, namely S-N curve approach and fracture mechanics approach. For fatigue design purpose, the S-N curve approach is widely used and it consists of three methods namely Simplified fatigue analysis, Deterministic fatigue analysis and Spectral fatigue analysis.

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2 Tubular Joints

Offshore structures comprise of three dimensional frames, composing of cylindrical steel members. The 'chord' is the main member of a tubular joint receiving the other components. It is necessarily a through member. The other tubulars are welded to it, without piercing through the chord at the intersection. Other tubulars belonging to the joint assembly may be as large as the chord, but they can never be larger. The 'can' is the section of the chord reinforced with an increased wall thickness, or stiffeners. The ***braces*** are the structural members which are welded to the chord. They physically terminate on the chord skin. The 'stub' is the extremity of the brace, locally reinforced with increased wall thickness. The geometry of a simple tubular K - joint is shown in the Fig.1. Different positions have to be identified along the brace - chord intersection line: 'crown' position is located where the brace to chord intersection crosses the plane containing the brace and chord, 'saddle' position is located where the brace to chord intersection crosses the plane perpendicular to the plane containing the brace and chord, which also contains the brace axis.

In general, the tubular joints may be classified into three groups. They are single joints, double joints and complex joints. As per API RP 2A-WSD, the joint classification is the process whereby the axial load in a given brace is subdivided into K, X, and Y components of loading corresponding to the three joint types for which capacity equations exist. Such subdivision normally considers all of the members in one plane at a joint. The classification can be a mixture between the above three joint types.

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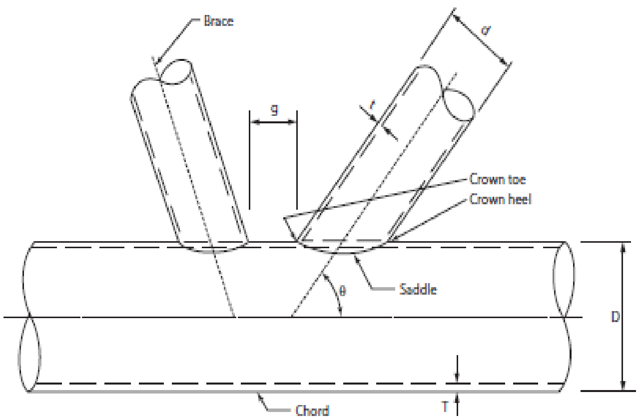

Fig. 1: Simple Tubular K – Joint

3 Stress concentration factor (SCF)

The Stress Concentration Factor (SCF) can be defined as the ratio of hot spot stress to nominal stress. Stress Concentration Factor is the most sensitive component in estimation of fatigue life of tubular joint. Stress concentration may occur due to geometric change of the load path and local welding profile effects. Based on several independent studies, a few set of parametric equations have been published, that have varying capabilities and degrees of accuracy in analyzing various joint geometries, which are used for the calculation of Stress Concentration Factors. In this study, the Stress concentration factors in tubular joint are calculated by using Efthymiou equations.

4 Hot Spot Stresses (HSS)

Hot-spot stress range in tubular joint are calculated based on stress concentration factors and nominal stresses using parametric equations given in the API RP 2A- WSD code (1) to (8). The evaluation of hot-spot stress ranges is considered at 8 spots around the circumference of the intersection between the braces and the chord as shown in Fig. 2.

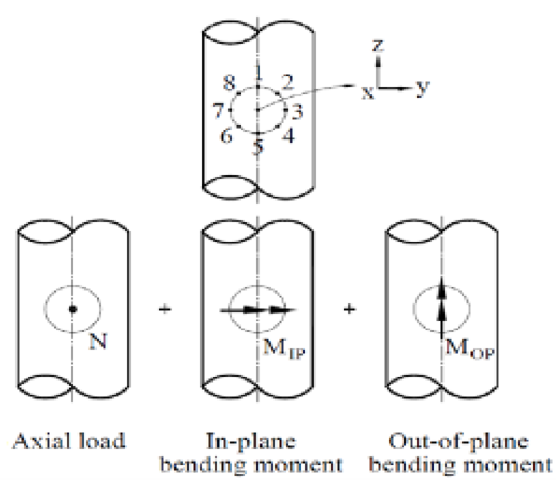

Fig. 2: Hot spot around the circumference of the intersection

Hot spot stress range at crown points: 1 and 5 takes account to maximum nominal stress of axial load and in-plane moment. While hot spot stress range at saddle points: 3 and 7 takes account to maximum nominal stress of axial load and out of plane moment. Points in-between saddle and crown points takes account to all three maximum nominal stresses: axial load, moment in-plane and moment out-of-plane. The hot spot stress ranges at these points is derived by a linear interpolation of the stress range due to the axial action at the crown and saddle and a sinusoidal variation of the bending stress range resulting from in-plane and out of plane bending. Thus the derived superposition stress equations for tubular joints in API RP-2A WSD is applied for evaluation of hot spot stress range around at 8 spots as,

$$\sigma_1 = SCF_{AC}\,\sigma_x + SCF_{MIP}\,\sigma_{my}$$

$$\sigma_2 = ½*(SCF_{AC} + SCF_{AS})\,\sigma_x + ½ * \sqrt{2}\,SCF_{MIP}\,\sigma_{my} - ½ *\sqrt{2}SCF_{MOP}\,\sigma_{mz}$$

$$\sigma_3 = SCF_{AS}\,\sigma_x - SCF_{MOP}\,\sigma_{mz}$$

$$\sigma_4 = ½*(SCF_{AC} + SCF_{AS})\,\sigma_x - ½ * \sqrt{2}\,SCF_{MIP}\,\sigma_{my} - ½ *\sqrt{2}SCF_{MOP}\,\sigma_{mz}$$

$$\sigma_5 = SCF_{AC}\,\sigma_x - SCF_{MIP}\,\sigma_{my}$$

$$\sigma_6 = ½*(SCF_{AC} + SCF_{AS})\,\sigma_x - ½ * \sqrt{2}\,SCF_{MIP}\,\sigma_{my} + ½ *\sqrt{2}SCF_{MOP}\,\sigma_{mz}$$

$$\sigma_7 = SCF_{AS}\,\sigma_x + SCF_{MOP}\,\sigma_{mz}$$

$$\sigma_8 = ½*(SCF_{AC} + SCF_{AS})\,\sigma_x + ½ * \sqrt{2}\,SCF_{MIP}\,\sigma_{my} + ½ *\sqrt{2}SCF_{MOP}\,\sigma_{mz}$$

Here, σ_x, σ_{mx} and σ_{my} are the maximum nominal stresses due to axial load and bending in-plane and out-of-plane respectively. SCF_{AS} is the stress concentration factor at the saddle for axial load and the SCF_{AC} is the stress concentration factor at the crown. SCF_{MIP} is the stress concentration factor for the in-plane moment and SCF_{MOP} is the stress concentration factor for out-plane-moment.

5 Fatigue analysis of tubular joints

Fatigue analysis can be carried out using the following two methods, namely S-N approach and fracture mechanism approach. The first approach is based on an experimentally accomplished S-N curve presented in design code. The second approach is based on Paris law derived by Paris and Erdogan in fracture mechanics. For fatigue design purpose, S-N curve approach is widely used and is the most suitable one. Fracture mechanism method is used to determine acceptable flaw size, assessing the fatigue crack growth, planning inspection and repair strategy, etc.

In the S-N curve approach, there are three methodologies for fatigue damage calculations, depending on the methods of determining fatigue loads.

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- Simplified Fatigue Analysis
- Deterministic Fatigue Analysis
- Spectral Fatigue Analysis

Deterministic Fatigue Analysis

Deterministic analysis has been done for many years and has proven to be a reliable approach for dynamically insensitive structures and for situations where all fatigue waves are of sufficiently long wave periods to avoid peaks and valleys of the structures transfer function. Deterministic fatigue analysis does not use wave spectra or transfer functions, but instead performs a relatively few discrete wave analyses to determine stress range values.

An appropriate number of wave heights with corresponding periods must be selected to define the relationship between wave height and stress range. The stress range for each wave and the number of occurrences are then used to determine fatigue damage.

The drawbacks of deterministic analysis are that it cannot account for the actual distribution of energy over the entire wave frequency range. Also, since the analysis is performed for only a few waves, the actual relationship between the ratio of structural responses and the wave height to the frequency (i.e. transfer function) cannot be accounted for. Therefore, the results of a deterministic analysis may be quite sensitive to the selection of waves and the corresponding periods.

Spectral Fatigue Analysis

Spectral fatigue is a statistical approach for calculating the fatigue damage to a structure. The spectral fatigue approach utilizes wave spectra and transfer functions, thus allowing the relationship of the ratio of structural response to wave height as a function of wave frequency to be developed for the wave frequency range. Cyclic stress depends on calculated stress range. Therefore, spectral fatigue accounts for the actual distribution of energy over the entire wave frequency range.

In a Spectral fatigue analysis, the stress range frequency relationship is defined by transfer functions. This requires that the user generate the cyclic loading required in order to obtain stress ranges. Typically, the user need not generate loading for all possible stress ranges. It is necessary to select only the loading required to yield an accurate and sufficiently detailed transfer function.

A transfer function defines the ratio of the range of cyclic stress to wave height as a function of frequency (usually for one direction of wave). If, for each frequency, the input to the system is a unit amplitude sinusoid of that frequency, then the steady state amplitude of the response is the transfer function at that frequency. In our case the input is the elevation of the sea at a point above its undisturbed position (wave height) and the responses are the brace stresses at the connections. In reality our system is not truly linear so the fundamental relationship is only approximately true, but the approximation is a very good one if the waves characterizing the fatigue environment are not too large. The Airy linear wave theory results in wave profiles that are pure sinusoids. All of the other theories produce waves having profiles that are not pure sinusoids, however for waves of small amplitude (as are typical in fatigue studies) the profiles are nearly sinusoidal and thus these waves can reasonably serve as transfer function generators.

To generate a transfer function for a particular fatigue case (wave direction), several waves of various heights but constant steepness are used to load the structure. These waves need not necessarily be the waves from the fatigue environment, but waves chosen based on the dynamics of the structure. The stress is calculated at various wave positions (per the user). The difference between the maximum and minimum stress, called the stress range, is determined for each wave.

Dividing these stress ranges by one-half of the corresponding wave height produces stress ranges for waves of unit amplitude (for sinusoidal waves, wave height equals twice the wave amplitude). The relationship between the stress ranges of unit amplitude and the corresponding wave frequency for all waves considered is the transfer function

Fatigue Damage

Palmgren-Miner rule is utilized to estimate fatigue life of tubular joint in this case. The rule is commonly practiced in fatigue analysis of considered welded detail.

$$D = \sum \frac{n_i}{N_i}$$

Where,

D - allowable cumulative fatigue damage varies for different structural members, n which should normally be less than 1

S_i - i_{th} stress range level

n_i - number of stress cycles applied at S_i

N_i - fatigue life at S_i, here N_i is calculated for the stress range S_i

6 Weld Improvement Techniques

For welded joints, improvement in fatigue performance can be obtained by a number of methods, including controlled burr grinding of the weld toe, hammer peening, or as welded profile control to produce a smooth concave profile which blends smoothly with the parent metal. The grinding improvement factor is not applicable for joints in seawater without adequate cathodic protection.

The effect of weld improvement technique is incorporated in the fatigue analysis by selecting suitable S-N curves in SACS software.

For welds with profile control, where the weld toe has been profiled, by grinding if required, to merge smoothly with the parent metal, the weld toe is free of surface and near-surface defects. This improvement is in addition to the use of hotspot stress at the actual weld toe location, and the reduced size effect exponent.

The Welded Joints (WJT) Curve applies to welds with no profile control. Where profile control is practiced, an enhanced curve (WJ1) should generally apply.

7 Structural model

In the present study, an attempt is made to investigate the fatigue behavior of different tubular joints of an offshore jacket platform by deterministic fatigue analysis and spectral fatigue analysis using SACS software.

The jacket platform considered for the study is a four legged jacket structure with battered legs located in Mumbai High South Field at a water depth of 70m. The thesis deals with the fatigue behaviour of different tubular joints and it is difficult to provide representative joints of all types with a single bracing configuration pattern. Hence two identical models with respect to structural data and environmental data but with different bracing configurations i.e., one with diagonal braces and other with X – braces are considered for the study.
The geometry of the two platform models with different face brace configurations are shown in Fig.3 (Diagonal brace configuration) and Fig.4 (X-brace configuration).

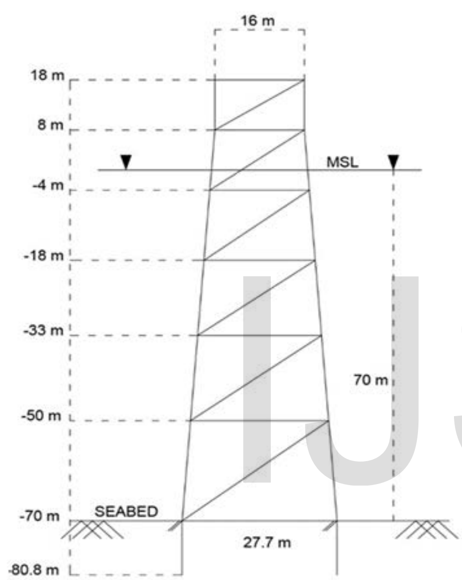

Fig.3: Diagonal braced platform

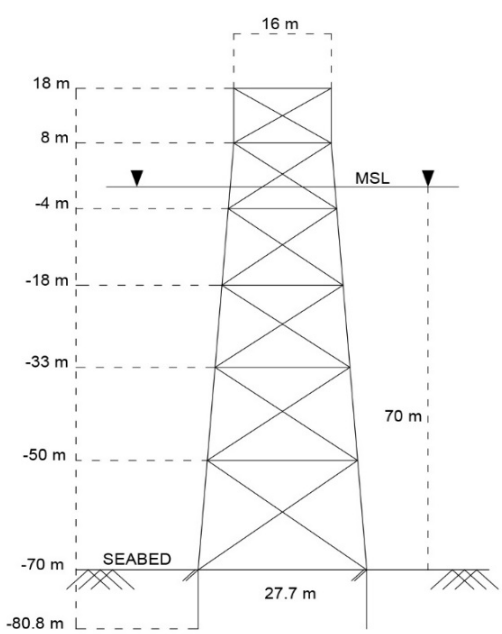

Fig.4: X- braced platform

The material properties and member properties of the jacket platforms considered are presented in Table 1 and Table 2 respectively.

Table 1. Material Properties

Property	Value
Young's modulus	2.1 x 108 kN/m2
Density of steel	7.85 x 103 kg/m3
Density of sea water	1.025 x 103 kg/m3
Hydrodynamic inertia coefficient, CM	2.0
Drag coefficient, CD	0.6
Poisson's ratio	0.3
Acceleration due to gravity, g	9.81m/sec2

Table 2. Member Properties

Members	Diameter(m)	Thickness(mm)
Leg members	1.4	35
Diagonal braces	0.65	16
Horizontal braces	0.65	16
Pile	1.2	25

Typical wave climate pertaining to Mumbai High South Field is considered for the analysis of the platform. Deterministic and spectral fatigue analysis is performed using the wave occurrence data and wave scatter data obtained from [15].

Effects of current are neglected and hence apparent wave period and current blockage is not considered. Morrison equation is used to calculate wave force and Stoke's fifth order wave theory is used to compute wave kinematics.

Four wave directions have been considered for both the analysis i.e., south direction, south-west direction**,** west direction and north-west direction. Seastate was used to generate the SACS load cases. For deterministic fatigue analysis, two SACS load cases, one for position of maximum base shear and one for minimum base shear, were created for each wave. The stress range for each wave was calculated using the "STD" option on the FTCASE input line. For spectral fatigue analysis, one SACS load case, for the wave position yielding maximum base shear was created for each wave. The stress range for each wave was double the stress calculated for that wave position. Dynamic amplification factor (DAF) is taken as 1.05**.** For performing the spectral fatigue analysis, the wave periods near the natural period of the structure is selected. The transfer function has been generated for various wave periods in the range of 2 to 10 seconds. The period interval is selected such that more number of points is generated near the natural period. The transfer function and the response are generated for maximum base shear case. A wave steepness of 1/20 is used for the calculation of wave height for each frequency. This has been used for the generation of the transfer function.

To study the effect of weld improvement technique on fatigue life, the deterministic and spectral analysis is carried out with and without the application of weld improvement. For welded joints without weld improvement technique, the S-N curve selected is Welded joints curve (WJT) and for welds with weld improvement technique, an enhanced curve (WJ1) is applied.

The corresponding SACS models are shown in Fig.5 and Fig.6.

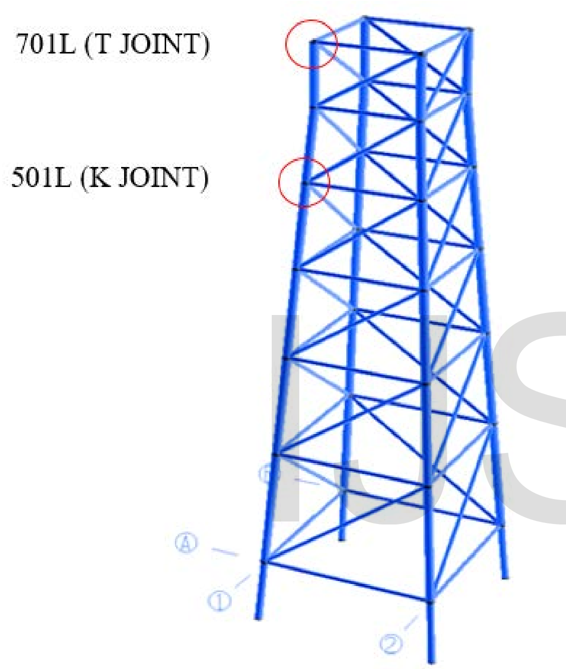

Fig.5: Diagonal braced platform

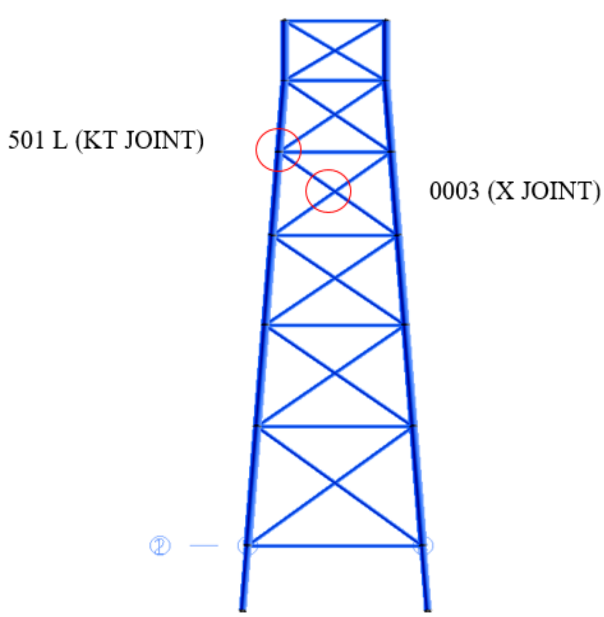

Fig.6: X- braced platform

8 Results and Discussion

The jacket platform in Fig.5. has diagonal braces forming K joints and T joints. Joints 501L (K joint) and 701L (T joint) are considered for comparison. The jacket platform in Fig.6 has X-braces forming KT joints, K joints and X joints, the joints considered are 501L (KT joint) and 0003 (X joint).

The comparison of the SCF values given in Table 3 to Table 5 shows that the Stress concentration factors (SCF) obtained from SACS and by Efthymiou equations in API RP 2A-WSD code are similar. The difference between the obtained SCFs and calculated SCFs being negligible, the modelling of the jacket platform is validated.

The comparison of the fatigue life values of the tubular joints such as K, T, X and KT joints are presented in Table 6, Table 7 and Table 8. Joints having fatigue life greater than 1500 years is marked as *. The comparison of the fatigue values shows that both methods predict fatigue life reasonably well for most of the joints, except for some joints at the bottom of the jacket, where the deterministic method predicts the fatigue life lower than the spectral methods. This is due to the fact that the dynamic response of the structure is over-predicted by deterministic method by approximate calculations of DAF due to course discretization of wave periods. For the joints near the top of the jacket, the predicted fatigue life using deterministic method seems to be higher than the spectral method. This may be due to the fact that the wave load and associated cyclic stresses are only due to the local wave loads rather than the dynamic response.

The comparison of the fatigue life values of the tubular joints such as K and KT joints are presented in Table 9 and Table 10. The application of weld improvement techniques on K and KT joints and performing the fatigue analysis in both deterministic and spectral fatigue methods, it is found that the fatigue life of all the joints with the application of weld improvement are increased when compared with the joints without the application of weld improvement techniques. This is because the profiled weld toe by the application of weld improvement is free of surface and near-surface defects thereby reducing the stress concentrations and hot spot stresses.

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Table 3. Stress Concentration Factor of K joint

Joint type	Member	Member Type	SACS			API		
			Axial	IPB	OPB	Axial	IPB	OPB
K	501L-502L	Brace	4.11	2.98	7.56	4.12	2.98	7.56
		Chord	4.14	2.68	7.42	4.13	2.68	7.42
	501L-602L	Brace	3.00	2.96	6.23	2.99	2.96	6.20
		Chord	3.19	2.24	6.11	3.15	2.23	6.09

Table 4. Stress Concentration Factor of T joint

Joint type	Member	Member Type	SACS				API			
			AC	AS	IPB	OPB	AC	AS	IPB	OPB
T	701L-702L	Brace	2.30	9.18	2.98	6.90	2.27	9.18	2.98	6.89
		Chord	2.77	9.31	2.69	6.77	2.75	9.30	2.69	6.77

Table 5. Stress Concentration Factor of KT joint

Joint type	Member	Member Type	SACS			API		
			Axial	IPB	OPB	Axial	IPB	OPB
KT	501L-502L	Brace	4.11	2.98	8.55	4.11	2.98	8.55
		Chord	4.14	2.68	8.39	4.14	2.68	8.39
	501L-602L	Brace	3.75	2.97	7.09	3.71	2.97	7.10
		Chord	4.12	2.39	6.96	4.14	2.39	6.98
	501L-602L	Brace	3.35	2.96	6.61	3.35	2.96	6.59
		Chord	3.75	2.24	6.48	3.76	2.23	6.47

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Table 6: Fatigue Life of K and T joint (Diagonally Braced)

Joint Type	Joint	Member	Member Type	Fatigue Life in cycles	
				Deterministic	Spectral
K	101L	101L-102L	Brace	61.54947	*
			Chord	65.2995	*
		101L-202L	Brace	14.94283	*
			Chord	12.15484	*
K	201L	201L-202L	Brace	23.31481	*
			Chord	39.535	*
		201L-302L	Brace	28.10709	*
			Chord	23.86723	*
K	301L	301L-302L	Brace	36.39465	764.7035
			Chord	34.09564	861.4203
		301L-402L	Brace	19.76899	*
			Chord	17.541	*
K	401L	401L-402L	Brace	65.10248	75.9218
			Chord	113.2621	90.60518
		401L-502L	Brace	22.57138	221.2593
			Chord	26.7293	680.9716
K	501L	501L-502L	Brace	46.39211	31.41365
			Chord	49.21906	40.70484
		501L-602L	Brace	*	*
			Chord	*	*
K	601L	601L-602L	Brace	1353.567	413.2853
			Chord	1448.705	440.61
		601L-702L	Brace	*	*
			Chord	*	*
T	701L	701L-702L	Brace	*	*
			Chord	*	*

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Table 7 Fatigue Life of K and KT joint (X-Braced)

Joint Type	Joint	Member	Member Type	Fatigue Life in cycles	
				Deterministic	Spectral
K	101L	101L-102L	Brace	*	*
			Chord	*	*
		101L-202L	Brace	216.1894	*
			Chord	74.2628	*
KT	201L	201L-202L	Brace	*	*
			Chord	*	*
		201L-102L	Brace	45.4215	*
			Chord	45.82447	*
		201L-302L	Brace	254.0379	*
			Chord	80.11561	*
KT	301L	301L-302L	Brace	*	*
			Chord	*	*
		301L-202L	Brace	65.34654	*
			Chord	61.54763	*
		301L-402L	Brace	51.06877	*
			Chord	40.33792	*
KT	401L	401L-402L	Brace	411.8784	156.456
			Chord	436.8721	194.0829
		401L-302L	Brace	40.90784	212.2839
			Chord	41.41487	278.7258
		401L-502L	Brace	20.6946	405.8098
			Chord	19.03889	855.2213
KT	501L	501L-502L	Brace	34.59614	33.22309
			Chord	36.79646	34.55082
		501L-402L	Brace	34.02532	42.96655
			Chord	42.36493	52.18561
		501L-602L	Brace	1423.101	*
			Chord	1446.389	*
KT	601L	601L-602L	Brace	90.0323	390.5582
			Chord	266.778	425.6074
		601L-502L	Brace	*	419.7466
			Chord	*	955.5092
		601L-702L	Brace	*	*
			Chord	*	*
K	701L	701L-702L	Brace	*	*
			Chord	*	*
		701L-602L	Brace	*	*

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			Chord	*	*

Table 8 Fatigue Life of X joint (X-Braced)

Joint Type	Joint	Member	Fatigue Life in cycles	
			Deterministic	Spectral
X	0	101L-202L	216.1894	*
		102L-201L	45.4215	*
X	1	201L-302L	254.0379	*
		202L-301L	65.34654	*
X	2	301L-402L	51.06877	*
		302L-401L	40.90784	212.2839
X	3	401L-502L	30.43681	405.8098
		402L-501L	21.93136	42.96655
X	4	501L-602L	1423.101	*
		502L-601L	*	419.7466
X	5	601L-702L	*	*
		602L-701L	*	*

Table 9: Fatigue life Comparison of K joint

Joint Type	Member	Member Type	Deterministic		Spectral	
			WJT	WJ1	WJT	WJ1
K	501L-502L	Brace	145.84	146.117	52.062	52.162
		Chord	63 .67	109.161	29.441	53.39
	501L-602L	Brace	9629.1	9647.91	12182.2	12206.1
		Chord	3944.9	7086.11	8333.66	15019.3

Table 10: Fatigue life Comparison of KT joint

Joint Type	Member	Member Type	Deterministic		Spectral	
			WJT	WJ1	WJT	WJ1
KT	501L-502L	Brace	107.51	107.71	48.78	48.878
		Chord	47.29	80.94	24.03	42.39
	501L-402L	Brace	73.86	74	94.2	94.40
		Chord	31.56	52.8	71.49	127.1
	501L-602L	Brace	5421.8	5432.40	6181.30	6193.43
		Chord	2089.15	3743.73	3645.56	6570.18

9 CONCLUSIONS

In the present study an attempt was made to investigate the fatigue behaviour of different tubular joints i.e. K, T, X and KT joints using deterministic fatigue analysis and spectral fatigue analysis. The effect of weld improvement techniques on the fatigue life of different tubular joints are also investigated. Based on the study certain useful conclusions are drawn and they are summarised below:

1. Generally, both methods predict fatigue life reasonably well for most of the joints except for some joints at the bottom of the jacket. The deterministic method predicts the fatigue life lower than the spectral method. This may be due to the fact that the dynamic response of the structure over-predicted by deterministic method by approximate calculations of Dynamic Amplification Factor (DAF) due to course discretization of wave periods.
2. For the joints near the top of the jacket, the predicted fatigue life using deterministic methods seems to be higher than the spectral methods. This may be due to the fact that the wave load and associated cyclic stresses are only due to the local wave loads rather than the dynamic response.
3. The fatigue life of tubular joints predicted by spectral fatigue analysis gives realistic values for joints located at a water depth less than half the water depth. This may be due to the fact that the velocity and acceleration of wave particles will be lower and thus wave force action is negligible at bottom region of water depth.
4. For performing the deterministic fatigue analysis, the value of Dynamic Amplification Factor used is not the exact value. So for large platforms to assess the fatigue life, it is recommended to use spectral fatigue analysis due to the inaccuracy introduced due to the usage of approximate value of Dynamic Amplification Factor.
5. Fatigue life of different tubular joints is found enhanced though marginally by the application with weld improvement technique.

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