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Assessment of Dynamic Effects of Wave Loads in Fatigue Analysis for Fixed Steel Offshore Structures

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Abstract

This paper presents an algorithm and develops a formula to evaluate the dynamic effect of wave loading on fixed steel offshore structures (jacket structures) through the fatigue damage ratio. Applying the algorithm and formula proposed in this paper to evaluate the dynamic effect of wave loads in fatigue analysis for 03 Jacket structures built at increasing water depth under one specific marine condition and provide specific recommendations on the limits of application of quasi-static and dynamic methods in the fatigue analysis of the jacket structures. This research is really necessary because currently, the current standards (API, DnV) only stop at evaluating the dynamic effects of wave loads acting on the Jacket structure in the strength analysis. These standards propose a limit for quasi-static or dynamic analysis based on the "3.0 s or 2.5 s rule" (use the quasi-static method when $T_{max} \leq 3.0$ s or ≤ 2.5 s), and it is advised that they only apply to waters within the North Sea and the Gulf of Mexico. This paper has demonstrated that it is not appropriate to use the specified standards for the North Sea and the Gulf of Mexico to select the method of fatigue analysis of the jacket structure in marine conditions outside the study area of the standard. Hoped that this paper will be a reference for engineers when choosing a fatigue analysis method for jacket structures in specific marine conditions at the location where the jacket structure has been installed.

Keywords: Dynamic Effects, Wave Load, Fixed Steel Offshore Structure, Fatigue Analysis.

1. Introduction

Fatigue analysis is an important step in the process of designing jacket structures. Currently, the standards only specify the evaluation of dynamic effects in fatigue analysis by the ratio of dynamic response to static response. In fatigue analysis, the desired result is the determination of the total fatigue damage ratio. The wave data used for fatigue analysis is a collection of many short-term sea states that are averaged over long-term sea states. The wave period and wave height of the long-term sea state are usually smaller than those of the extreme sea state. Therefore, the dynamic effect in the fatigue analysis is different from the dynamic effect in the endurance analysis. The API-RP2A standard published from 1993 to 2007, agrees to simple fatigue calculation conditions when: the water depth is less than 122m (400 ft), the jacket structure uses ductile steel, and has a natural period of the jacket structure $T_{max} \leq 3.0$ sec [1]. The API-RP2A standard published in 2014 recommends detailed fatigue calculations for all structural details. The applicable waters specified in standard [1] are in the United States (US waters).

As for the ABS standard (2018) [2], there are fatigue assessment views as follows: Three important methods of assessment are called the Simplified Method, the Spectral Method, and the Deterministic Method. The determination of fatigue demand should be accomplished by appropriate structural analysis.

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The authors of Khalifa et al. [3] performed a fatigue analysis of a steel jacket structure at a water depth of 33.5 m in the Gulf of Suez, Egypt, using SACS software [4] and standard API-WSD [1]. The article has performed the fatigue assessment by a simple method and a dynamic method with the natural period (T_1) range of the structure being changed from 2.5 sec to 3.5 sec (changing the natural period (T_1) by adding weight addition) and concluded: with a natural period T_1< 3 sec, the fatigue life of the nodes changed on average by 15%, and with a natural period T_1> 3sec, the fatigue life of the nodes changed on average by 50%. Azarhoushang & Nikraz [5], used SACS software [4] and API-WSD [1] for dynamic fatigue analysis of a steel jacket structure at a water depth of 41.6 m, constructed in the Persian Gulf. In conclusion, there are recommendations: For jacket structures with a natural period T_1>3 sec, in Persian Gulf conditions, the dynamic effect is significant.

Nallayarasu et al. at ICOE, IIT Madras [6] used SACS software [4] and API-WSD [1] to analyse fatigue according to two calculation methods: the quasi-static method (using predetermined waves) and the dynamic method (using wave spectrum). The structures that Azarhoushang & Nikraz [5] used for fatigue analysis include Jacket 1: a wellhead with 4 main legs and 8 skirt piles at a water depth of 76.2 m, and Jacket 2: a multifunctional platform (MNP) with 8 main legs and 16 skirt piles at a water depth of 72 m. Jackets 1 and 2 were built in Bombay, India. The results of Azarhoushang & Nikraz [5] show that the fatigue life predicted by the quasi-static method has a lower value than that of the dynamic method. And Azarhoushang & Nikraz [5] recommended the use of dynamic methods for fatigue analysis of jacket structures for conditions at Bombay High Field. Thomas and Augustine [7] check the fatigue analysis of offshore structures under various dynamic loads, the effect of thermal loads, and study the welded joints in offshore structures. with the following conclusions: Fatigue life for tubular joints increases as the diameter increases; the thickness of tubular joints has much influence on the fatigue life of structures; and fatigue damage for tubular joints also decreases as the diameter ratio changes.

Ali & Kadim [8] focus on the risks that have been found in the dynamic analysis of offshore structures and the following conclusions: By using Cnoidal theory, the wavelength plays an important factor in increasing the structure response by a large amount until *Ursell Number* approximately approaching to 1000, after that the wave behavior is converted to the solitary type and no changes in the structural response are noted or occurred; The wave direction is an important property which has a great influence on structural behavior. Aeran et al. [9] suggest a new framework for possible life extension is proposed in this paper. The proposed approach results in a remaining life of ten years as compared to one year using the conventional approach. Recommendations are also made on increasing the remaining fatigue life using life improvement techniques.

In Kim et al. [10], spectral fatigue analyses were performed for the topside structure of an offshore floating structure. It could be determined that the combined fatigue damage considering each frequency was more conservative than that found through simple addition. Therefore, the wind fatigue damage cannot be ignored because of the damage combination, even though the wave-induced fatigue damage is much bigger than the wind fatigue damage. In Siriwardane et al. [11], fatigue lives are calculated and compared with the conventional approach. The proposed curve can be directly applied to any tubular joint in seawater without having additional CF tests, which is an advantage. Kim & Lee [12] deal with the fatigue life of offshore wind turbine support structures. It is necessary to consider the dynamic effects of loads and structures and to develop a simple method that solves time problems. In addition to the wind turbines, the analysis method of this study is expected to improve the safety evaluation technology of various ocean structures. Damilola et al. [13] carried out the fatigue analysis of an offshore support system. In this study, a consideration of the theoretical formulation of the forces acting on the structures, wave kinematics, and the computation of the various forces, which included the computation of inertia and drag forces using the Morison equations.

The above contents show that different sea areas will have different wave parameters. The wave parameters and water depth in the sea areas will determine the scale of jacket structures. The structural parameters, sea waves, and sea depth in different sea areas will serve as the basis for selecting the appropriate method for fatigue analysis of the structure. In each sea area, different methods will also give different structural analysis results. Therefore, it is necessary to study to select an appropriate analytical method for each sea area. The current design standards for jacket structure in the world are mainly proposed in Europe and America. The European - American standard systems are built based on the sea conditions of the North Sea and the Gulf of Mexico. Direct application of European - American standards to design jacket structures in other sea areas in the world has many shortcomings.

Currently, there are many studies in the world to propose standards for the design and construction of jacket structures under the actual conditions in the seas outside of Europe - America. This paper will study and evaluate the dynamic effects of wave loads acting on the jacket structure of jacket structures in fatigue analysis, to assess the safety of structures at water depths up to 150 m and apply to Vietnamese sea conditions. Selecting a suitable method for fatigue analysis of jacket structure in the process of designing jacket structures for oil and gas exploitation in the sea of Vietnam. This is an essential study.

2. Algorithm to Evaluate Dynamic Effects of Wave Load on Jacket Structures in Fatigue Analysis

This paper will develop an algorithm to evaluate the dynamic effects of wave loads on steel jacket structures in fatigue analysis, based on the Palmgren-Miner method for fatigue analysis of jacket structures. The Palmgren-Miner ruler is based on the liner damage hypothesis and evaluates cumulative damage. There are two formulations of this rule:

- Discrete formulation: used for deterministic fatigue analysis;
- Continuous formulation: used probabilistic fatigue analysis.

In section 2.1, this paper summarizes the pre-determined fatigue analysis method detailed in Barltrop & Adams [14] and develops an algorithm for application to evaluate fatigue life for jacket structures, which is the research objective of this paper.

2.1. Palmgren - Miner (P-M) Method, Predetermined Fatigue Analysis

2.1.1. Fatigue Curve (S-N)

When the stress σ(t) changes according to the symmetric harmonic function. Figure 1 shows that each change of $\sigma_{max} = S_M$ to $\sigma_{min} = S_m$ will correspond to one period T [1]. Stress increment $\Delta\sigma = S = S_M - S_m$ and the number of stress change cycles are the two main influences leading to structural fatigue failure.

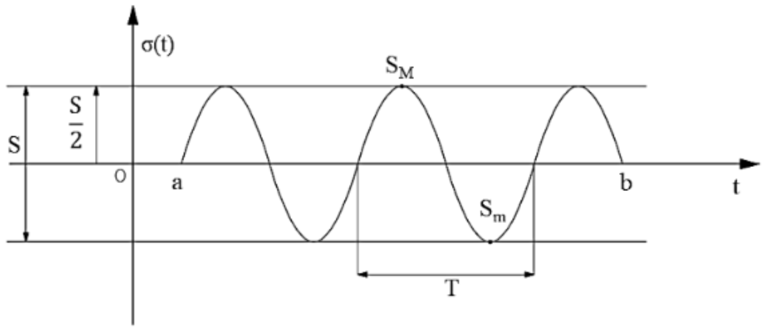


Figure 1. Harmonic variation stress diagram with symmetry cycle

Performing tests on samples of each type of material, subject to a harmonic variable load with a symmetric cycle, obtains the number of cycles of stress change N causing fatigue failure (at stage 1) proportional to stress increment $S = \Delta\sigma = S_M - S_m$ according to the following formula:

$$N = aS^{-m} \quad (1)$$

where, a and m are parameters, depending on the material, determined experimental. Equation 1 is called the Wohler fatigue curve equation, used in the P-M fatigue calculation method. In the fatigue calculation, a linear form of the Wohler fatigue curve is used by taking the log of Equation 1: log10(N) = log10(a) - log10(S), where a is a constant and m is the slope inverse of the S-N curve, m has a value of 3 to 5 depending on the node type (welded or prefabricated) and the number of stress change cycles N. Figure 2 is the SN fatigue curve according to the API [1].

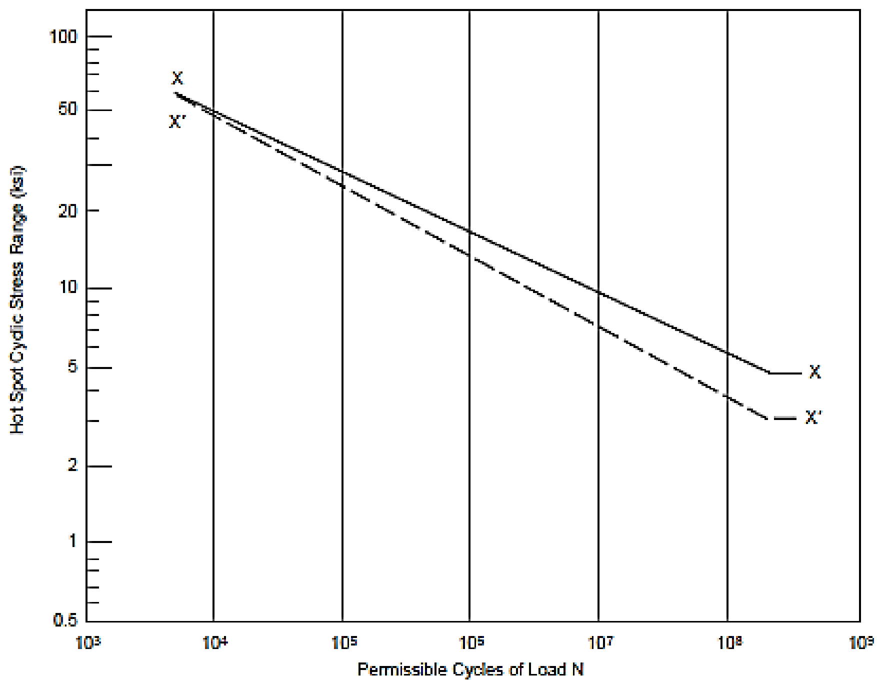


Figure 2. S-N fatigue curve according to API [1]

2.1.2. Determination of Stress for Fatigue Analysis at Hot Spots

Locate Hot Spots for Fatigue Analysis

Hot spots are points at which stress concentration occurs, which are discontinuous locations of the structure. Its exact location and value depend on the geometry of the connection and the loading conditions. In Jacket construction, the hot spot is usually the point of the welds of the interface of the members. According to API [1], it is necessary to check at least 4 hot spots at each member joint (4 points in the main member and 4 points in the branch member), see Figure 3. DnV standard [15] gives 8 hotspots (8 points in the main member, 8 points in the branch member).

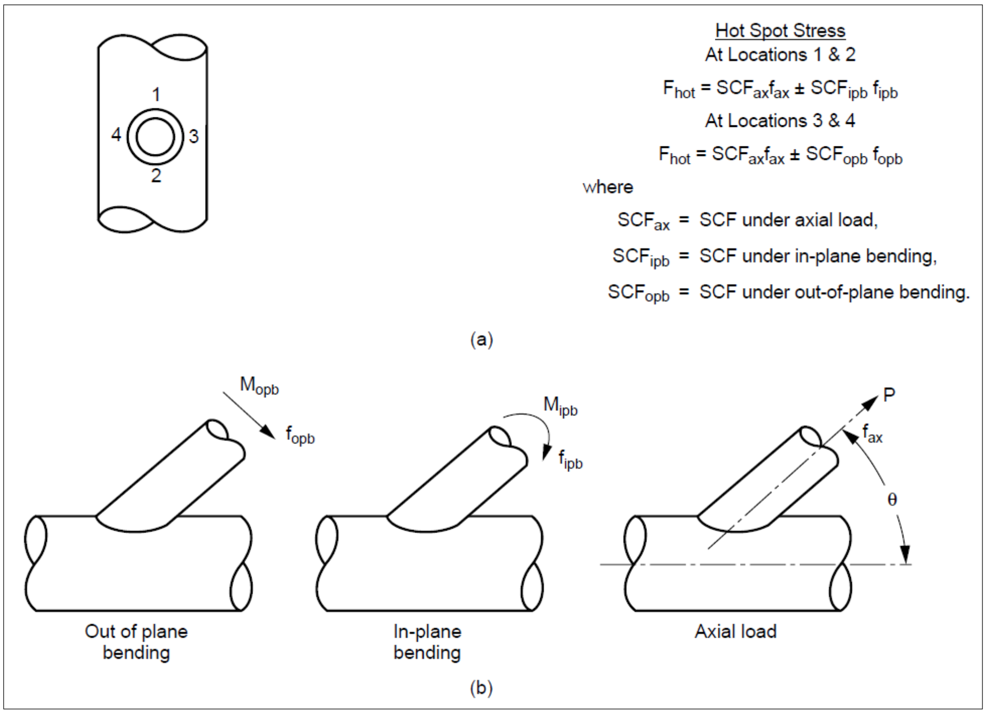


Figure 3. (a) Location of 4 hotspots at the node (1, 2, 3, 4) and (b) 3 types of node internal forces according to API [1]

Determination of Stress for Fatigue Analysis at Hot Spots

The stress for fatigue analysis at hot spots is determined by multiplying the nominal stress σnominal (calculated according to the overall scheme of the structure) by the stress concentration factor (SCF), i.e.: $\sigma_{hotspot} = \sigma_{nominal}$*SCF. Figure 4 shows the stress at the hot spot (local stress) according to the DnV standard [15].

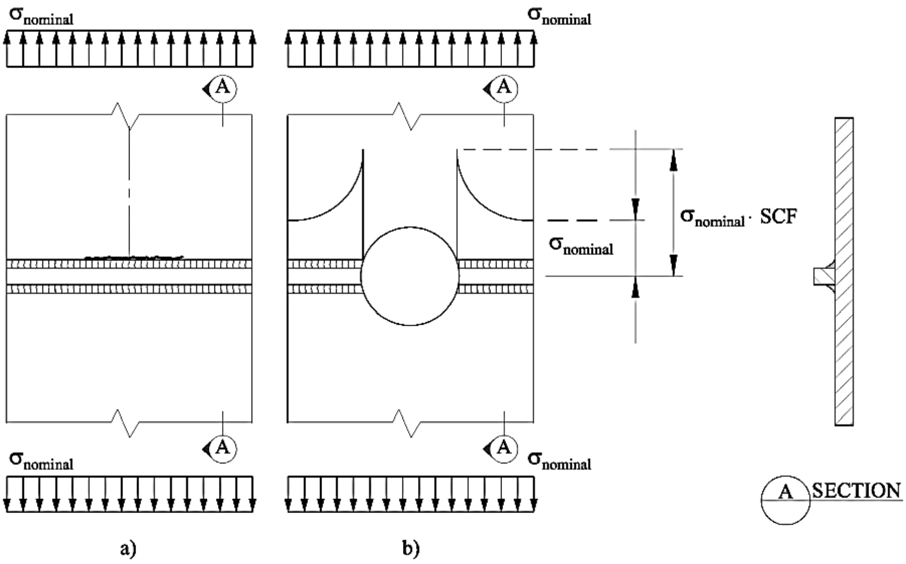


Figure 4. Stress representation at the hot spot (local stress) [15]

The SCF, which is determined depending on the type of node, the type of force applied to the node, and the location of the hotspot, can be calculated as specified in the current Design Standard [1, 15-17].

2.1.3. Determination of Fatigue Damages

In the general, the Jacket structure is subjected to many groups of wave loads, in which each group is a harmonic load, which will cause stress at a hot spot. There are many groups of harmonic stresses, corresponding to many short-term sea states. Figure 5 represents a symbolic representation of the stress function σ(t) at a hot spot in a short-term sea state.

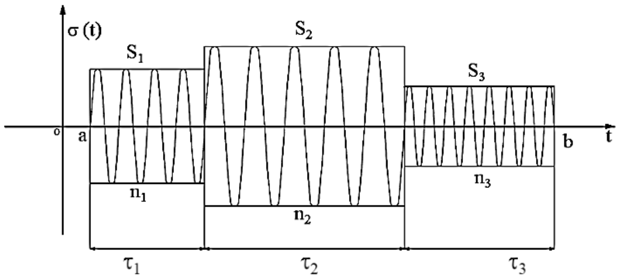


Figure 5. Stress $\sigma(t)$ at a hotspot consisting of many constant amplitude stress groups

We can determine the cumulative fatigue damage ratio in the short-term sea state, including Mi stress groups as follows:

$$D_t = \sum_{j-1}^{M_i} \frac{n_j}{N_j} \tag{2}$$

where n_j is the number of stress cycles in the j[th] group, with stress increment S_j (j = 1, M_i); N_j is the number of stress cycles causing fatigue failure corresponding to S_j (S_j found in the fatigue curve S-N).

The cumulative fatigue damage in 1-time unit (e.g. 1 year), including M short-term sea state, is determined as follows:

$$D(1\text{ year}) = \sum_{i=1}^{M} D_i = \sum_{i-1}^{M} \sum_{j=1}^{M_{ij}} \frac{n_{ji}}{N_{ji}} \tag{3}$$

Fatigue safety condition is the cumulative fatigue damage ratio at any time of operation τ must satisfy Equation 4:

$$D(\tau) = \sum_{\tau} D_i \le [D] \tag{4}$$

where, $[D]$ is the destructive fatigue damage ratio, normally according to the P-M rule, the value [D] = 1. However, in practice the design standards of jacket structures are given specific [D] values with different factors of safety, mainly depending on the location of structures that can be inspected, repaired, or difficult to inspect and repair, as specified by API [1] and DnV [15]. In this study, we apply the provisions of the API, specifically: for non-destructive structures, [D] = 0.5 for the location of structures that can be inspected; [D] = 0.25 for locations of structures that are difficult to check.

2.1.4. Determination of Fatigue Life

From Equation 3, we can determine the fatigue damage at the end of the fatigue life ($D(\tau_{FL})$) as follows:

$$D(\tau_{FL}) = \tau_{FL} \sum_{i-1}^{M} \sum_{j=1}^{M_{ij}} \frac{p_{ji}}{T_{ji} N_{ji}} \tag{5}$$

where τ_{FL} is the fatigue life at the hotspot, p_{ji} % is the percentage time part of the group of stress increments S_j in the short-term sea state; T_{ji} is the period of the stress group S_j in the short-term sea state; N_{ji} is the number of cycles of the group of stress increments S_j causing fatigue failure (according to the fatigue curve S-N).

Combining Equations 4 and 5, we have:

$$D(\tau_{FL}) = \tau_{FL} \sum_{i-1}^{M} \sum_{j=1}^{M_{ij}} \frac{p_{ji}}{T_{ji} N_{ji}} = [D] \tag{6}$$

From Equation 6, the design fatigue life at the hot spot can be determined according to Equation 7:

$$\tau_{FL} = [D] \left\{ \sum_{i-1}^{M} \sum_{j=1}^{M_{ij}} \frac{p_{ji}}{T_{ji} N_{ji}} \right\}^{-1} \text{ (sec)} \tag{7}$$

where $\sum_{i=1}^{M}\sum_{j=1}^{M_{ij}}\frac{p_{ji}}{T_{ji}N_{ji}}$ is fatigue damage in 1 time unit (1 sec), calculated according to the average statistics of one year.

The steps for calculating fatigue loss according to the P-M method and determining the fatigue life at a hot spot of the Jacket structure subjected to the harmonic wave load are as follow:

Step 1: Set up the structure diagram, and determine wave data for fatigue analysis corresponding to the fatigue calculation time in one year;

Step 2: Analyze the structure and determine the stress at the hotspot, determine the stress concentration factor (SCF) of the node;

Step 3: Determine the groups of values of stress increments including SCF at each hotspot of the node under consideration corresponding to the harmonic load groups due to the action of sea waves;

Step 4: Determine the number of repetition cycles of the fatigue load, corresponding to each group of stress increments at hot spots according to the fatigue curve S-N;

Step 5: Determination of accumulated fatigue damages D_i at each hotspot;

Step 6: Determine the total cumulative fatigue damages ratio in one year (D) at each hotspot;

Step 7: Determine the fatigue life of the button.

2.1.5. General Algorithm for Calculating Predetermined Fatigue

Predetermined fatigue analysis is performed according to the algorithm diagram shown in Figure 6, in which the content of specific blocks is as follows:

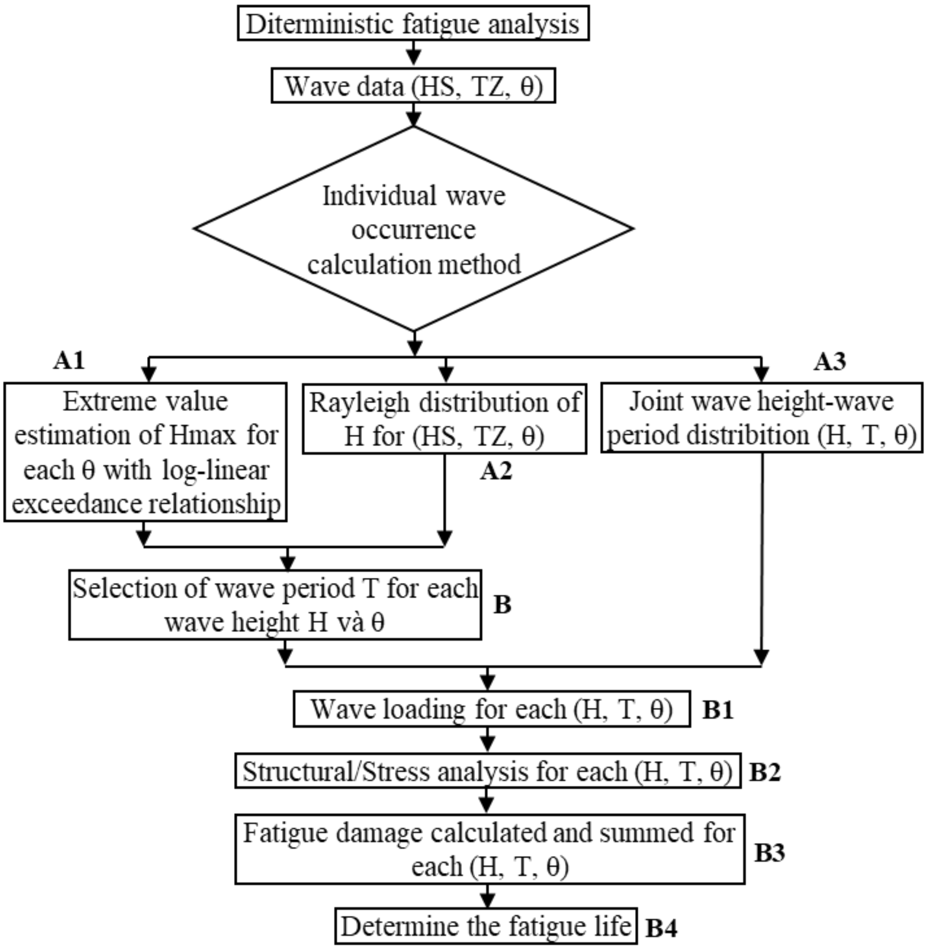


Figure 6. Schematic diagram of predetermined fatigue analysis of Jacket structure [14]

Input data: Wave data of short-term sea conditions with parameters (H_S, T_Z, θ); From the input data, select 1 of 3 methods (A1, A2, A3) to determine the data for each individual predetermined wave for fatigue analysis:

1) **Block A1**: Determine the H_{max} for each wave direction (θ);

2) **Block A2**: Based on Rayleigh distribution, determine wave parameters for each short-term $_{sea}$ state (H_S, T_Z, θ);

3) **Block A3**: Determine the relationship between (H, T, θ).

Determination of wave loads and structural analysis:

4) **Block B**: Select wave period for each wave height (H) and wave direction (θ);

5) **Block B1**: Determine wave load for each case of (H, T, θ);

6) **Block B2**: Analyze Jacket structure and determine stress at hot spots for each case of (H, T, θ);

7) **Block B3**: Based on the results of block B2 and fatigue curve SN, determine fatigue damages for each case of (H, T, θ), and sum them for all short sea states term;

8) **Block B4**: Based on the total fatigue damages of block B3, determine the fatigue life of the button, which is being investigated.

2.2. Evaluation of Dynamic Effects in Fatigue Analysis

The summaries of fatigue analysis methods for Jacket structure according to the quasi-static method and predetermined dynamical method (with the predetermined dynamic load as wave load), are done in section 2.1 of this paper. In the following, we will set up an algorithm to determine the dynamic effect of wave loads in quasi-static analysis and pre-determined dynamics analysis in Jacket structure fatigue analysis, as follows:

2.2.1. Dynamic Effects for Fatigue Analysis

Fatigue analysis for jacket structure with average statistical waves in one year [1]. Equation 8 is the non-fatigue failure condition:

$$D \le [D] \tag{8}$$

where, *D* is the cumulative fatigue damages ratio; [D] is the destructive fatigue damages ratio (allowable fatigue damages).

According to Ali & Kadim [8] and Aeran et al. [9], dynamic stress can be found through static stress as follows:

$$\sigma_D = DAF_i \sigma_t = \left(DAF \vee DAF_D \right) \sigma_t \tag{9}$$

Therefore, for each jth wave parameter (H_j, T_j, n_j) the jth dynamic fatigue damages ratio is determined by Equation 10:

$$D_{Dj} = \frac{n_j}{N_j} = n_j a S_{Dj}^m = n_j a \left(S_{tj} * DAF_{Dj} \right)^m = D_{tj} \left(DAF_{Dj} \right)^m \tag{10}$$

With;

$$S_D = \Delta\sigma_D = \sigma_{D-\max} - \sigma_{D-\min} = DAF_D \left(\sigma_{t-\max} - \sigma_{t-\min} \right) = DAF_D S_t \tag{11}$$

where j represents the parameters of the jth wave; D_{Dj} is the dynamic fatigue damages ratio; D_{tj} is the static fatigue damages ratio; n_j is the number of stress cycles; N_j is the number of fatigue failure cycles; a, m is a parameter dependent on the type of material, determined based on the fatigue curve S-N; S is the stress increment, $S = \Delta\sigma = (\sigma_{max} - \sigma_{min})$.

With the action of the jth wave, the dynamic effect in fatigue analysis is evaluated through the jth fatigue damages ratio as follows:

$$DAF_{Fj} = \frac{D_{Dj}}{D_{tj}} = \left(DAF_{Dj} \right)^m \tag{12}$$

where DAF_{Dj} is the dynamic effect of the load of the jth wave acting on the structure.

The structure is always affected by many different load groups, so the total accumulated fatigue damages ratio in a short-term sea state i, including Mi stress groups is determined by Equation 2. Fatigue cumulative damages in a time unit (eg 1 year), including M short-term sea conditions, is determined by Equation 3. Then, dynamic effects in fatigue analysis including M short-term sea states are determined as follows:

$$DAF_F = \frac{\sum_{i=1}^{M} \sum_{j=1}^{M_i} D_{D_{ij}}}{\sum_{i=1}^{M} \sum_{j=1}^{M_i} D_{t_{ij}}} = \frac{\sum_{i=1}^{M} \sum_{j=1}^{M_i} D_{D_{ij}} \left(DAF_{D_{ij}} \right)^m}{\sum_{i=1}^{M} \sum_{j=1}^{M_i} D_{t_{ij}}} \tag{13}$$

2.2.2. Algorithm Diagram to Evaluate Dynamic Effects in Fatigue Analysis

The evaluation of dynamic effects in this paper will be done in two directions, namely: Analysis of Jacket structure according to the quasi-static method and predetermined dynamic method. The calculation method will be selected according to the diagram Figure 7, branch 1 or branch 2a.

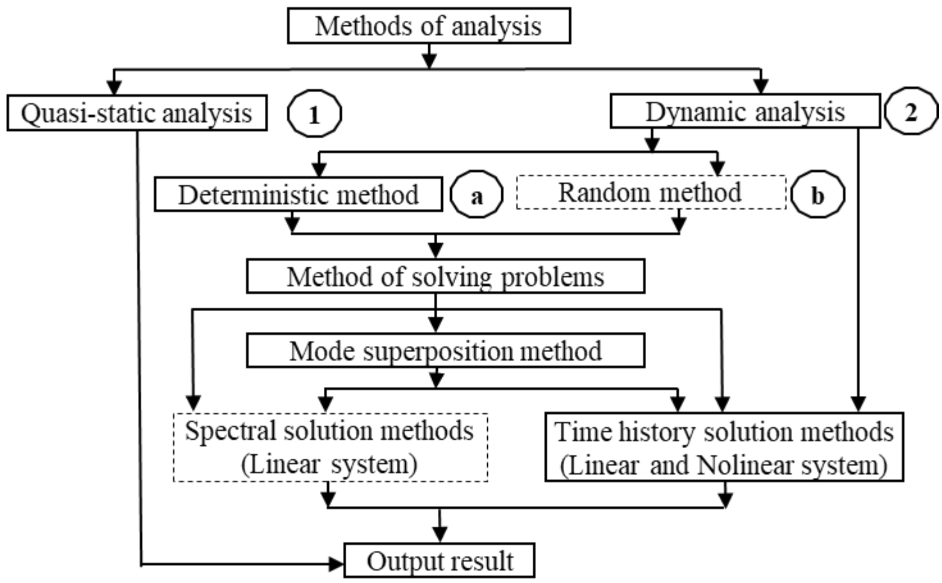


Figure 7. The general schematic diagram for analysis method

Diagram Figure 7, combined with the algorithm of SACS software [4], we build a general schematic diagram for strength analysis and fatigue analysis based on quasi-static and dynamic methods as shown in Figure 8.

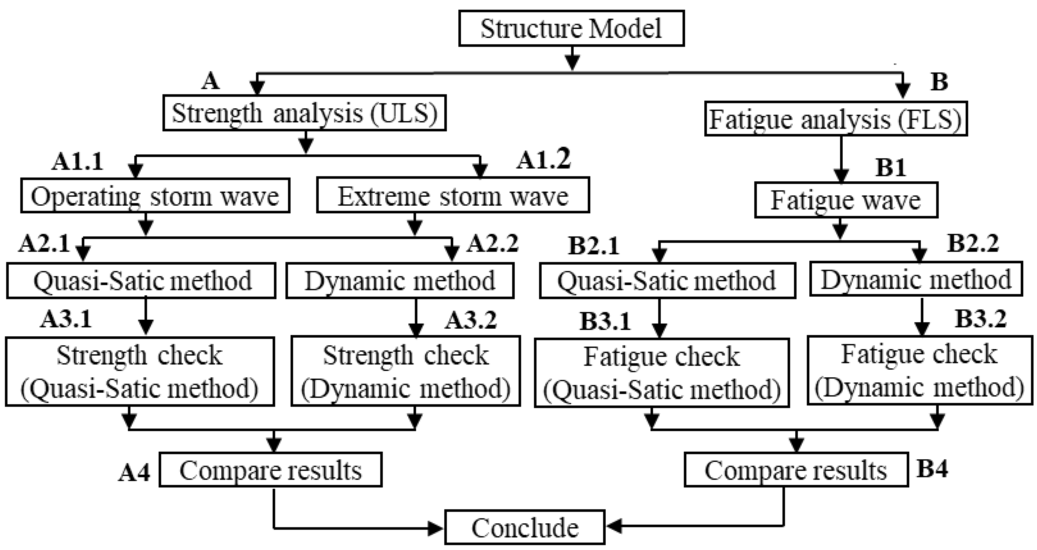


Figure 8. The general schematic diagram for strength and fatigue analysis based on quasi-static and dynamic methods

Fatigue analysis is performed according to branch B of Figure 8, including the following blocks:

1) **Block B1**: Determine wave load with statistical wave data, repeat period of 1 year;

2) **Block B2.1**: Using the wave load determined in block B1 to analyze the structure by quasi-static method (see detailed algorithm diagram in Figure 9).

3) **Block B2.2**: Using the wave load determined in block B1 to analyze the structure by dynamic method (see detailed algorithm diagram in Figure 9);

4) **Block B3.1**: Using the results of internal forces according to the quasi-static method B2.1 to evaluate fatigue life;

5) **Block B3.2**: Using internal force results according to the dynamic method of block B2.2 to evaluate fatigue life;

6) **Block B4**: Compare results from B3.1 and B3.2 and evaluate those results through DAF values (DAF_{QS}, DAF_D, DAF_F) and fatigue damages ratio values D (D_t, D_D) - Equation 13.

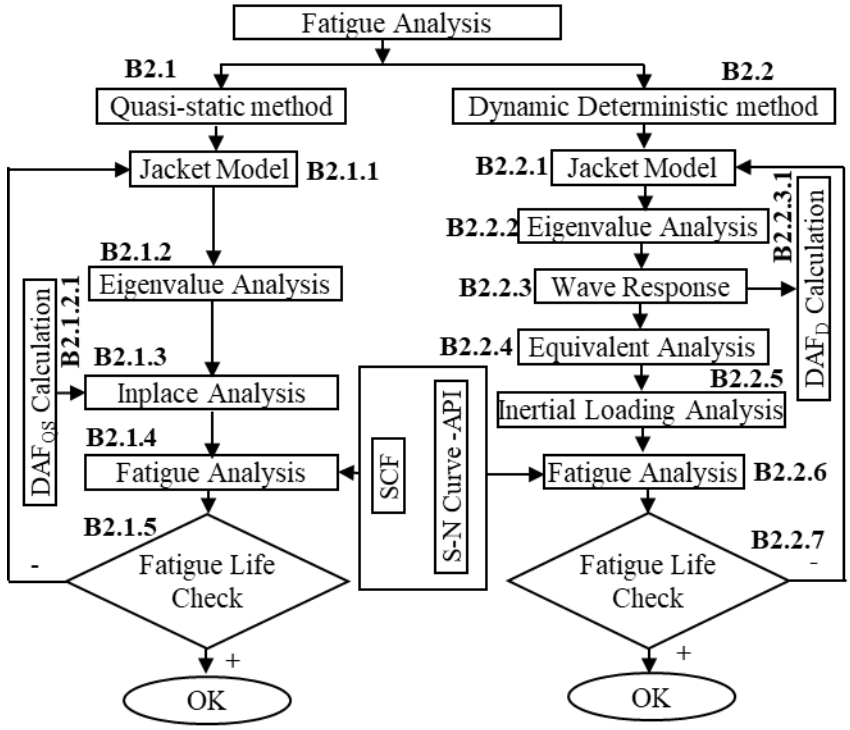


Figure 9. Schematic diagram for fatigue analysis

Algorithm diagram Figure 9 presents the fatigue analysis algorithm according to the quasi-static method and the predetermined dynamic method, including the following blocks.

2.2.3. Quasi-Static Methods: Block B2.1

1) **Block B2.1.1**: Modeling jacket structure: modeling elements, nodal connections, materials, loads (including the mass of materials, equipment, marine growth, and accompanying water) and associated with the background (boundary conditions), …;

2) **Block B2.1.2**: Calculate the natural period of the Jacket structure according to the calculation diagram modelled in block B2.1.1;

3) **Block B2.1.2.1**: Determine the dynamic coefficient DAF_{QS} (dynamic effect with the quasi-static model, Equation 12 for each wave corresponding to each wave direction, statistics in a year;

4) **Block B2.1.3**: Structural analysis with load combinations (including DAF_{QS} dynamic coefficient, which is the result in block B2.1.2.1);

5) **Block B2.1.4**: Based on the nominal stress in block B2.1.3, determine the stress at the hotspot (including the stress concentration factor SCF). Determine the number of fatigue stress cycles according to the S-N curve. Determine the cumulative fatigue loss ratio at each hotspot. Determine the total cumulative fatigue loss ratio in 1 year at each hotspot. Determine the fatigue life of the button;

6) **Block B2.1.5**: Compare the fatigue life of the button (including the safety factor) with the allowable fatigue life. If the fatigue life of the button is less than the allowable fatigue life, it means that the button has a fatigue condition. The fatigue test is over. If the fatigue life of the node is greater than the allowable fatigue life, it is possible to return to adjusting the structural model in block B2.1.1. The loop will end depending on the intention of the structural designer.

2.2.4. Dynamic Deterministic Method: Block B2.2

1) **Block B2.2.1**: Modeling jacket structure: modeling elements, nodal connections, materials, loads (including the mass of materials, equipment, marine growth, and accompanying water) and associated with the background (boundary conditions), …;

2) **Block B2.2.2**: Calculate the natural period of the Jacket structure according to the calculation diagram modeled in block B2.2.1;

3) **Block B2.2.3**: Determine the dynamic response of wave load by mode analysis method for each wave corresponding to each wave direction, which statistics for a year;

4) **Block B2.2.3.1**: Block B2.2.3 determines the total dynamic bottom shear force and the total static bottom shear force. From the results of block B2.2.3.1, the dynamic coefficient DAF_D is calculated according to Equation 12, for each wave corresponding to each wave direction, which statistics for a year;

5) **Block B2.2.4**: Equivalence analysis from wave load response in block B2.2.3;

6) **Block B2.2.5**: From the results in block B2.2.4, determine the inertial force in the dynamic response, under the action of wave load;

7) **Block B2.2.6**: Analyze the structure, and determine the nominal stress of the elements. Determine the stress at the hot spot (including the stress concentration factor SCF). Determine the number of fatigue stress cycles according to the S-N curve. Determine the cumulative fatigue damages ratio at each hotspot. Determine the total cumulative fatigue damages ratio in 1 year at each hotspot. Determine the fatigue life of the button;

8) **Block B2.2.7**: Compare the fatigue life of the button (including the safety factor) with the allowable fatigue life. If the fatigue life of the button is less than the allowable fatigue life, it means that the button has a fatigue condition. The fatigue test is over. If the fatigue life of the node is greater than the allowable fatigue life, it is possible to return to adjusting the structural model in block B2.2.1. The loop will end depending on the intention of the structural designer

3. Assessment of Dynamic Effects of Wave Loads in Fatigue Analysis for Jacket Structures

3.1. Characteristics of Jacket Structure in Vietnam

Jacket structure in Vietnam today most of the typical shape is a truncated pyramid of 4 legs, 8 legs, and 12 legs, the number of diaphragms from 3-6, piles are inserted in the legs or using skirt piles, the water depth is from 30-130 m, the material is steel according to API 5L standards or equivalent.

Through the statistical table of the main technical parameters (type of Jacket; the number of the diagram; the number of piles; water depth; natural period) of 82 Jacket structures recently (up to 9/2017) [18], we built the relationship graph between the water depth d_0 and the natural period T_1 of Jacket structure built in Vietnam, Figure 10.

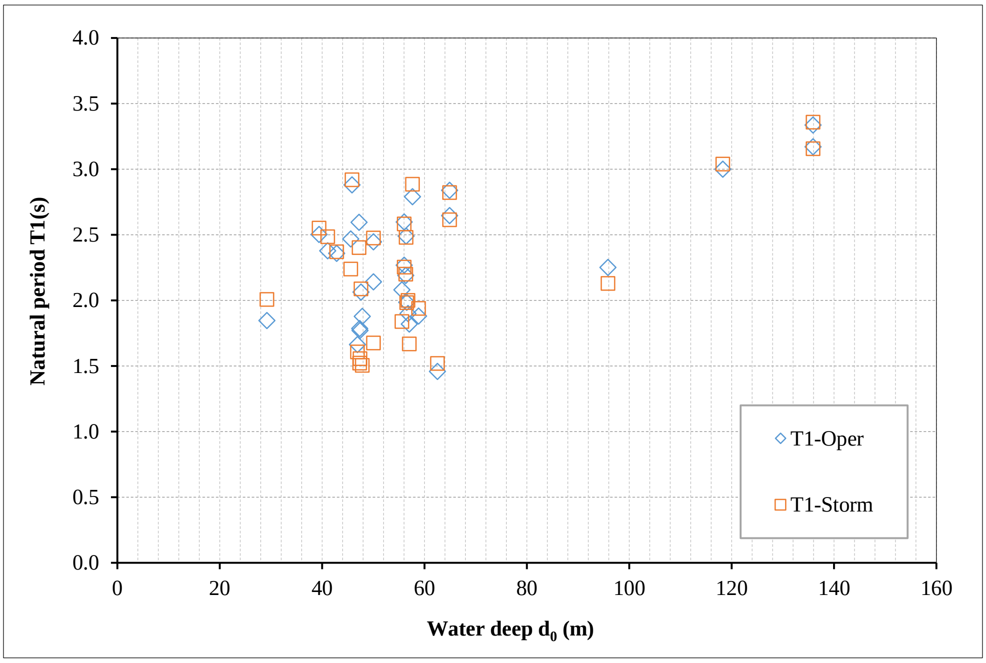
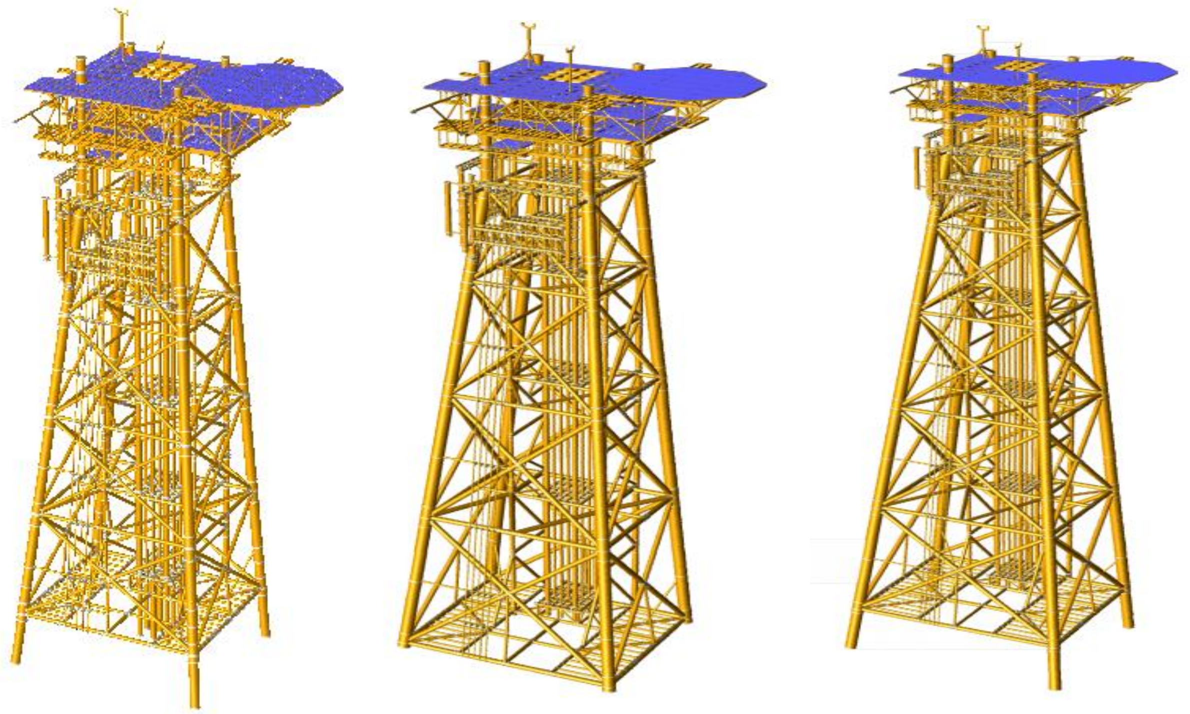


Figure 10. The relationship graph between the water depth d_0 and the natural period T1 of Jacket structure built in Vietnam

3.2. Main Parameters of Jacket for Assessment of Dynamic Effects

To clarify the dynamic effect of wave load on Jacket structures corresponding to Vietnam sea conditions when building from shallow water to deep water area, we analyze and survey the dynamic effect with 03 jacket structures at water depths 65 m, 90 m, and 120 m. The main parameters of 03 jacket structures are shown in Figure 11 and Table 1 below.



(a) Jacket 01 (b) Jacket 02 (c) Jacket 03

Figure 11. Structural diagrams of Jackets used to perform survey calculation

Table 1. Main parameters of Jacket structures for analytical calculations

Main parameters	Jacket 01	Jacket 02	Jacket 03
Water depth (m)	65	90	120
Topside (m)	24×28	24×28	24×28
Number of legs	4	4	4
Number of diaphragms	4	5	6
Legs (mm)	1650×25	1965×30	2290×40
Topside weight (T)	1680.3	1680.3	1680.3
Jacket weight (T)	3526.4	4951.9	7804.8
Natural period T1 - Operating (s)	2.144	2.800	3.287
Natural period T1 - Storm (s)	2.110	2.775	3.266

3.3. Wave Parameters and the Thickness of Marine Growth on a Jacket Structure in Vietnam Sea Conditions

Wave data were taken from oil and gas exploration site lot numbers 01/97 and 02/97 of the Southern sea of Vietnam. According to FUGRO [19], the thickness of marine growth on Jacket structures used as input to evaluate the dynamic effect in fatigue analysis for jacket structures are listed in Table 2 and the wave parameters for fatigue analysis are listed in Table 3.

Table 2. The thickness of marine growth on a Jacket structures under Vietnamese conditions

Water deep (m) from MSL	Thickness of marine growth (mm)
MSL	51.0
-4.60	153.0
-48.80	102.0
Seabed elevation	25.0

Table 3. The wave parameters for fatigue analysis

		T_i (s)															Total
		1.41	4.23	7.05	9.87	12.69	15.51	18.33	21.15	23.97	26.79	29.61	32.43	35.25	38.07	40.89	
	13.875					2											2
	13.875				4	4											18
	13.125				16	14											30
	12.375				26	35											61
	11.625				51	73	4										128
	10.875				128	154	17										299
	10.125				248	253	35										536
	9.375				458	453	76										987
	8.625			4	1080	811	168	9									2072
H_i (m)	7.875			20	2296	1462	279	14									4071
	7.125			33	4430	2361	496	38									7358
	6.375			233	9401	3758	878	93	7								14370
	5.625			1075	17621	7007	1806	165	22		1						27697
	4.875		66	6359	30805	12454	2571	254	16	2							52516
	4.125		760	21350	49586	22417	3547	513	31	7							98211
	3.375		542	62761	89090	33803	4621	685	66	13							191581
	2.625		5394	185551	142843	44727	5023	594	49	7							384388
	1.875		66818	501774	226962	49734	5752	789	28	3							851860
	1.125		582153	1144851	208320	44789	7935	630	25	2							2088705
	0.375		1610646	981617	166819	14672	2334	892	315	67	31	10	7	2	1		2828043
Total		50630	2266368	2905628	1050184	239193	35542	4676	559	101	32	10	7	2	1		6552933

3.4. Software and Standards for Analysis

The software used in the computational analysis is SACS software [4]. The standard applied in the computational analysis is the API RP2A-WSD 2000 [1]. The software and standards applied to analyze Jacket structure are current software and standards widely applied in Vietnam as well as in the world and accepted by international registry firms.

4. Dynamic Effect Assessment Results

Dynamic effects of wave loading in fatigue analysis (DAF_{QS} and DAF_D) of Jacket 01, Jacket 02 and Jacket 03 are performed for wave directions 0^0, 45^0, 90^0, 135^0, 180^0, 225^0, 270^0, 315^0 and presented in the Figures 12 to 19 and Tables 4 to 7.

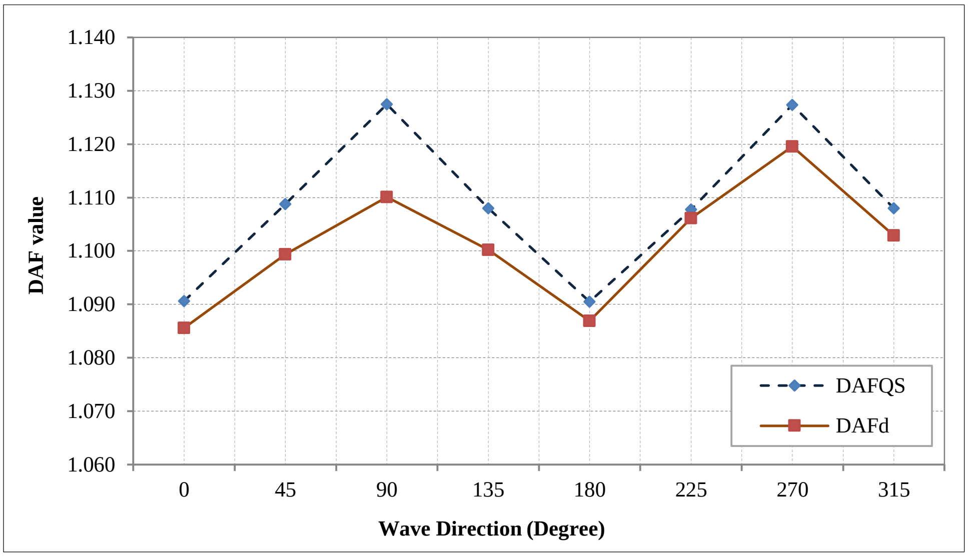


Figure 12. Correlation between DAFQS and DAF_D -Jacket 01

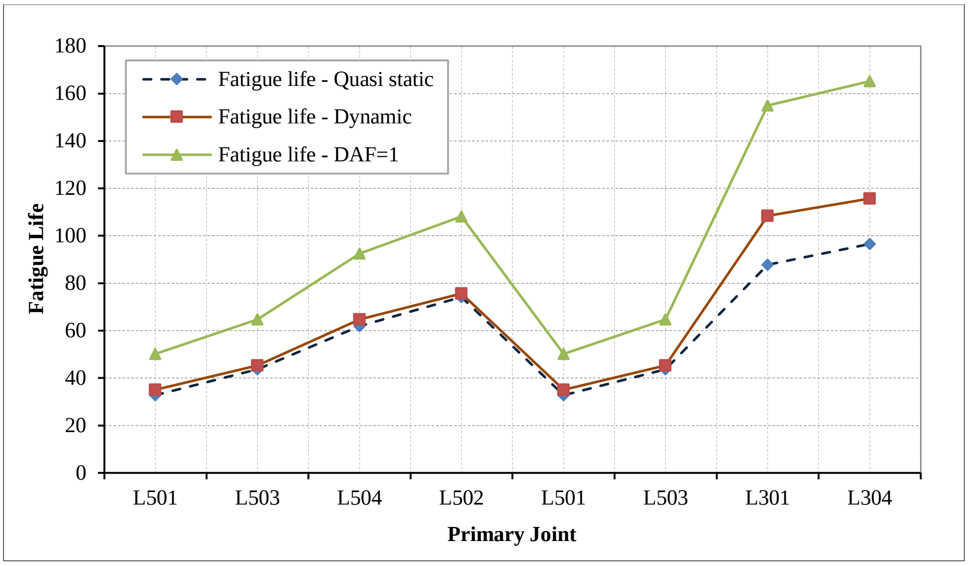


Figure 13. Fatigue life correlation representation - Jacket 01

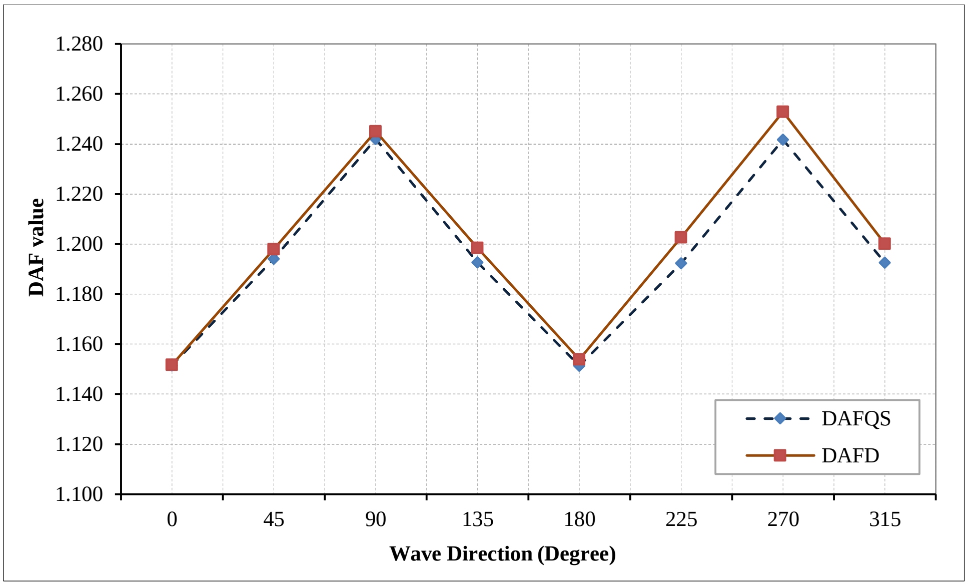


Figure 14. Correlation between DAF_{QS} and DAF_D - Jacket 02

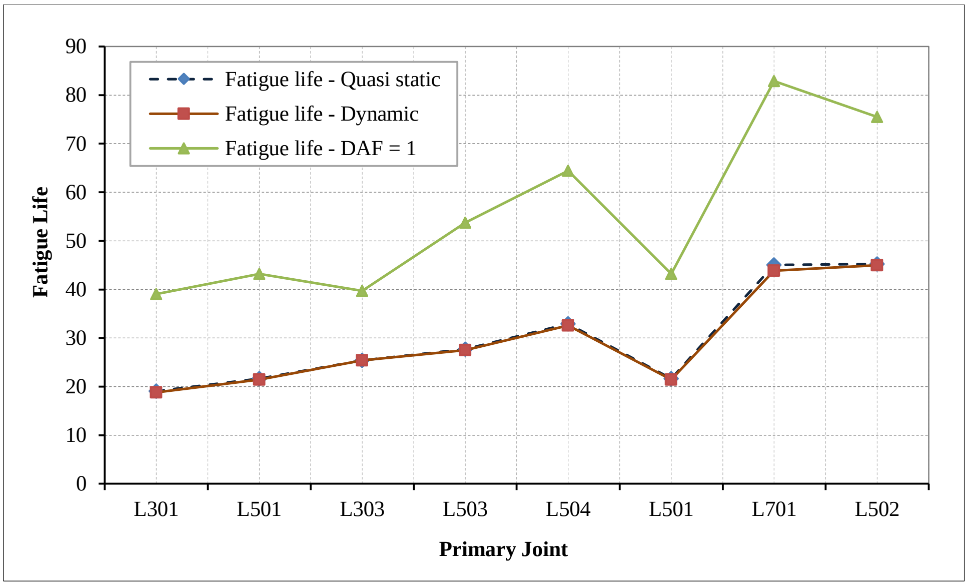


Figure 15. Fatigue life correlation representation - Jacket 02

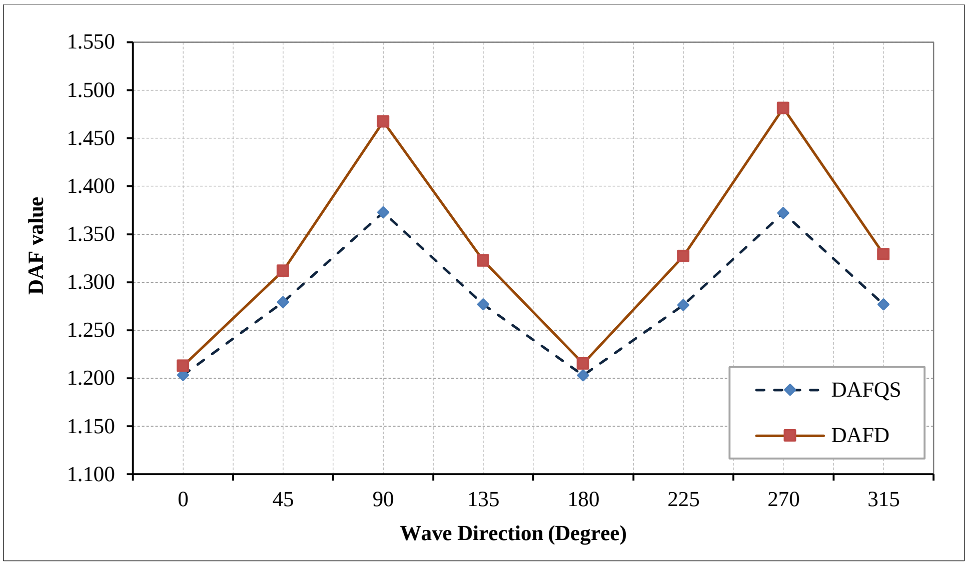


Figure 16. Correlation between DAF_{QS} and DAF_D - Jacket 03

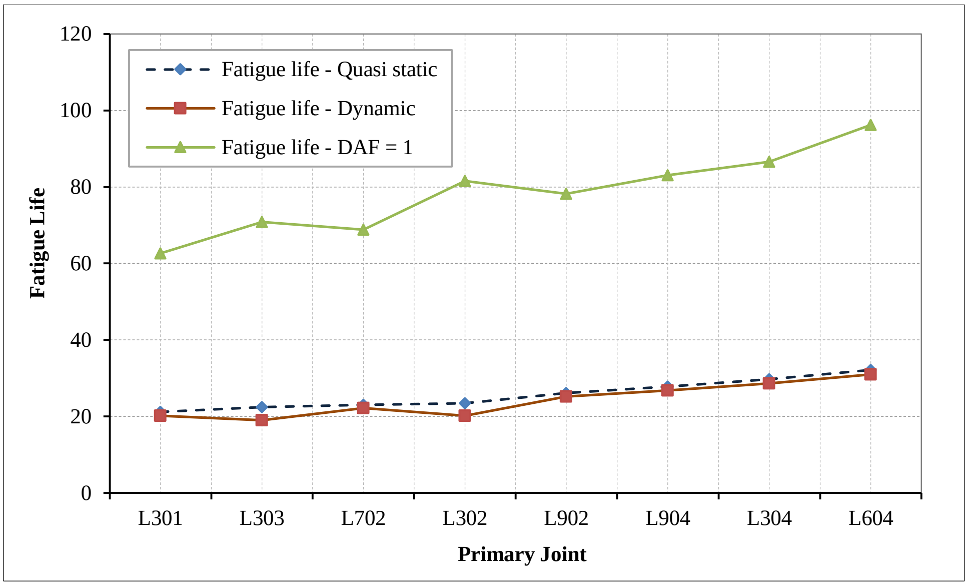


Figure 17. Fatigue life correlation representation - Jacket 03

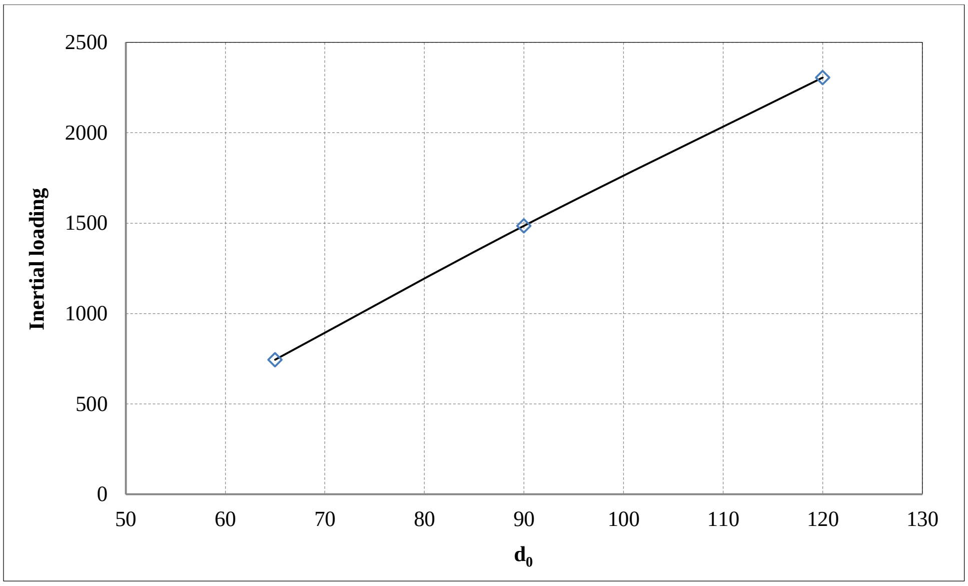


Figure 18. Inertia force - Jacket 01, Jacket 02 and Jacket 0

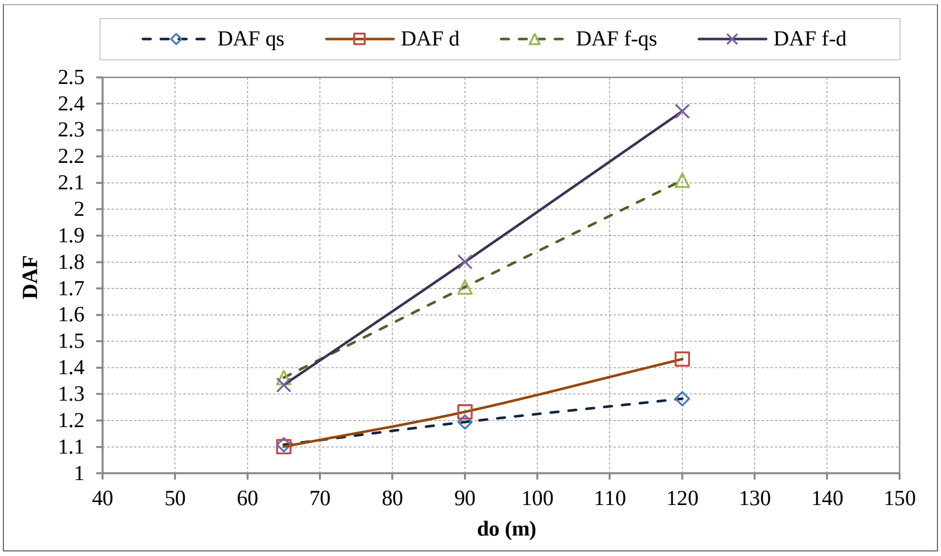


Figure 19. The values DAF_{QS} and DAF_D and DAF_{F-QS} and DAF_{F-D} of Jacket 01, Jacket 02 and Jacket 03

Fatigue analysis results for the above 03 Jacket structures show that:

- Dynamic effects (DAF) are all greater than 1. The force of inertia will increase gradually with water depth. Most of the fatigue life of buttons is more than 20 years.
- The dynamic effect of dynamic analysis (DAF_D) tends to start to be greater than the dynamic effect when using the quasi-static analysis (DAF_{QS}) with a water depth of approximately greater than 70 m.
- Assessment of dynamic effect through fatigue damage accumulation (DAF_F) will give much greater value than dynamic effect assessment through DAF_{QS} or DAF_D.

5. Discussion

Dynamic effects in fatigue analysis DAF_{Fj} and DAF_F are evaluated through fatigue damage ratio in Equations 12 and 13 giving much larger value than dynamic effect value in strength analysis (see [17, 18] and Figure 19), because DAF_{Fj} and DAF_F in fatigue analysis are exponential dependent m in the fatigue curve S-N, with $m \geq 3$. Figure 19, (incorporating the research results of [16-18]), shows that the dynamic effects of strength analysis and fatigue analysis are different. This is easy to explain because the input wave data for strength analysis and fatigue analysis are different. The variation of the dynamic effect of wave load on jacket structure tends to increase with increasing water depth. Dynamic effects in the dynamic fatigue analysis tend to increase and begin to overcome the dynamic effects in the quasi-static fatigue analysis at a position corresponding to a water depth of about 70 m. According to Barltrop & Adams [14], at a water depth of 70m, the boundary for choosing the static method and the dynamic method is T_{max}=1.8 s.

The difference in the dynamic effect of wave loading in fatigue analysis between the dynamic method and the quasi-static method increases with water depth: At a water depth of 65m ($T_{max} \approx 2.1$ s) the difference is -1.98%; At a water depth of 90m ($T_{max} \approx 2.8$ s) the difference is 5.63%; At a water depth of 120 m ($T_{max} \approx 3.2$ s), the difference is 12.42% (see Table 8). Thus, at a water depth of about 90 m, under Vietnamese sea conditions, the difference in dynamic effects in static and dynamic fatigue analysis has exceeded 5%, which is not allowed by many standards.

Table 4. Fatigue Life - Jacket 01

Joint	Member	Group	Main parameters of members		Joint type	Member type	Quasi-static method		Dynamic method		Quasi-static method DAF=1	
			OD (cm)	WT (cm)			D	T	D	T	D	T
L501	L501- 602	D3K	61	1.5	TK	BRC	0.611	32.711	0.570	35.073	0.399	50.104
L503	602-L503	D3J	61	1.5	TK	BRC	0.458	43.667	0.441	45.338	0.309	64.769
L504	L504- 600	D3F	61	1.5	TK	BRC	0.323	61.964	0.309	64.733	0.216	92.475
L502	600-L502	D3C	61	1.5	TK	BRC	0.270	74.133	0.264	75.703	0.185	108.147
L501	L501- 602	D3K	61	1.5	TK	BRC	0.611	32.711	0.570	35.073	0.399	50.104
L503	602-L503	D3J	61	1.5	TK	BRC	0.458	43.667	0.441	45.338	0.309	64.769
L301	L301-L403	L1I	173	6.5	TK	CHD	0.228	87.767	0.184	108.485	0.129	154.979
L304	L304- 306	H2B	50.8	1.2	TK	BRC	0.207	96.594	0.173	115.659	0.121	165.227

Table 5. Fatigue Life - Jacket 02

Joint	Member	Group	Main parameters of members		Joint type	Member type	Quasi-static method		Dynamic method		Quasi-static method DAF=1	
			OD (cm)	WT (cm)			D	T	D	T	D	T
L301	L301-L403	L1I	203.5	6.5	TK	CHD	1.047	19.102	1.065	18.785	0.512	39.053
L501	L501-L701	L4F	200.5	5	TK	CHD	0.924	21.650	0.933	21.433	0.463	43.211
L303	L303-L203	L1H	203.5	6.5	TK	CHD	0.788	25.394	0.787	25.401	0.504	39.714
L503	L703-L503	L4F	200.5	5	TK	CHD	0.721	27.728	0.727	27.500	0.372	53.757
L504	L504-L453	L3A	200.5	5	TK	CHD	0.608	32.914	0.614	32.597	0.311	64.401
L501	L501-L701	L4F	200.5	5	TK	CHD	0.924	21.650	0.933	21.433	0.463	43.211
L701	L801-L701	L4A	200.5	5	TK	CHD	0.444	45.023	0.456	43.884	0.241	82.893
L502	L702-L502	L3C	200.5	5	TK	CHD	0.442	45.245	0.445	44.962	0.265	75.470

Table 6. Fatigue Life - Jacket 03

Joint	Member	Group	Main parameters of members		Joint type	Member type	Quasi-static method		Dynamic method		Quasi-static method DAF=1	
			OD (cm)	WT (cm)			D	T	D	T	D	T
L301	L301-L403	L1I	203.5	6.5	TK	CHD	1.047	19.102	1.065	18.785	0.512	39.053
L501	L501-L701	L4F	200.5	5	TK	CHD	0.924	21.650	0.933	21.433	0.463	43.211
L303	L303-L203	L1H	203.5	6.5	TK	CHD	0.788	25.394	0.787	25.401	0.504	39.714
L503	L703-L503	L4F	200.5	5	TK	CHD	0.721	27.728	0.727	27.500	0.372	53.757
L504	L504-L453	L3A	200.5	5	TK	CHD	0.608	32.914	0.614	32.597	0.311	64.401
L501	L501-L701	L4F	200.5	5	TK	CHD	0.924	21.650	0.933	21.433	0.463	43.211
L701	L801-L701	L4A	200.5	5	TK	CHD	0.444	45.023	0.456	43.884	0.241	82.893
L502	L702-L502	L3C	200.5	5	TK	CHD	0.442	45.245	0.445	44.962	0.265	75.470

Table 7. Inertia force - Jacket 01, Jacket 02 and Jacket 03

Combination	Inertia force - Jacket 01		Inertia force - Jacket 02		Inertia force - Jacket 03	
	Fx (kN)	Fy (kN)	Fx (kN)	Fy (kN)	Fx (kN)	Fy (kN)
401	-79.75	0.12	-118.22	-10.53	479.9	3.9
402	-5.89	-6.46	-10.7	-9.98	-12.7	-2.8
403	0.05	-14.02	0.29	-13.01	-0.2	-2.3
404	36.09	-26.95	29.93	-255.97	399.5	-134.6
405	183.62	20.13	306.26	4.27	391.4	37.6
406	29.84	31.88	23.76	112.72	122.2	156.9
407	-0.69	231.59	0.33	97.39	-1.4	253.9
408	-40.85	45.6	7.93	137.67	-120.1	220.4
421	-127.15	3.69	-208.72	7.61	-268.2	-41.9
422	-18.12	-31.53	-14.57	-16.12	-19.2	-20.5
423	-0.58	-31.56	-0.44	-57.05	0.2	-76.9
424	70.86	-80.06	171.08	-282.57	39.0	-583.5
425	313.23	-10.7	528.93	33.57	1283.6	-6.1
426	52.79	72.83	139.53	278.31	82.7	233.3
427	-0.15	72.56	1.22	139.44	-4.4	277.4
428	-68.9	98.66	-156.56	400.07	-22.2	308.3
Sum	743.65		1485.23		2306.41	

Table 8. The values DAFF-QS and DAFF-D of Jacket 01, Jacket 02 and Jacket 03

Jacket	DAF_{F-QS} (The average value)	DAF_{F-D} (The average value)	Difference between DAF_{F-D} and DAF_{F-QS} (%)
Jacket 01, d_0=65m, T_1=2.1 s	1.362	1.335	-1.982
Jacket 02, d_0=90m, T_1=2.8 s	1.705	1.801	5.630
Jacket 03, d_0=120 m, T_1=3.2 s	2.109	2.371	12.423

6. Conclusions

This paper has developed a formula (Equation 13) to evaluate the dynamic effect of wave loads on the jacket structure in fatigue analysis, through the cumulative fatigue loss ratio. This is a new formulation and a dedication to the paper on theoretical development. The study also proposed an algorithm to use specialized software programs (SACS) to find intermediate results that are cumulative fatigue loss ratio (D) as input to Equation 13 to determine the dynamic effects of wave loads in the fatigue analysis of jacket structures. The algorithm diagrams presented in this paper are in fact developments in calculation methods for evaluating the dynamic effects of wave loads in fatigue analysis of jacket structure.

The algorithm proposed in this study has been applied to evaluate the dynamic effect of wave loads in fatigue analysis of 03 Jacket structures, built at water depth from 60 m to 120 m, in Vietnam Sea conditions. From the research results of this paper, the authors have conclusions and recommendations on the limit to applying quasi-static method and dynamic method for fatigue analysis of jacket structures in Vietnam sea conditions as the Limit to choose fatigue analysis method for jacket structures at Vietnam sea conditions is the water depth of 70 m or a maximum specific period of jacket structure = 1.8 s. (when water depth exceeds 70 m or when T_{max}>1.8 s, it is necessary to use a dynamic method for fatigue analysis for jacket structures in Vietnamese marine conditions).

The research results of the paper show that the application of design standards (API or DnV) for analysis for all other seas in the world is difficult to accept. In each sea area in the world, if the design engineers research to select a limit to choose the method of structural analysis suitable to the local conditions, it will bring higher efficiency. Considering this criterion, the study of this paper is a suggestion, and the formula (Equation 13) is completely reliable enough to be used for different sea areas.

7. Declarations

7.1. Author Contributions

Conceptualization, D.Q.C.; methodology, D.Q.C. and B.T.A.; software, B.T.A.; validation, D.Q.C. and B.T.A.; formal analysis, B.T.A.; investigation, D.Q.C. and B.T.A.; resources, D.Q.C. and B.T.A.; data curation, D.Q.C.; writing—original draft preparation, D.Q.C.; writing—review and editing, D.Q.C. and B.T.A.; visualization, D.Q.C.; supervision, D.Q.C.; project administration, D.Q.C. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] API-RP2A-WSD. (2014). Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design. American Petroleum Institute, Washington, United States.

[2] ABS. (2020). Guide for Fatigue Assessment of Offshore Structures. American Bureau of Shipping, Houston, United States.

[3] Khalifa, A. A., Aboul Haggag, S. Y., & Fayed, M. N. (2014). Fatigue assessment analysis of offshore structures with application to an existing platform in Suez Gulf, Egypt. World Applied Sciences Journal, 30(8), 1000–1019. doi:10.5829/idosi.wasj.2014.30.08.14126.

[4] SACS Version 5.3.1.1. (2018). Offshore structural analysis and design software, Executive Service Pack1, Version 5.3.1.1. Bentley, Pennsylvania, United States.

[5] Azarhoushang, A., & Nikraz, H. (2012). Dynamic fatigue assessment of fixed offshore platform. The Twenty-second International Offshore and Polar Engineering Conference, 1142–1147, 17-22 June, 2012, Rhodes, Greece.

[6] Nallayarasu, S., Goswami, S., Manral, J. S., & Kotresh, R. M. (2010). Spectral Fatigue Analysis of Jacket Structures in Mumbai High Field. The International Journal of Ocean and Climate Systems, 1(3–4), 209–221. doi:10.1260/1759-3131.1.3-4.209.

[7] Thomas, M., & Augustine, D. (2018). Fatigue analysis of offshore steel structures. International Research Journal of Engineering and Technology (IRJET), 5(4), 4693-4696.

[8] Ali, A. A. M., & Kadim, J. A. Risks and Propsed Solutions for Dynamic Analysis of Offshore Structures”. International Journal of Scientific & Engineering Research, 8(7), 150–155.

[9] Aeran, A., Siriwardane, S. C., Mikkelsen, O., & Langen, I. (2017). A framework to assess structural integrity of ageing offshore jacket structures for life extension. Marine Structures, 56, 237–259. doi:10.1016/j.marstruc.2017.08.002.

[10] Kim, D.-H., Ahn, J.-W., Park, S.-G., Jun, S.-H., & Oh, Y.-T. (2015). Spectral Fatigue Analysis for Topside Structure of Offshore Floating Vessel. Journal of Advanced Research in Ocean Engineering, 1(4), 239–251. Doi:10.5574/jaroe.2015.1.4.239.

[11] Siriwardane, S. C., Adasooriya, N. D., & Pavlou, D. (2021). Fatigue Strength Curve for Tubular Joints of Offshore Structures under Dynamic Loading. Dynamics, 1(1), 125–133. doi:10.3390/dynamics1010007.

[12] Kim, D. H., & Lee, G. N. (2018). Fatigue life evaluation of offshore wind turbine support structure considering load uncertainty. The 2018 Structures Congress (Structures18), 27-31 August, 2018, Songdo Convesia, Incheon, Korea.

[13] Damilola, O. J., Augustine, E. A., & Godspower, N. O. (2021). Fatigue Evaluation of Offshore Steel Structures Considering Stress Concentration Factor. International Journal of Research and Review, 8(10), 307–313. doi:10.52403/ijrr.20211041.

[14] Barltrop, N. D., & Adams, A. J. (2013). Dynamics of fixed marine structures. Butterworth-Heinemann, Oxford, United Kingdom.

[15] DNV-PR-C203. (2012). Fatigue Design of Offshore Steel Structures. Det Norske Veritas (DNV), Oslo, Norway.

[16] Jagite, G., Bigot, F., Malenica, S., Derbanne, Q., Le Sourne, H., & Cartraud, P. (2022). Dynamic ultimate strength of a ultra-large container ship subjected to realistic loading scenarios. Marine Structures, 84, 103197. doi:10.1016/j.marstruc.2022.103197.

[17] Dinh, Q.C., Bui, T.A., Hoang, D.N. (2019). Dynamic Effects of Wave Loads in Analysis to Check Strength and Fatigue for Fixed Steel Jacket Structure. Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering, Lecture Notes in Civil Engineering, 18. Springer, Singapore. doi:10.1007/978-981-13-2306-5_66.

[18] Offshore Department - VR. (2017). The data set of Jacket structures has been approved and stored at the Vietnam Register. Vietnam Register, Hanoi, Vietnam.

[19] FUGRO (2010). Block 01/97 and 02/97, Vietnam metocean criteria study (C50631/5751/R1). Fugro Geos, Oxfordshire, United Kingdom.