Estimation of Overall Fatigue Life of Jack-up Leg Structure

Dinh Quang Cuong [1*], Vu Dan Chinh [1]

[1] Institute of Construction for Offshore Engineering, National University of Civil Engineering, 55 Giai Phong, Hanoi, Vietnam.

Abstract

Jack-up platforms are designed to work in three conditions: Transit, Preloading and Operating. The fatigue life of the jack-up platforms in operating condition will be determined to be similar to that of offshore fixed steel structures. In preloading conditions, fatigue damage is usually ignored. Up to now, the fatigue damage of the jack-up leg structure in transit conditions has been calculated at approximately 20% of the total fatigue damage of the jack-up leg structure in two conditions (transit and operating). The approximate calculation method is usually accepted by consultants and register agencies. If the approximation is used, the fatigue life of the jack-up leg structure will be calculated only as for the jacket structure of the fixed offshore structure, with 80% of the allowable fatigue life based on standards. The approximation proved to have many disadvantages: the different travel times of each jack-up rig cannot be mentioned; hot spots that need to be maintained during the transit condition have not been pointed out; it is difficult to guarantee the safety of the jack-up leg structures in the transit condition. In order to overcome the limitations of the approximation method, this paper will propose a method to predict the overall fatigue life of the jack-up leg structure in three main problems. Firstly, we use the analysis method of fatigue of fixed steel offshore structures for jack-up leg structures in operating conditions. Secondly, we suggest a method to analyze the fatigue of the structures in transit conditions. Herein, motion analysis and determination of inertia forces on the leg structure are performed by the Boundary Element Model (BEM) in SACS software. Then the inertia forces are assigned to a Finite Element Model (FEM) in SACS to decide the internal forces of the structures. Hotspot stresses are determined by combining nominal stress from FE analysis results with a concentrated stress factor from the analysis of joint local models in the ANSYS program. Then, fatigue damage and fatigue life of hotspots of the structure are determined in the transit condition. Finally, a formula is suggested to determine total fatigue damage in operating conditions and transit conditions with different cases in relation to different fraction factors. These results are used to predict fatigue life corresponding to the most dangerous cases of structural joints. These new suggestions are applied to fatigue analysis for jack-up Tam Dao 05. Currently, the Tam Dao 05 platform has been operating in the Vietnam East Sea.

Keywords: Jack-up Leg Structures; Fatigue Analysis; Total Fatigue Damages; Operating Conditions; Transit Conditions.

1. Introduction

Jack-up structures include three main parts: a hull, legs, and spudcan structures. Under operating conditions (Figure 1-a), the platform structures work in the same way as fixed offshore structures. In wet tow conditions (Figure 1-b), the structures work the same way as floating structures. In the dry tow conditions (Figure 1-c), the jack-up rig is a large structure transported on a barge. The strength of jack-up structures is assessed based on ultimate limit state (ULS) in operating conditions, preloading conditions, and transit conditions according to standards [1], DNV-RP-C104 (2012) [2], and American Bureau of Shipping (2014) [3].

(a)

(b)   (c)
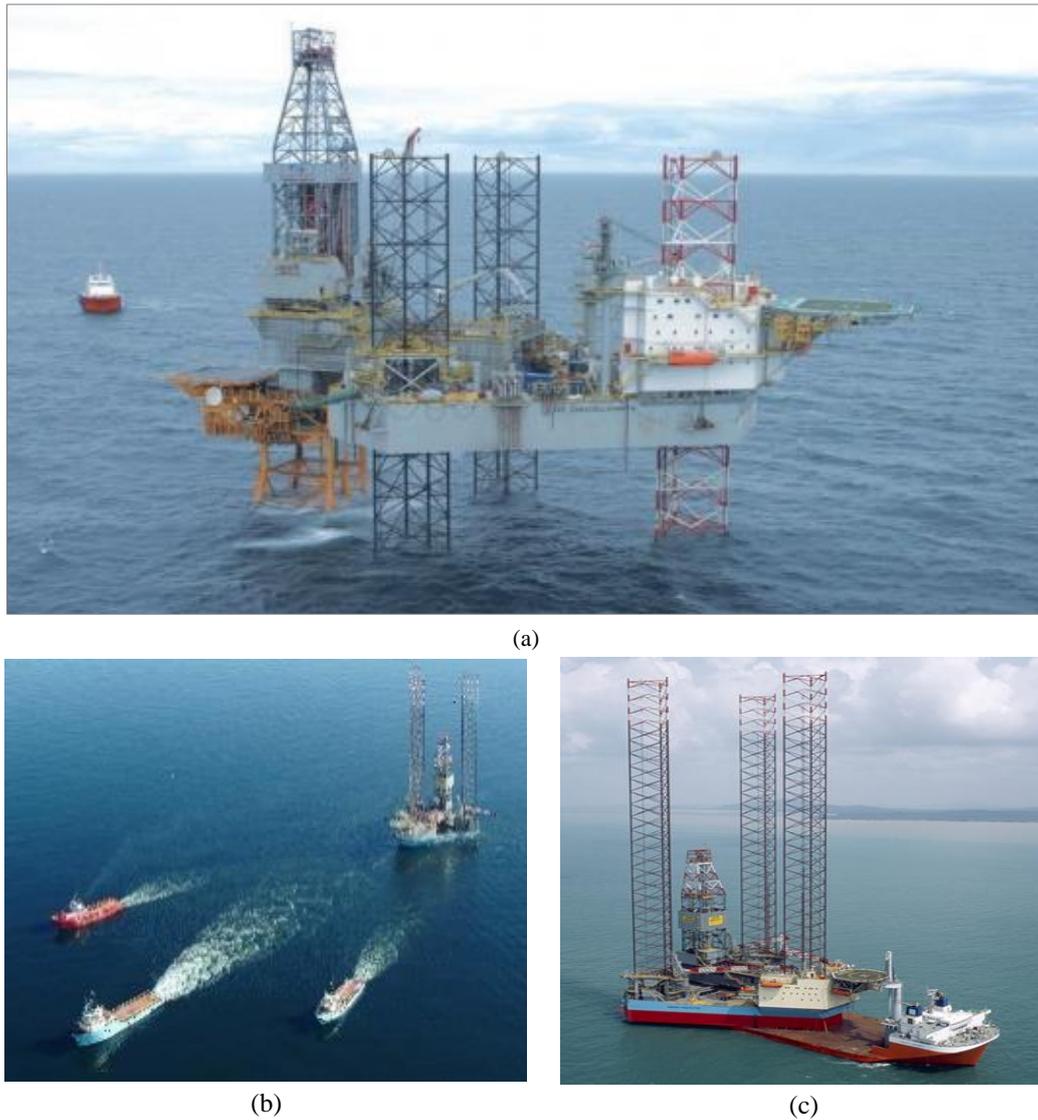
Figure 1. Illustrations of Jack-up platform in operating and transit conditions a) Jack-up platform in operating conditions; b) Jack-up platform in wet tow conditions; c) Jack-up platform in dry tow conditions

Besides, the fatigue life of the structures is evaluated based on Fatigue Limit States (FLS) in operating conditions and transit conditions. In FLS, the fatigue damage in operating conditions is presented by Barltrop & Adams [1] and DNV-RP-C104 (2012) [2], American Bureau of Shipping [4, 5]. Cuong & Chinh (2019) and Quang & Vu (2021) clarified a method to evaluate the fatigue life of the structures in transit conditions [6, 7].

As per current standards, the method of assessing fatigue life jack-up leg structures can be summarized in steps as follows:

Step 1: Assessing fatigue life of jack-up leg structures in the operating conditions.

In the operating conditions, the jack-up rig operates as an offshore fixed steel structure. The fatigue life of the jack-up leg structures in the operating conditions, under the influence of sea waves acting directly on the jack-up leg structures, can be determined by the Palmgren-Miner method and has been clearly presented in Barltrop & Adams (1991) [1]. In this paper, the fatigue life of the jack-up leg structures in the operating conditions is denoted as T_{op}.

Step 2: Evaluation of the overall fatigue life of the jack-up leg structures.

Herein, fatigue damage in transit condition is ignored. In return for this situation, the design life of the structures is reduced by 20%. So the fatigue condition can be assessed as below:

Safety conditions: $T_{op} \geqslant 80\%[T]$ (1)

whereas: [T] is design life.

Considering that the transit time is equal to 20% of the fatigue life of jack-up leg structures is incorrect. This statement can be clarified for the following reasons:

- In fact, the transit time of each jack-up rig is different. There are jack-up rigs that move very little and only inside the oil and gas field. In contrast, many jack-up rigs are used for oil and gas exploration at sea, so the transit time is often very large compared to the total lifetime of the jack-up structure. Thus, the transit time of all jack-up rigs should be considered to be the same and, equal to 20% of the jack-up structural life, as a basis to approximate the total fatigue damage in the transit conditions of the jack-up rig is equal to 20% of total fatigue damage of jack-up structure is incorrect.

- The results of the fatigue analysis will predict the fatigue life of the structure. The fatigue life of the structure is the fatigue life of the hot spots. Pointing out the hot spots of the structure, in addition to the purpose of predicting the structural fatigue life, also gives the locations that need a detailed survey to promptly correct defects or possible problems to ensure safety and prolong the life of the structure. This is an important step in the analysis and re-evaluation of the structure as a basis for the re-design of the structure. The approximation method does not show hot spots on the jack-up structure in the transit conditions, it will be difficult to track, ensuring the safety of the jack-up structure in the transit conditions.

- Usually, the location of hot spots of the jack-up foot structure in the transit conditions is different from the position of the hot spots in the operating conditions. Most of the hot spot locations that occur in the operating conditions, in the transit conditions, the location will not be the hot spot. The addition of fatigue life in two conditions (transit and operating) at a location of the structure is possible only when that location is a hotspot in both conditions. This is very unlikely, and this is a limitation of the approximation method. However, the fatigue damage determined in the two conditions can be added. Then the fatigue life of the hot spot in the two conditions will be the inverse of the sum of the fatigue damage of the two conditions. The approximation method does not help us to do this.

- Considering that the fatigue damage of the jack-up rig in the transit conditions accounts for 20% of the total fatigue damage of the jack-up structure, it means that there will not be a hot spot on the jack-up structure in the transit conditions. This is not practical because, for jack-up structures, there is a large travel time and distance, especially when traveling long distances in bad weather, there is a risk of hot spots. In this case, the movement of the jack-up structure is not guaranteed.

In order to overcome the shortcomings of the approximate method, this paper proposes a new method to evaluate the overall fatigue life of jack-up leg structures including the fatigue damages in the transit conditions [8]. The new method consists of three steps as follows:

Step 1: Assess the fatigue damage of the jack-up leg structures in the operating conditions (D_{op}).

Step 1 is carried out in the same way as the current method used to evaluate the fatigue life of steel jacket of fixed offshore platforms.

Step 2: Assess the fatigue damage of the jack-up leg structures in the transit conditions (D_{ts}).

Herein, the authors propose a new method to evaluate fatigue damage of the jack-up rig leg structure in the transit conditions, replacing the approximate method currently being implemented in the world. In transit conditions, almost the jack-up leg structures are not directly subjected to wave loads. Fatigue loads are inertia forces generated by motions of the structural systems under the actions of waves.

Step 3: Evaluation of overall fatigue life of the jack-up leg structures takes into account the total fatigue damage of the structure in the operating and transit conditions. Step 3 will, based on the results of step 1 and step 2, propose formulas to evaluate the overall fatigue life of jack-up legs structures.

It is necessary to include fatigue damage in transit conditions to estimate the overall fatigue life of the Jack-up leg structure. The calculation that ignores the fatigue damage in the transit conditions and replaces it by reducing the design life by 20% is incorrect. The three calculation steps proposed in this paper are a new method, aiming to replace the calculation method that is usually accepted by Consultants and Register agencies.

2. Prediction of Fatigue Life of Jack-up Leg Structures in Operating Conditions

In operating duration, jack-up leg structures are impacted directly by wave loading of different environmental conditions and at different locations. So, in the lifetime, any point of the structures always bears many stress groups Generally, a hotspot of a jack-up structure is assumed to resist m group of stresses ranges Si induced by short-term sea-states which specified by significant wave heights H_{si} and number of cycles n_i (i=1÷m). Whereas, the stress ranges are calculated by multiplication of nominal stresses and stress concentration factors [9, 10]. According to Palmgren-Miner rule [1], the fatigue cumulative damage ratio of the hotspot is expressed by formula as below:

$$D = \sum_{i=1}^{m} \frac{n_i}{N_i} \tag{2}$$

Commonly, jack-up legs are made of high strength steels with yield limits large than 500MPa, so fatigue limit cycles N_i can be determined based on S_i (MPa) by the S-N curve in DNV RP-C203 [11], as below:

$$LogN_i = 17.446 - 4.7LogS_i \tag{3}$$

The fatigue life of a hot spot can be determined by the Equation 4, with a safety factor γ_f. The factor value depends on standards [11, 12]:

$$T = \frac{1}{\gamma_f D} \tag{4}$$

As mentioned above, jack-up platforms must be worked in different locations with various water depths. To analyze fatigue damage in a whole life time, the structures should be simulated by corresponding models. According to basic theories, authors suggested a procedure of fatigue analysis of jack-up structures in operating conditions in Figure 2 as below:
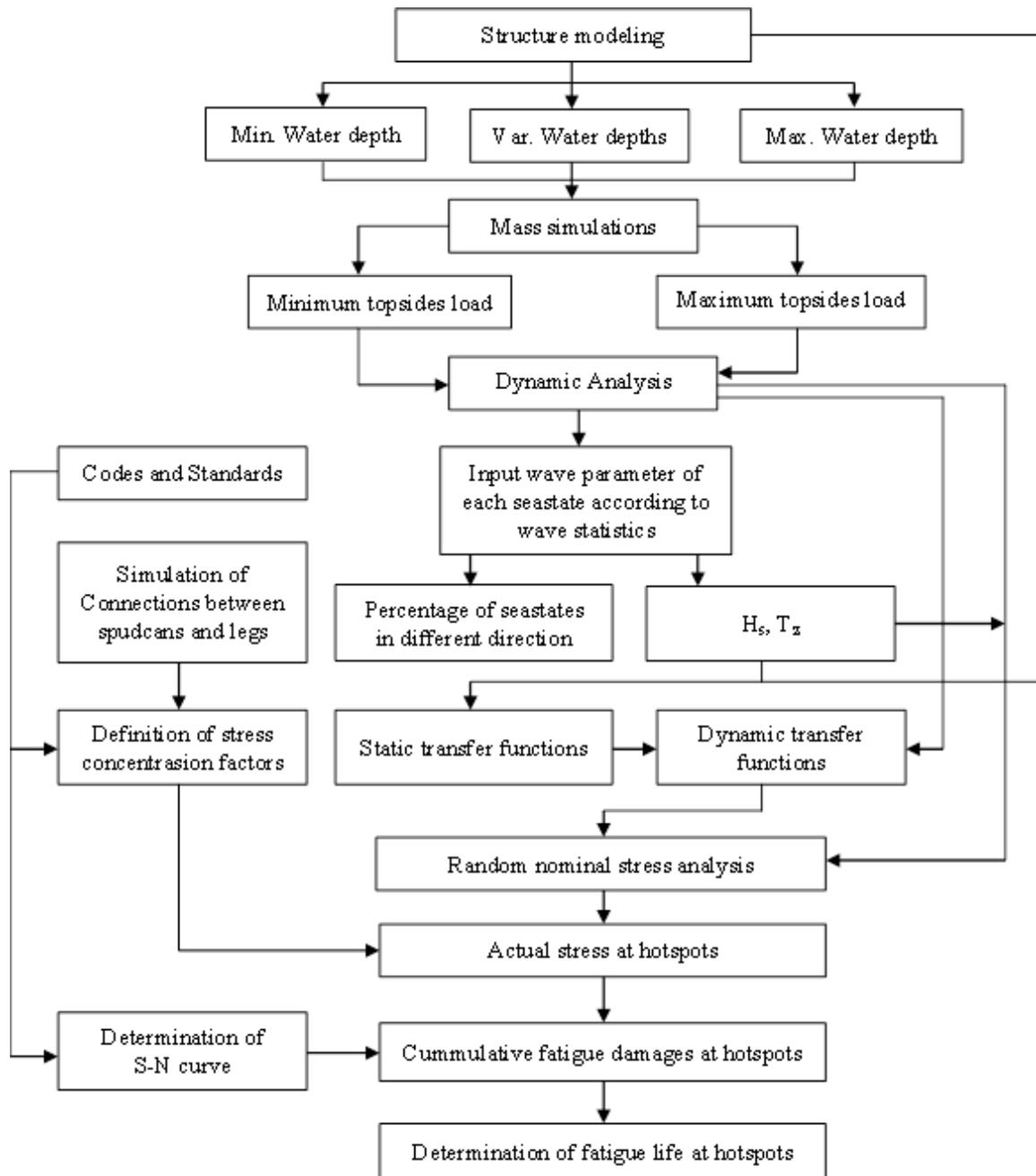

Figure 2. Procedure of Fatigue Analysis of Jack-up Structures in Operating Conditions

3. Fatigue Life of Jack-up Leg Structures in Transit Conditions

Generally, fatigue analysis of jack-up legs structures in transit conditions are performed as the same as in operating conditions. However, in transit conditions, the jack-up legs are not directly subjected to wave loads. Fatigue load for fatigue analysis of jack-up rig leg structure in transit conditions is the inertia force, caused by shaking vibrations of jack-up rig structure under the action of waves and currents. The following sections will briefly present the calculation of the inertia force and establish the algorithm to evaluate the fatigue life of the jack-up leg structures in transit conditions.

3.1. Inertial Load for Jack-up Structural Fatigue Analysis in Transit Conditions

Floating structural motion components are signified in Figure 3. The equation of motion can be expressed in the following Equation:

$$(M + A)\ddot{U} + C\dot{U} + K_{hys}U = F(t) \tag{5}$$

where: M is a structural mass matrix in global axis; A is added mass matrix determined from radiation wave potential on the mean wetted body surface of the hull; Damping matrix C is determined from radiation wave potential; Hydrostatic Stiffness Matrix K_{hys} is determined from hydrostatic pressure effect on the wet surface of the hull; $\dot{U}, \ddot{U}$ vectors of motion velocities and accelerations; F(t): the vector of wave loads based on incident wave potentials and diffraction wave potentials. Motions at the center of gravity of a jack-up platform are determined by Equation 5 induces inertial forces at i^{th} mass point of the structure. The inertial force includes the components of the translational inertia, the centrifugal inertia and the tangential inertia, which are determined according to DNV-RP-C104 (2012) [2].


1. Surge (along X)
2. Sway (along Y)
3. Heave (along Z)
4. Roll (about X)
5. Pitch (about Y)
6. Yaw (about Z)
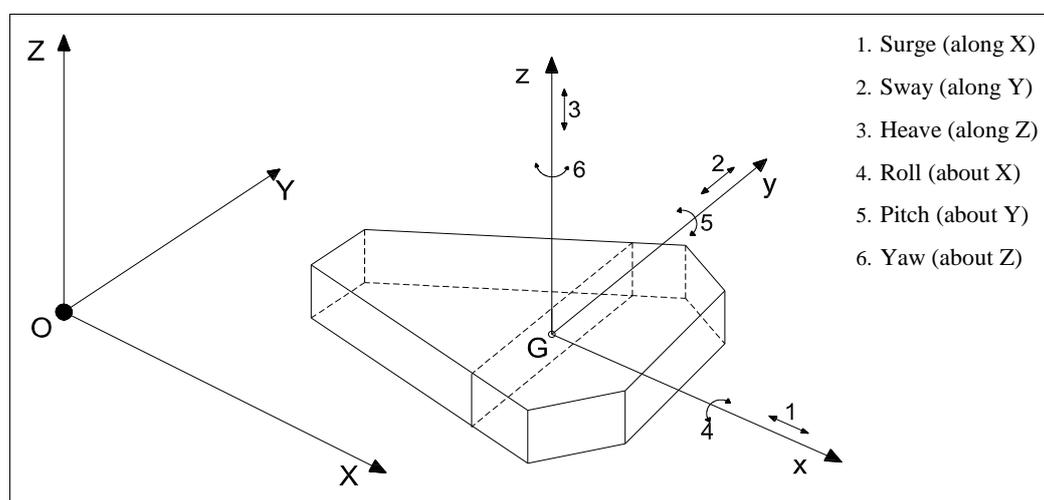
Figure 3. Definition of Axis Systems and Floating Rigid Motions

3.2. Determine the Stress at the Hotspot

Assuming that incident waves are stationary random processes specified by spectrum density functions $S_{\eta\eta}(\omega)$, the response spectrums of the structures can be expressed in formula as below:

$$S_{uu}(\omega) = RAO(\omega)^2 . S_{\eta\eta}(\omega) \tag{6}$$

whereas, $RAO(\omega)$ is Response Amplitude Operator of the structural response u(t). According to DNV-RP-C104 (2012) [2], based on $S_{uu}(\omega)$, the inertial force spectrums at mass m_i can be determined depending on response accelerations of the structural center of gravity, roll and pitch angles, distances from m_i to the center of gravity. The structures will be analyzed by the finite element method, the stress spectrums $S_{\sigma\sigma}(\omega)$ are determined at the hotspot of the structures, including stress concentration factors [5]. Finally, the stress ranges and number of cycles are determined by the formula in [13]. Actually, joints of jack-up legs are complicated, so the hotspot stress concentration factors (SCF) are commonly determined by analysis of local FE models [2, 5].

3.3. Prediction of fatigue Life of Jack-up Leg Structures in Transit Conditions

The fatigue cumulative damage ratio of the hotspot is expressed by Equation 2. S-N curve in DNV RP-C203 [12] are presented in Equation 3. The fatigue life of a hot spot can be determined by the Equation 4. Herein, the authors establish the general algorithm for fatigue analysis of Jack-up legs structures in transit conditions in Figure 4.
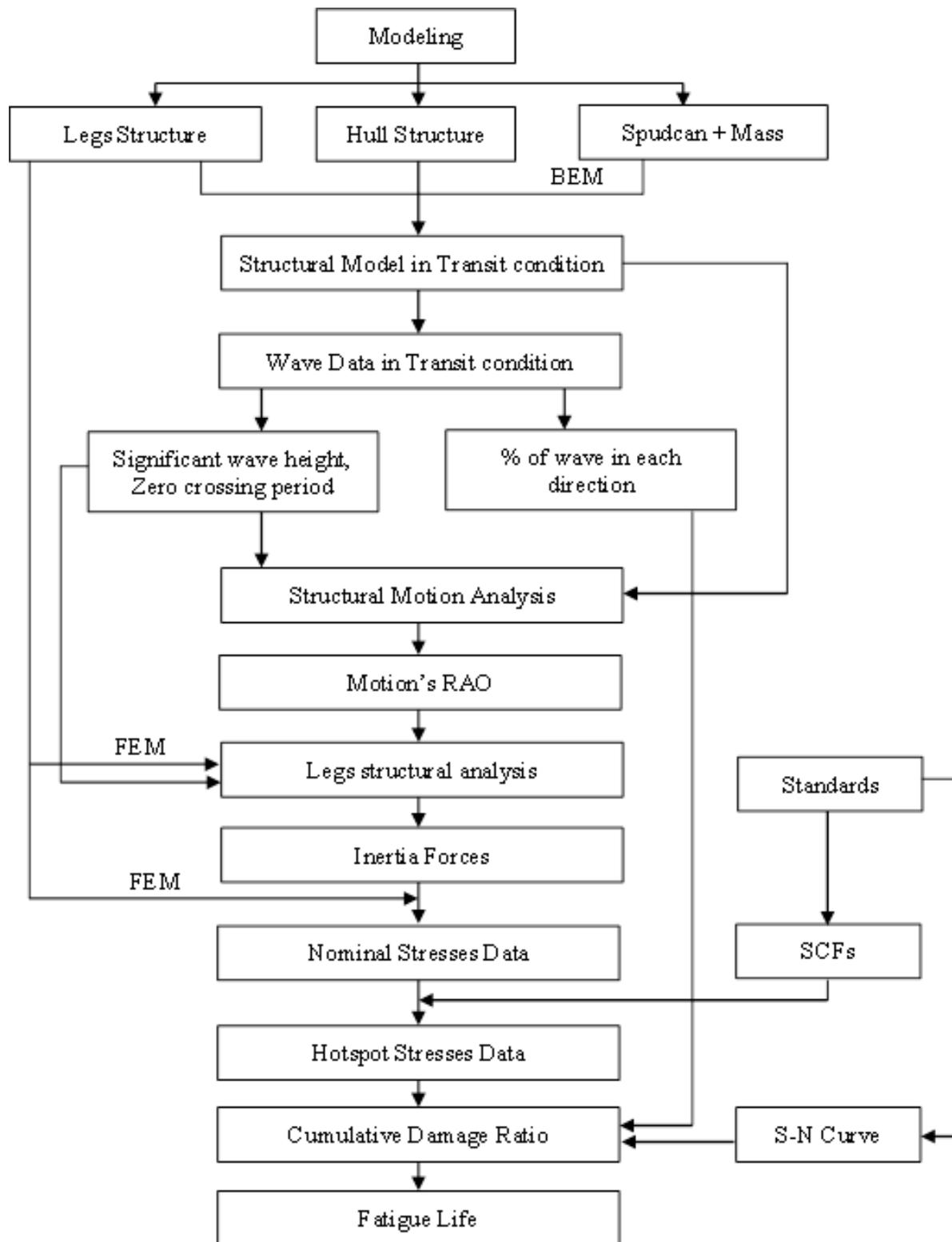
Figure 4. Procedure of Fatigue Analysis of Jack-up Structures in Transit Conditions

4. Estimation of Total Fatigue Life of Jack-up Leg Structures

To call fatigue cumulative damage of a hotspot of jack-up leg structures in operating conditions and transit conditions in a year are D_{op} and D_{ts}, respectively. The damage in operating duration with n of different water depths can be expressed by the formula as below:

$$D_{top} = \sum_{i=1}^{n} \alpha_i D_{opi} \qquad (7)$$

And the total damage of the hotspot, D_{tot}, is calculated:

$$D_{top} = D_{op} + \beta D_{ts} \tag{8}$$

whereas, α_i is a fraction of fatigue life at i^{th} water depth condition (i=1÷n) and β is the average fraction of fatigue life of transit condition in a year. Due to the independent damage and linear relationship, the safety factor is equal to Equations 7 and 8, α_i and β are satisfied the equation:

$$\sum_{i=1}^{n} \alpha_i + \beta = 1 \tag{9}$$

The total fatigue life of the hotspot in a year can be calculated as:

$$T_{tot} = \frac{1}{D_{tot}} = \frac{1}{D_{tot} + \beta D_{ts}} = \frac{1}{\sum_{i=1}^{n} \alpha_i D_{opi} + \beta D_{ts}} \tag{10}$$

The suggested formulas will be used to estimate the total fatigue life of a jack-up leg structure in Vietnamese conditions as below.

5. A Vietnamese Case Study

5.1. Input Data

In the case study, we perform fatigue analysis of jack-up platform Tam Dao 05 which is operating in Thien Ung field of Vietnam. Input data are summarized in Table 1:

Table 1. Summary of Structural Data

Main parameters	Values
Water depth (m)	122
Length of Legs (m)	167
Hull dimensions (L×B×D), (m)	$70.4 \times 76.0 \times 9.4$
Distance between legs (vertical × horizontal), (m)	47.6×45.7
Total live load of the hull in operating condition (mton)	3766
Weight of hull in operation (ton)	8500
Weight of Spudcan (ton)	1082.56
Total tonnage, cargo and ballast in transit condition (ton)	24642
Transit Draft (m)	7.320

Statistic wave data for fatigue analysis in operating conditions: Wave scattering diagram is from the following report "Metocean criteria and statistics 8 to 9°N, 107 to 109°E, Offshore South Vietnam. V1.0 for the Thien Ung Project Feed Design" [14-16]. The distribution of waves in accordance with the directions is given below (Table 2, Figure 5). In transit conditions, fatigue wave data for all directions can be assumed: Wave height H = 3m; Period T = 6s.

Table 2. Fatigue Wave Scatter

| Wave Direction (from)	Percentage distribution (%)
North	0.45
Northeast	44.53
East	9.28
Southeast	0.95
South	1.79
Southwest	29.21
West	13.35
Northwest	0.43
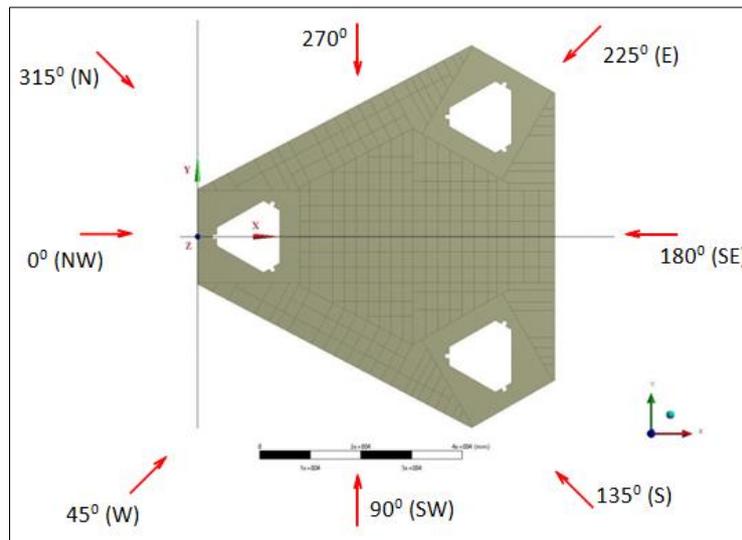
Figure 5. The correlation of Tam Dao 05 Jack-up platform and wave scattering

5.2. Structural Modeling

TD-05 jack-up platform structure can be modeled by SACS software [17], including: Mass, Hull and Legs models. There are two models corresponding to operating conditions (Figure 6) and transit conditions (Figure 7). In operating conditions, hull structures are modeled by an equivalent system with equivalent stiffness according to DNV-RP-C104 (2012) [2]. The structure is analyzed by the Finite Element Method. In transit conditions, hull structures are modeled by an absolute stiffness body with similar geometry to analyze the interaction between waves and large bodies [18-21]. The structural motions are determined by Boundary Element Method. Then the motions are used as input data to analyze jack-up leg structures by Finite Element Method.
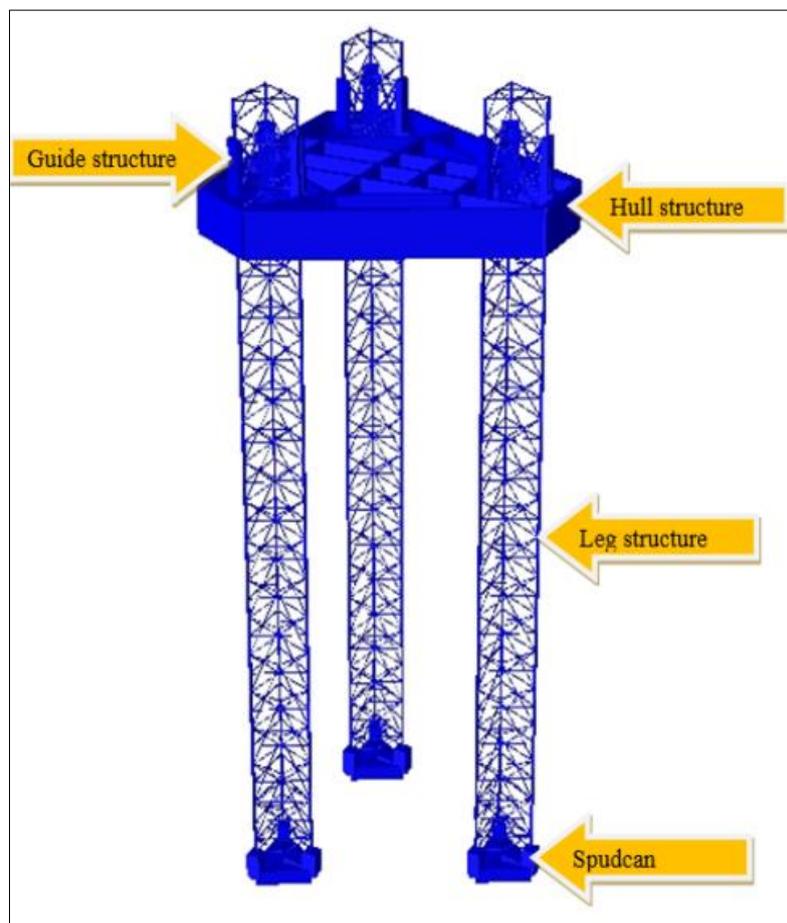

**Figure 6. Jack-up Structure Model in Operating Conditions**
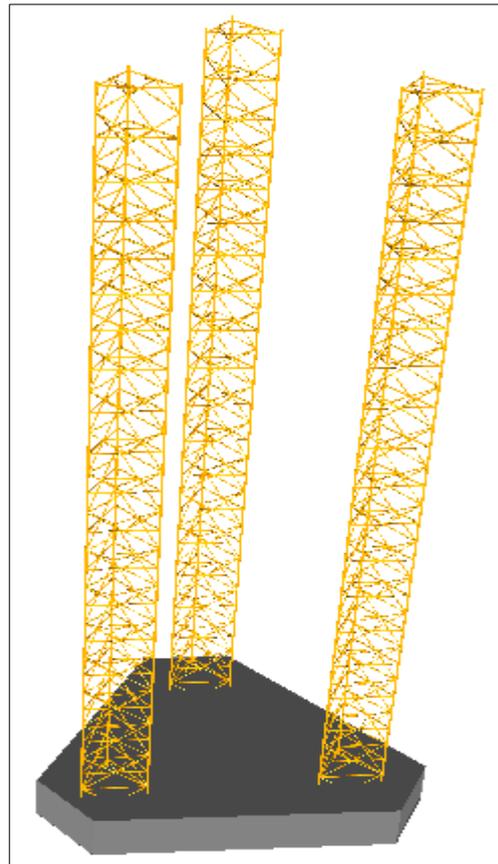
Figure 7. Jack-up Structure Model in Transit Conditions

5.3. Joint Local Modeling

Joints of jack-up legs are special structures, so there is no formula to determine local stresses in current standards, so stress concentrated factor (SCF) of joints must be found by Local Finite Element Models. In the paper, the joints are modeled by ANSYS software [22]. A typical joint and concentrated stresses are illustrated in Figure 8.
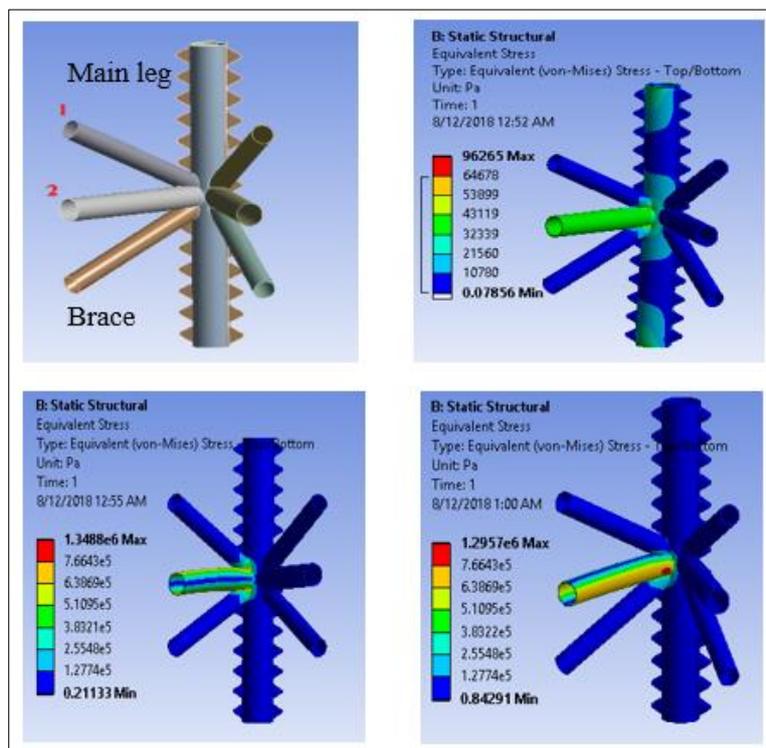

Figure 8. Model of a main joint of jack-up leg and stress distributions

According to the analyses, the maximum SCF corresponding to axial force, in-plane bending and out-plane bending are 2.55, 2.43 and 2.33, respectively.

5.4. Natural Vibrations

Natural vibrations of jack-up structures are analyzed in relation to 3 water depths in operating conditions as the procedure in figure 3. The first period of the vibrations are 9.13s, 9.32s and 10.42s. The vibration shapes are illustrated in Figures 9, 10 and 11, respectively.
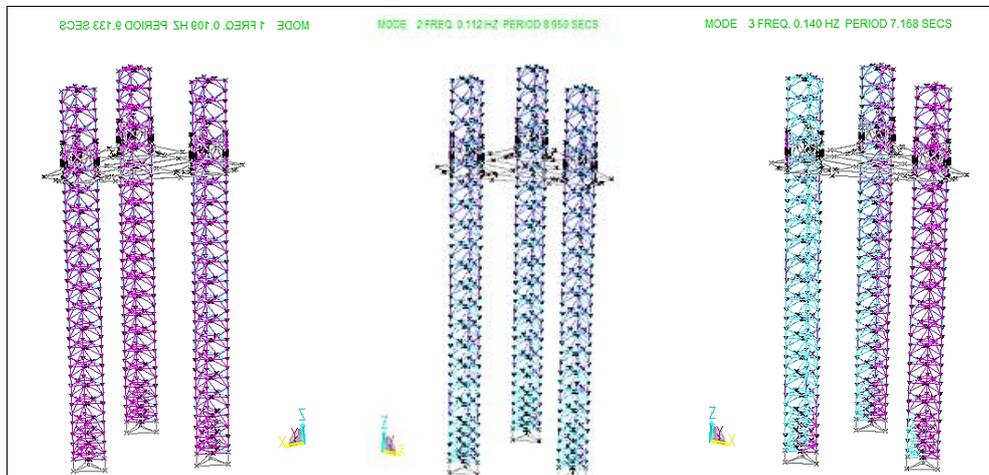

Figure 9. The first three specific vibrations when the jack-up rig operated at a depth of 100m
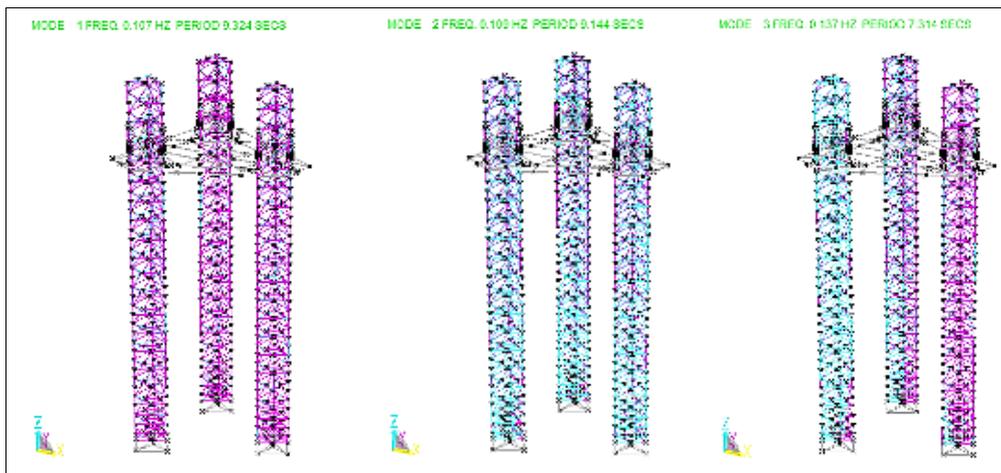

**Figure 10. The first three specific vibrations when the jack-up rig operated at a depth of 107m**
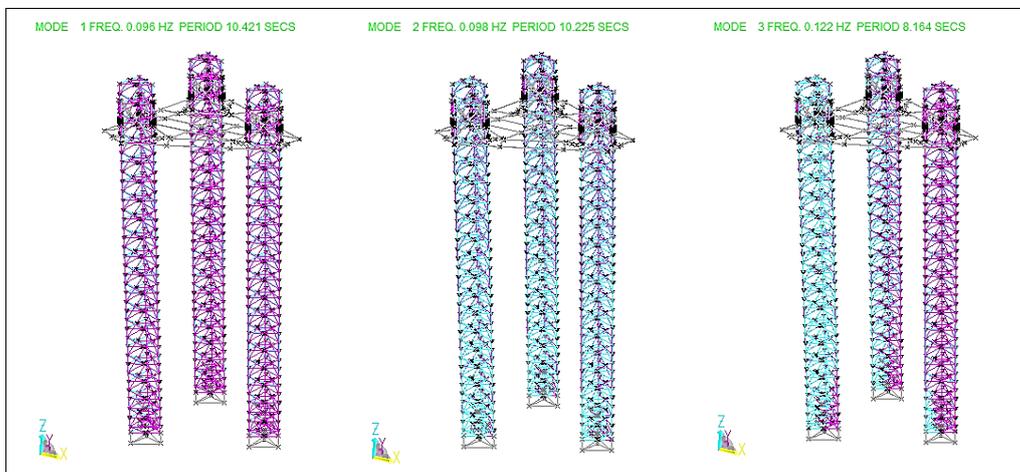
Figure 11. The first three specific vibrations when the jack-up rig operated at a depth of 122m

5.5. Motions of Jack-up in transit Conditions

Motion's RAO of the structure is determined in 8 directions corresponding to wave directions in transit conditions. The typical RAOs corresponding to 0°, 45° and 90° wave directions are expressed in Figures 12 to 14. The RAOs are used to calculate inertia forces' impact on leg structures. The forces are fatigue loading in transit conditions.
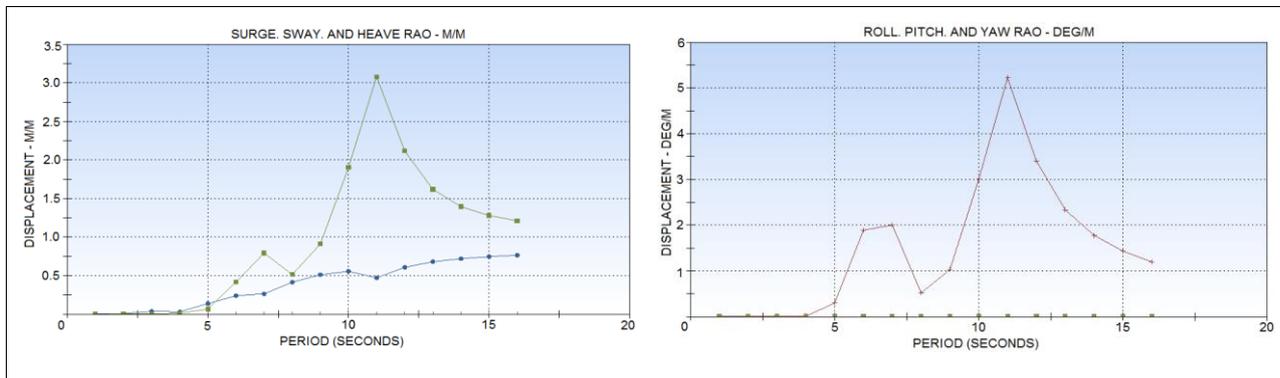

Figure 12. Motion's RAO of TD-05 Platform corresponding to 0o wave direction
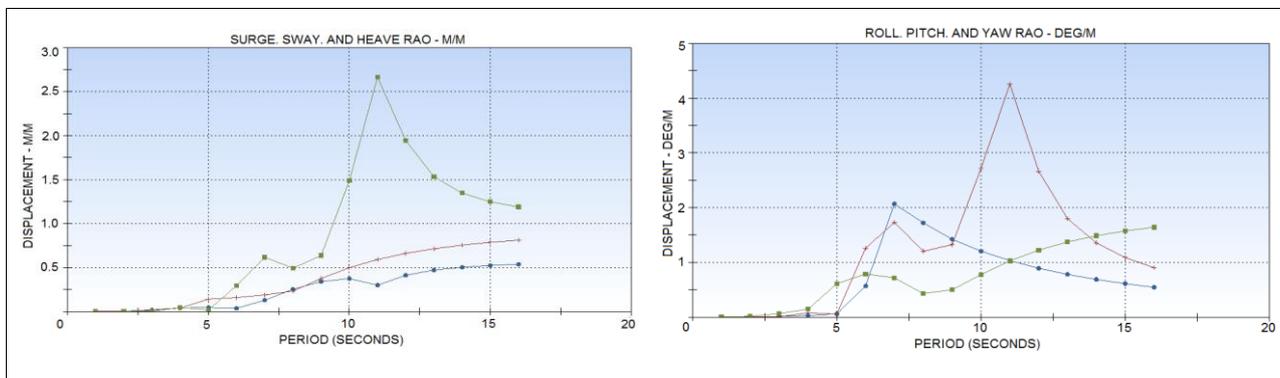
Figure 13. Motion's RAO of TD-05 Platform corresponding to 45o wave direction
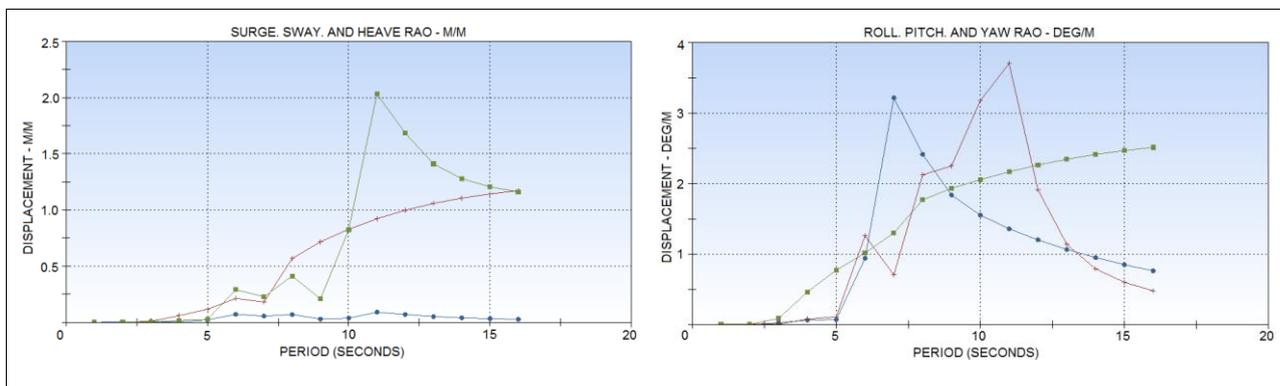
Figure 14. Motion's RAO of TD-05 Platform corresponding to 90o wave direction

5.6. Fatigue Analysis and Results

Fatigue damage of the structural hotspots is analyzed by SACS software. In operating conditions, wave data is given in section 5.1 with Pierson-Moskowitz Spectrum. Joints with the most damage are shown in Figure 15. A typical hotspot stress spectrum and maximum damage of joint 0283 of member 0275-0283 is presented in Figure 16.

In transit conditions, wave data is given in section 5.1 as above with Pierson-Moskowitz Spectrum. Joints with the most damages are shown in Figure 17. A typical hotspot stress spectrum and maximum damage of joint 1009 of member 1009-1031 is presented in Figure 18.
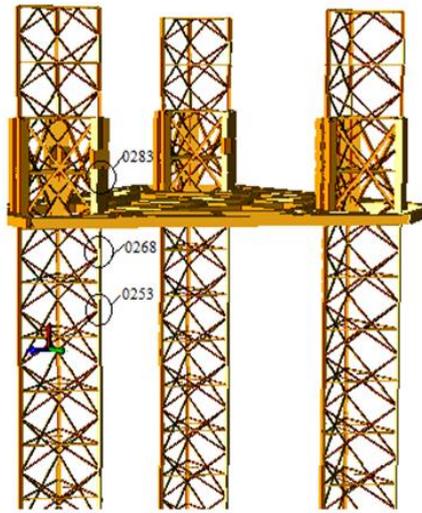
Figure 15. Location of joints with maximum fatigue damages in Operating conditions
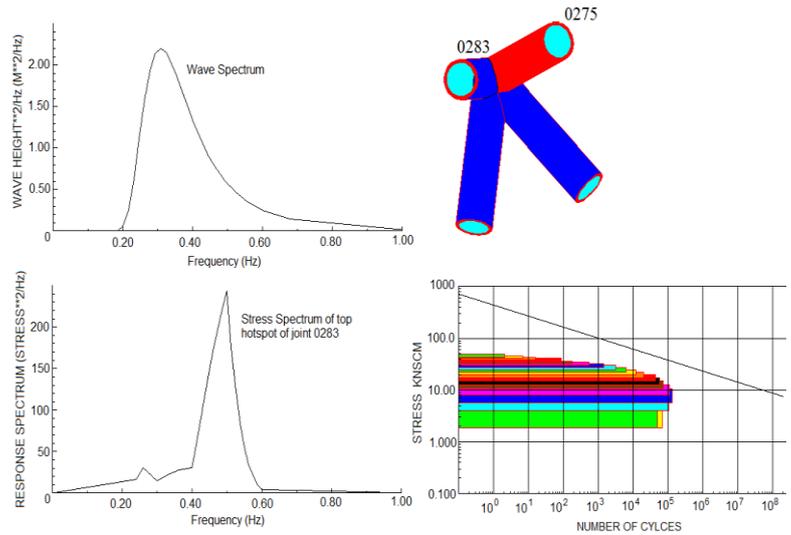
Figure 16. Fatigue damages results of typical joints in Operating conditions
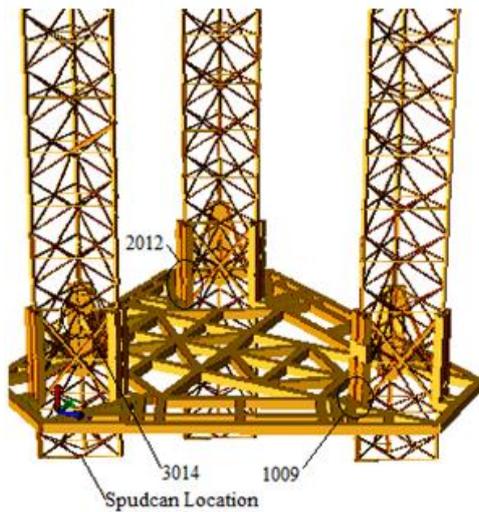
Figure 17. Location of joints with maximum fatigue damages in Transit conditions
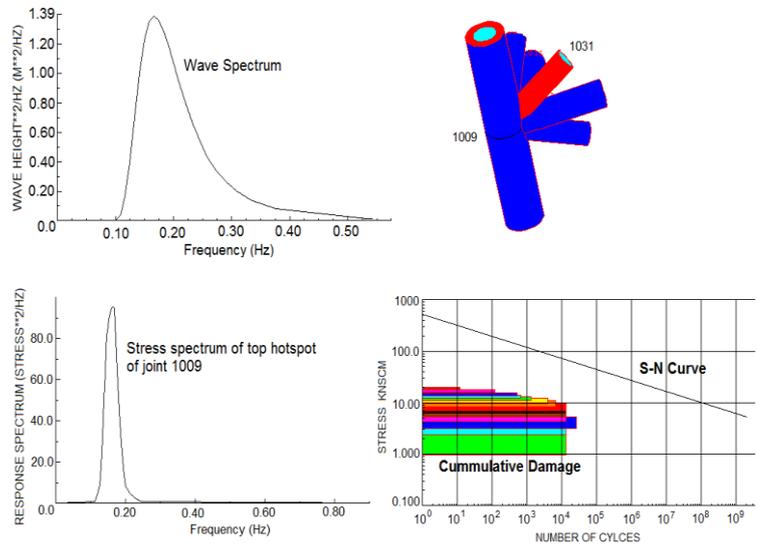
Figure 18. Fatigue damages results of typical joints in Transit conditions

Herein, we will choose 6 typical joints to analyze total fatigue life: 3 joints with maximum damage in operating condition and 3 joints with maximum damage in transit condition fatigue life. The results are listed in Tables 3 and 4 as below:

Table 3. Summary of fatigue damages of typical joints in operating condition per year

Joint	Member	Location in section	Damage (100m of W.D)	Damage (107m of W.D)	Damage (122m of W.D)
0283	0275-0283	Top point	0.031	0.032	0.051
0268	0260-0268	Top point	0.026	0.028	0.050
0253	0245-0253	Top point	0.024	0.027	0.048
1009	1009-1031	Top point	0.009	0.01	0.014
3014	3014-3025	Top point	0.0006	0.0007	0.0007
2012	2012-2026	Top point	0.001	0.0015	0.0016

Table 4. Summary of fatigue damages of the structure in transit condition per year

Joint	Member	Location in section	Damage
1009	1009-1031	Top point	0.028
3014	3014-3025	Top point	0.0266
2012	2012-2026	Top point	0.024
0283	0275-0283	Top point	Infinitive
0268	0260-0268	Top point	Infinitive
0253	0245-0253	Top point	Infinitive

5.7. Total Fatigue Life Estimation

Total fatigue lives of the above hotspots of the leg structures will be determined according to the traditional method and suggested method depending on different fraction factor scenarios in six cases as below:

Case 0: For the traditional method, the fatigue damage of a hotspot in operating conditions is determined by an average of the damage corresponding to water depths. Besides, the design life when skipping transit time is equal to 80% design life = 25×0.8 = 20 years.

Table 5. Summary of overall fatigue life of the structure according to the traditional method

Joint	Member	Location in section	Average Damage per year in Operating conditions	Total Fatigue Life	Design Life
0283	0275-0283	Top point	0.0380	26.32	20
0268	0260-0268	Top point	0.0347	28.85	20
0253	0245-0253	Top point	0.0330	30.30	20
1009	1009-1031	Top point	0.0110	90.91	20
3014	3014-3025	Top point	0.0007	1500	20
2012	2012-2026	Top point	0.0014	731.71	20

Case 1: Fractions of fatigue life in a year for operating conditions at 100, 107, 122 m of water depth and in transit condition are 0.25, 0.25, 0.3 and 0.2, respectively.

Table 6. Summary of overall fatigue life of the structure (Case 1)

Joint	Member	Location in section	Average Damage per year	Total Fatigue Life	Design Life
0283	0275-0283	Top point	0.031	32.52	25
0268	0260-0268	Top point	0.029	35.09	25
0253	0245-0253	Top point	0.027	36.83	25
1009	1009-1031	Top point	0.015	68.73	25
3014	3014-3025	Top point	0.006	168.49	25
2012	2012-2026	Top point	0.006	169.35	25

Case 2: Fractions of fatigue life in a year for operating conditions at 100, 107, 122 m of water depth and in transit condition are 0.8, 0.0, 0.0 and 0.2, respectively.

Table 7. Summary of overall fatigue life of the structure (Case 2)

Joint	Member	Location in section	Average Damage per year	Total Fatigue Life	Design Life
0283	0275-0283	Top point	0.0248	40.32	25
0268	0260-0268	Top point	0.0224	44.64	25
0253	0245-0253	Top point	0.0216	46.30	25
1009	1009-1031	Top point	0.0136	73.53	25
3014	3014-3025	Top point	0.0060	167.79	25
2012	2012-2026	Top point	0.0060	166.67	25

Case 3: Fractions of fatigue life in a year for operating conditions at 100, 107, 122 m of water depth and in transit condition are 0.0, 0.8, 0.0 and 0.2, respectively.

Table 8. Summary of total fatigue life of the structure (Case 3)

Joint	Member	Location in section	Average Damage per year	Total Fatigue Life	Design Life
0283	0275-0283	Top point	0.0256	39.06	25
0268	0260-0268	Top point	0.0208	48.08	25
0253	0245-0253	Top point	0.0192	52.08	25
1009	1009-1031	Top point	0.0128	78.13	25
3014	3014-3025	Top point	0.0059	170.07	25
2012	2012-2026	Top point	0.0056	178.57	25

Case 4: Fractions of fatigue life in a year for operating conditions at 100, 107, and 122 m of water depth and in transit condition are 0.0, 0.0, 0.8 and 0.2, respectively.

Table 9. Summary of total fatigue life of the structure (Case 4)

Joint	Member	Location in section	Average Damage per year	Total Fatigue Life	Design Life
0283	0275-0283	Top point	0.0400	25.00	25
0268	0260-0268	Top point	0.0400	25.00	25
0253	0245-0253	Top point	0.0384	26.04	25
1009	1009-1031	Top point	0.0168	59.52	25
3014	3014-3025	Top point	0.0060	167.79	25
2012	2012-2026	Top point	0.0061	164.47	25

Case 5: Fractions of fatigue life in a year for operating conditions at 100, 107, 122 m of water depth and in transit condition are 0.2, 0.2, 0.3 and 0.3, respectively.

Table 10. Summary of total fatigue life of the structure (Case 5)

Joint	Member	Location in section	Average Damage per year	Total Fatigue Life	Design Life
0283	0275-0283	Top point	0.0276	36.23	25
0268	0260-0268	Top point	0.0258	38.76	25
0253	0245-0253	Top point	0.0246	40.65	25
1009	1009-1031	Top point	0.0164	60.98	25
3014	3014-3025	Top point	0.0086	116.69	25
2012	2012-2026	Top point	0.0082	122.25	25

5.8. Discussions

Based on the analysis results, we draw diagrams to express the variation of fatigue life of joints in each case (Figure 19) and the variation of fatigue life of each joint in Case 0 (Tradition Method) and 5 cases with different fraction factors (Figure 20).

According to results in tables and Figures 19 and 20, there are some recommendations:

- There are some results that are not reasonable when analyzed by the traditional method:

  o Joints 3014 and 2012 have high fatigue life. It is caused by only considering operating conditions. Besides, these joints are located below, near the spud-cans. In fact, these joints will have significant damage in transit conditions.

  o Joints 0283, 0268, and 0253 have fatigue life which is smaller than those in comparison with reality. In fact, these joints have trivial damage in transit conditions, but they are always considered as having a certain damages 5 years when analyzed by an approximate method.

- Based on the results in case of analyzing by suggested method, there are some points that can be seen as below:

  o Fatigue damage is almost maximum at connecting joints between legs and guides.

  o Joints 0283, 0268, 0253 are almost not affected by fatigue in transit conditions. It can be explained that in these

conditions, they are on the top level of the legs, so internal forces are small. Whereas, fatigue damages of joints below such as 1009, 3014, 2012 in transit conditions are significant.

o In operating duration, jack-up platforms may be worked in some areas with different water depths, so total fatigue damage is depended on locations and percentage of exploitation at each location. The fatigue damage tends to increase accordingly with water depths.
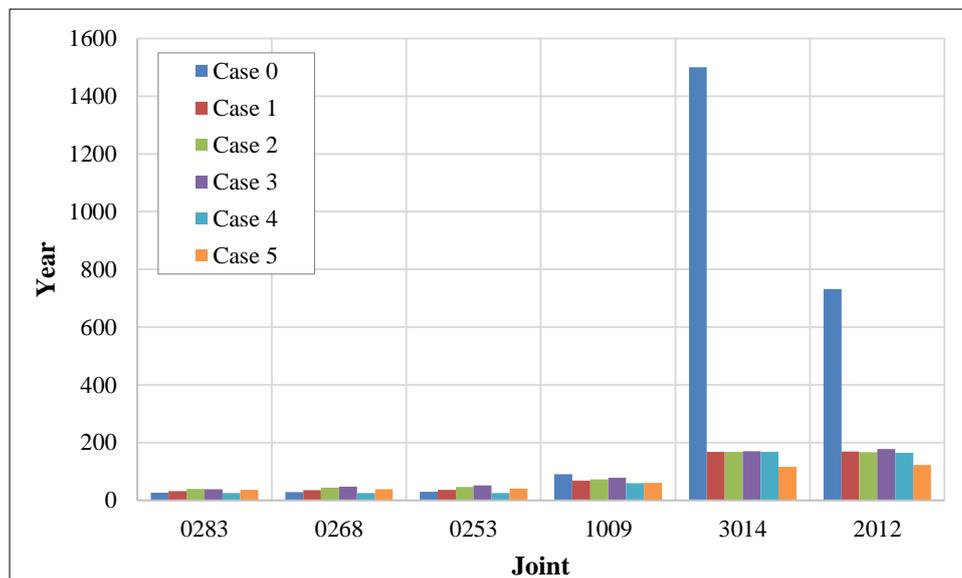

**Figure 15. Total fatigue life chart of considered joints**
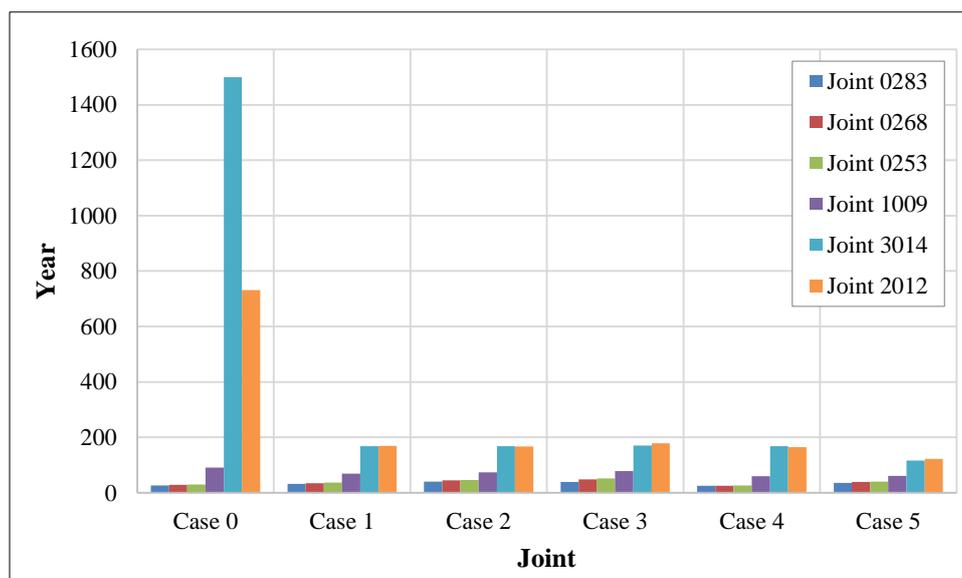
Figure 16. Total fatigue life chart of considered joints in 5 cases

6. Conclusions

• This paper has proposed a new formula (Equation 10) to determine the overall fatigue life of the jack-up leg structure in operating and transit conditions, replacing the approximate method (assuming the fatigue life is equal to 80% of design life and skipping fatigue damage in transit conditions).

• Equation 10 is built on the basis of the fatigue analysis method of the jack-up leg structure in the operating and transit conditions, as shown in two algorithms in Figures 2 and 4. These algorithms are nothing new. The algorithms will obtain the fatigue life of the jack-up leg structure in two states. The two values of the fatigue life in two states are not the overall fatigue life of the jack-up leg structure. This paper uses intermediate results, which are the fatigue damage of the jack-up leg structure in two conditions (operating and transit). When the fatigue damage is obtained, it is easy to calculate the total fatigue damage accumulation at any point on the structure of the jack-up rig legs. The overall fatigue life is the inverse of the total fatigue damage in the two conditions (operating and transit) at each survey point.

- Algorithms in Figures 2 and 4 have been established into specialized software programs. When using software programs, it is easy to determine the fatigue damage (see Tables 3 and 4). Fatigue life (Tables 6 to 10) is just the application of Equation 10 in specific conditions.

- The proposed formula for assessing the overall fatigue life of the hot spot of the jack-up leg structure was also considered under the condition that the jack-up rig operates in different water depths and each jack-up rig has different transit times. The above factors are mentioned by the coefficients: α_i is a fraction of fatigue life at i^{th} water depth condition (i=1÷n) and β is the average fraction of fatigue life of transit conditions in a year.

- The theoretical research results of this paper have solved all the limitations of the approximation method that the paper has set out.

- The research results of this paper have been applied in the design and manufacture of the jack-up rig TAMDAO 05 in Vietnam. The jack-up rig TAMDAO 05 has received the certificate of ABS registration. Currently, the jack-up rig TAMDAO 05 is operating well, which is a testament to the correctness of the research results presented in this paper.

6.1. Recommendations

- Fatigue damage of jack-up structural legs in transit conditions is significant and not the same at different locations. Besides, it is dependent on environmental conditions in the moving area, so fatigue life, taking into account fatigue damage in transit conditions by reducing 20% of design life, is only a reference value in design.

- The fatigue damage in operating conditions and transit conditions usually changes in opposite directions, along with leg structures. Therefore, it is necessary to calculate total fatigue damage at every hotspot of the structures in a total of operating and transit durations. Based on the calculation results, the hotspot with the maximum damage will be found.

- The fraction factors of different working conditions in Equations 7 to 9 have a significant influence on the total fatigue life of jack-up leg structures, so it is necessary to study their sensitivity to make the best operating plans for jack-up platforms in their life cycle next time.

- The research results in this paper will be used as a reference for engineers to design or evaluate the foot structure of jack-up rigs in Vietnam in the future.

7. Declarations

7.1. Author Contributions

Conceptualization, D.Q.C.; methodology, D.Q.C. and V.D.C.; software, V.D.C.; validation, D.Q.C. and V.D.C.; formal analysis, V.D.C.; investigation, D.Q.C. and V.D.C.; resources, D.Q.C. and V.D.C.; data curation, D.Q.C.; writing—original draft preparation, D.Q.C.; writing—review and editing, D.Q.C. and V.D.C.; 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

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Barltrop, N. D., & Adams, A. J. (1991). Dynamics of fixed marine structures (3rd Ed.). Butterworth-Heinemann, Oxford, United Kingdom.

[2] DNV-RP-C104. (2012). Self-Elevating Units. Recommended Practice. Det Norske Veritas AS, Høvik, Norway.

[3] American Bureau of Shipping (ABS). (2014). Ruled for building and classing, Mobile offshore drilling units. Rules for building and classing. American Bureau of Shipping (ABS), Houston, United States.

[4] American Bureau of Shipping (ABS). (2002). Guidance Notes on Spectra-Based Fatigue Analysis for Floating Production, Storage and Offloading (FPSO) System. Guidance notes. American Bureau of Shipping (ABS), Houston, United States.

[5] American Bureau of Shipping (ABS). (2005). Spectral-base fatigue analysis for floating offshore structures. Guidance Notes. ABS, American Bureau of Shipping, Houston, United States.

[6] Cuong, D. Q., & Chinh, V. D. (2019). Fatigue Analysis of Jack-up Leg Structures in Transit condition. CIGOS 2019, Innovation for Sustainable Infrastructure, 123–129. doi:10.1007/978-981-15-0802-8_16.

[7] Quang, C. D., & Vu, C. D. (2021). An estimation of total fatigue life of jack-up leg structures induced by wave loading. Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations, 2034–2040. doi:10.1201/9780429279119-276.

[8] Ferris, L. D. & Jackson. G. E. (2003). Review of Jack-ups: safety in transit (JSIT) technical working group. Research report 40. BMT Fluid Mechanics Limited, Teddington, United Kingdom. Available online: https://www.hse.gov.uk/research/rrpdf/rr049.pdf (accessed on January 2022).

[9] Uthamanthil, N. K., & Drake, K. R. (2021). An investigation into the influence of analysis methods upon fatigue damage predictions for jack-up rigs. Ships and Offshore Structures, 1–11. doi:10.1080/17445302.2021.1912458.

[10] Zhang, J., Yue, X., Qiu, J., Chen, L., & Shen, W. (2021). A Bracket-Stiffened Two-Planar Overlapped Tubular KT-Joint for Offshore Jack-Up Fatigue Analysis. Advances in Civil Engineering, 2021, 1–18. doi:10.1155/2021/8890075.

[11] DNV RP-C203. (2005). Fatigue Strength Analysis of Offshore Steel Structures. Recommended Practice. Det Norske Veritas AS, Høvik, Norway.

[12] API–RP-2A-WSD. (2007). API Recommended Practice 2A-WSD. Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design. American Petroleum Institute (API) Recommended Practice, American Petroleum Institute, New York, United States.

[13] Newman, J. N. (1979). The Theory of Ship Motions. Advances in Applied Mechanics 18, 221–283. doi:10.1016/s0065-2156(08)70268-0

[14] Cuong, Đ. Q., & Chinh, V. Đ. (2018). Methodology for global analysis of the Jack-up in operating, extreme, transportation and installation conditions. Report N01, a part of National Scientific Project: Design, construction, integration of 400ft jack-up platform in Vietnam's conditions and development, modification of mobile Jack- up unit for marine economic & national security. Project Code, SPQG.02b.01.

[15] Cuong, Đ. Q., & Chinh, V. Đ. (2018). Data of Numerical Model based on FEM for 400ft Jack-up platform. Report N02, a part of National Scientific Project: Design, construction, integration of 400ft jack-up platform in Vietnam's conditions and development, modification of mobile Jack- up unit for marine economic & national security. Project Code, SPQG.02b.01.

[16] Cuong, Đ. Q., & Chinh, V. Đ. (2018). Fatigue checking data of technical-structural system of 400ft Jack-up platform in Vietnamese long term sea state. Report N04, a part of National Scientific Project: Design, construction, integration of 400ft jack-up platform in Vietnam's conditions and development, modification of mobile Jack- up unit for marine economic & national security. Project Code: SPQG.02b.01.

[17] SACS 5.3. (2018). Offshore structural analysis and design software, Executive Service Pack1, Version 5.3.1.1. Bentley, Pennsylvania, United States.

[18] Ma, K. Y., Kim, J. H., Park, J. S., Lee, J. M., & Seo, J. K. (2020). A study on collision strength assessment of a jack-up rig with attendant vessel. International Journal of Naval Architecture and Ocean Engineering, 12, 241–257. doi:10.1016/j.ijnaoe.2019.10.002.

[19] Saadian, R., & Taheri, A. (2017). Fatigue damage analysis of an existing fixed offshore platform using spectral method for life extension. Journal of Marine Science and Technology, 23(4), 877–887. doi:10.1007/s00773-017-0517-z.

[20] F&G JU-2000E. (2013). Jackup drilling rig. Construction Specifications. Friede and Goldman LTD, Houston, Texas, United States.

[21] Farizhendy, M. M., Golabchi, M., & Noorzai, E. (2021). Identifying the required infrastructure to improve the jack-up maintenance process based on effective criteria in the Persian Gulf. Journal of Facilities Management, 19(2), 263–283. doi:10.1108/jfm-04-2020-0019.

[22] ANSYS. Inc. (2015). AQWA Theory Manual. Pennsylvania, United States. Availble online: https://cyberships.files.wordpress.com/2014/01/wb_aqwa.pdf (accessed on February 2022).