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◉ Technical Paper

Fatigue Analysis for Transportation of Harmony Jacket[+]

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하모니 자켓 운송을 위한 피로 해석

김대연 • 장영식 • 윤석용 • 조규남

Key Words : Fatigue(피로), Probabilistic Analysis(확률적 해석), Harmony Jacket(하모니 자켓), Sea Transportation(해상운송), Quasi-static Structural Analysis(의정적 구조해석)

초 록

지금까지 건조된 jacket 중에서 가장 큰 것으로 알려진 미국 Exxon사의 Harmony jacket이 현재 현대중공업에 의해 제작되고 있다. Harmony jacket은 제작완료 후 울산으로부터 미국 California서안의 Santa Ynez 해역으로 운송될 예정인데, 이와 같이 긴 해상운송시에 jacket과 seafastening 부재들은 피로에 의하여 상당히 손상을 입을 수 있다.

본 연구에서는 두가지의 가능한 운송항로에 대해, jacket과 tie-down 부재가 받는 피로에 의한 손상 정도를 계산하고 그 결과를 비교하였다.

몇 가지 가정하에 행하여진 해석 결과에 따르면, 피로에 의한 손상을 적게 주는 운송항로는 Hawaii를 경유하는 남쪽 항로이며, 운송 barge와 인접하는 부분, 특히 barge 양단 부근의 jacket joint들이 손상을 받기 쉽다는 것을 알 수 있다.

1. Introduction

Exxon's Harmory jacket, one of the largest in the world, is under construction at Ulsan yard of HHI. After completion, it will be loaded out onto the 853′×207′×49′ Heerema barge and transported from Ulsan in Korea to Santa Ynez, U.S.A., which will take quite a long period. During such a long transportation, the jacket and seafastenings are supposed to be considerably impaired by the fatigue.

In this work, fatigue analysis for the jacket joints and tie-downs during ocean towage are performed for two possible towing routes and the results are compared. Generally, methods for treating the fatigue problems involve various uncertainties in the specification of the stress concentration, stress-fatigue life relation, long term sea state statistics, and so on.[1] For the analysis, some assumptions are made due to the lack of data, which may have an effect on the results. And, although the flexibility of the barge is not included at this time because of the problems in computer program, the computational procedure which considers the flexibility is documented.

In spite of the assumptions and restrictions described above, the comparison of the results for two possible towing routes gives a noticeable criterion in the route selection. Since not only the current analysis technique involes considerable uncertainties but also there is no information about some neccessary data, the present results provide only qualitative estimates.

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2. Analysis Procedeure

Typical procedures for the probabilistic fatigue analysis during transportation are well described in some literatures.[2,3,4)

The computational procedure is as follows.

(1) Jacket and barge structural models are prepared and they are combined through the seafastening models.

(2) The mass properties such as C.G. and mass moment of inertia of the jacket/barge system including ballast water are calculated.

(3) The six-degree-of-freedom motion RAOs of the system are computed on a per unit amplitude wave basis for three heading angles.

(4) With the translational, angular accelerations and angular velocities at the center of gravity of the system obtained from the motion analysis, the inertia force fields acting on the members of the jacket/barge system are computed. Additional forces caused by the weight eccentricity due to the rotational motions of the system, i.e. roll and pitch, are computed.

(5) Compute the hydrodynamic pressure loads on the hull due to the combined effects of the incident wave, the diffracted wave, and the six-degree-of-freedom motions. (This step can be omitted if the barge flexibility is not included in the fatigue analysis.)

(6) The forces obtained in step 4 and 5 are used to compute stresses of the members of the jacket and tie-downs. Consequently, the nominal stress transfer functions are obtained at 8 circumferential points of each member end for three heading angles.

(7) The hot spot stress RAOs at 8 circumferential points of each member end are computed by multiplying the nominal stress RAOs by the appropriate stress concentration factors.

(8) Through the study of wave and wind data, the weather climates along the towing routes are determined.

(9) The hot spot stress spectrums at 8 circumferential points of each member end are determined from the hot spot stress RAOs and the wave spectrums relevant to the seastates.

(10) By assuming that the stress peaks follow a Rayleigh distribution, the stress range density function and the average mean period are computed for all seastates.

(11) Using the average mean period and stress range density function, the largest value of total cumulative damage ratio among the 8 points per member end is computed by summing the damage ratios at all seastates for three headings.

3. Prerequisite and Assumptions

The assumptions and limitations of this analysis are summarized in this chapter.

(1) Barge Flexibility

Recent studies show that the barge flexibility should be included in the transportation analysis for the large structure on the barge, especially when the structure overhangs the barge at one or both ends. The barge flexibility is not included at this time because of the problems in computer program, so that the barge is assumed to be infinitely rigid.

(2) Weight distribution, Draft, Trim

For motion analysis and, then, fatigue analysis during transportation, the structural weight distribution of the jacket/barge system should be known. Since the information about the ballasting plan is not available, it is assumed that the total weight of the system including ballast equals the displacement at the 762*m* draft condition and that the ballast water is appropriately distributed along the length and breadth of the barge in order not to cause the system to be trimmed or heeled in still water condition.

(3) Towing Speed

The towing speed effect is neglected in motion analysis and, consequently, in the fatigue analysis. But for the calculation of towing duration, the average towing speed is assumed to be 6.62 ***knots***.

(4) Roll Damping

Generally the joints in the jacket are more vulnerable to the forces due to the roll motion than any other mode of motion. Consequently the exact estimation of the roll motion is important in the transportation analysis. But the roll motion of the barge is typically lightly damped and exhibits nonlinear characteristics. Due to this nonlinearity, the damping coefficients in regular waves depend not only on wave amplitude but also on the wave steepness(wave height/wave length). In this analysis, it is assumed that the damping coefficients do not depend on the wave amplitudes and the wave steepness value is assumed to be 1/20.

(5) RAO-frequency number

In defining stress transfer functions, the discrete frequencies must be chosen such as to correctly represent the physical phenomena, and to enable accurate integration of the corresponding spectra over the whole frequency range. Due to the problems in using the computer-C.P.U time and disc space, 6 frequencies are selected in this analysis. These frequencies are decided in consideration of motion responses and the wave spectrums-i.e. the frequencies where the peaks of motions and wave spectrums occur and they are 0.314, 0.370, 0.698, 0.878, and 1.571 *rad/sec*.

(6) Sea State-Hs, Tm

For the determination of the average seastates during the towage, the observed significant wave heights and mean periods are used.

(7) Stress Concentration Factor

For the estimation of the fatigue at the most highly stressed points (hot spot), the adequate prediction of the stress concentration factors(*SCFs*) for all joints are needed. The *SCFs* can be computed based on the load path by assuming simple geometry at the joints and using the equations of Kuang et al or Smedley.[5,6] However, the *SCFs* of all jacket joints are assumed to be 3.0 for simplicity in this analysis.

(8) *S-N* Curve

The adopted *S-N* curve should be in agreement with the type of structural detail. Under the assumption that the welding profile is not improved for all joints, API-XI' curve is used in this analysis.[7]

(9) Quasti-static Approach

Generally the lowest natural structural vibration frequency of the system is one order of magnitude higher than those corresponds to the direct wave action, therefore, the quasi-static approach to the problem is made.

(10) Member Offset

Stress variation due to the jacket member offset is not considered.

(11) Jacket Submergence

Due to the large portions of the overhanged parts. the jacket is susceptable to be submerged and, consequently, subjected to wave slamming forces during the transportation. However, the contribution to fatigue from the wave slamming is not included in this analysis.

4. Tow Route-Environmental Conditions

The tow routes are shown in Fig. 1. Using the "Winds and Waves of the North Pacific Ocean"[8], the wave statistics along the actual navigation routes are applied to the determation of the weather climates.[9]

5. Modelling

Various models are required to carry out the fatigue analysis during transportation. In order to get the motion responses and to calculate hydrodynamic pressure loads acting on the barge hull, the hydrodyamic model of the barge is needed. And to analyze the structural responses due to the motions, the structural models of the jacket, barge and tie-downs are required.

The aggregate model of the system should reflect the primary structural properties such as torsion and bending stiffnesses, and the mass properties such as the total mass and the mass distribution.

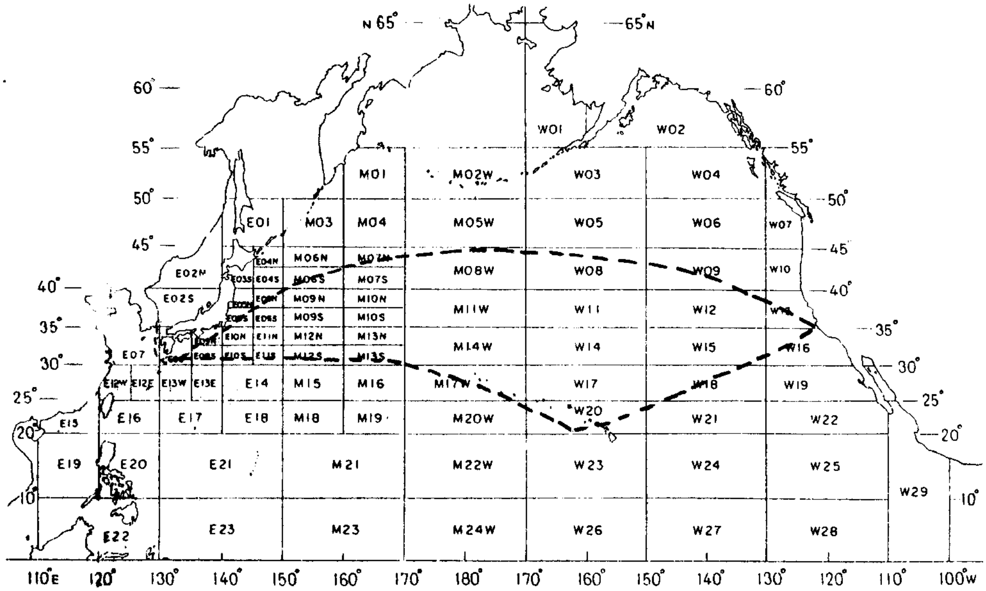

Fig. 1 Tow routes-from Ulsan to Santa Ynez and division of sea area into sub-zones

5.1 Jacket Model

Because it is assumed that the jacket experiences no submersion during the transportation, no hydrodynamic model of the jacket for the slamming analysis was prepared.

Exxon Jacket structural model consists of 1905 tublar beams and 663 joints. And total weight of the jacket is $4.05 \times 10^8 N$. Fig. 2 shows the Exxon Jacket structural mode. The mass distribution of the jacket was determined by multiplying the volume of each member by the density. In the jacket model, the weight density ($8.84 \times 10^4 N/m^3$) was chosen. which is higher than that of steel($7.60 \times 10^4 N/m^3$) in consideration of appurtenances, i.e. anodes and hydrostatic rings, which are attached to almost all jacket members and provide no structural contributions but hold significant weights. Other appurtenances effects on the system were considered by applying nodal weights or the distributed weights along some members.

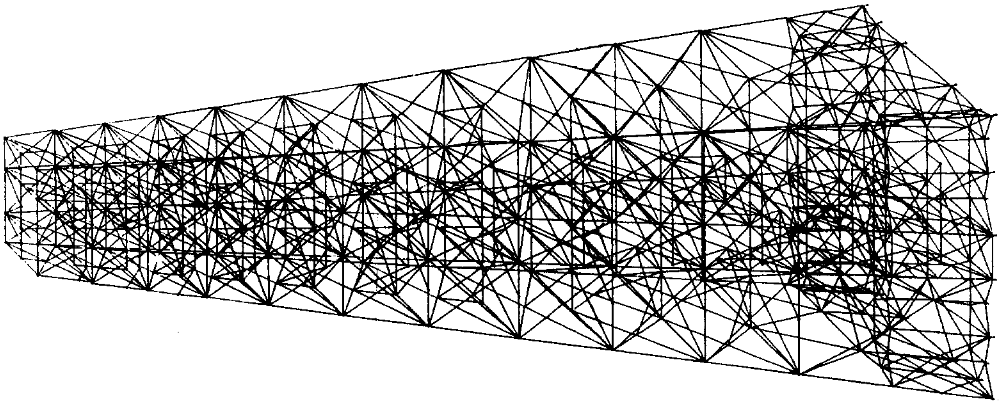

Fig. 2 Structural model of harmony jacket

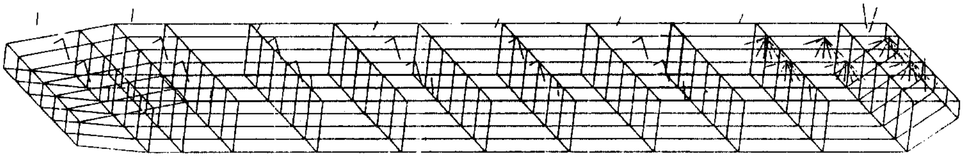

Fig. 3 Structural model of Heerema Barge and distribution of tie-downs

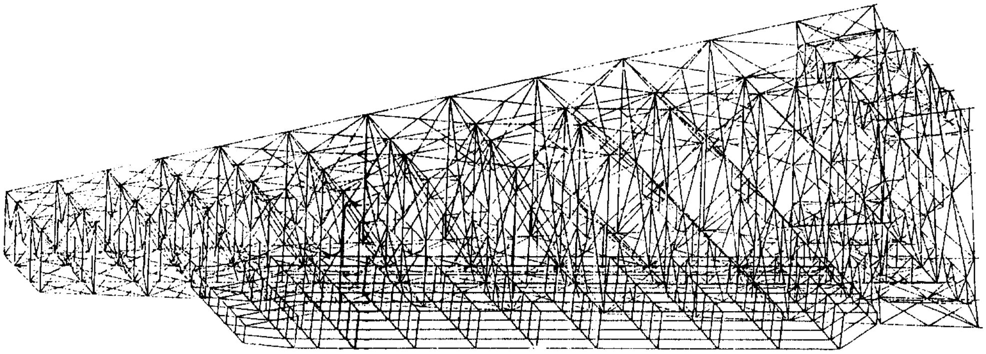

Fig. 4 Jacket/barge/seafastenings : combined medel

5.2 Barge Model

5.2.1 Hydrodynamic Model

The barge was represented by 29 contour lines which have the rectangular section profiles.

5.2.2 Structural Model

In order to take into account the barge flexibility in fatigue analyiss, the structural model of the barge should be prepared. The barge structural model consists of 300 plate elements and 182 joints. All decks, bulkheads, and side shells were modelled with plate elements. Beacause of the nature of the finite plate element, the thickness had to be modified in order to give the proper stiffness.(Otherwise, finer meshes should be used.)

Once the entire barge model was built, an iterative procedure was performed to calibrate the bending and torsional properties of the model. In order to ensure that the plate model represent the structural properties of the barge accurately.

5.3 Tie-downs, Skid-beams and Tiltbeams

There are 156 tie-downs which support jacket launch legs, and 18 on each side of the barge. Fig. 3 shows the tie-downs distribution on the barge.

In reality, the tie-down members may experience only tension force in the presence of the skid beams. To model this phenomena mathematically is difficult. And in this analysis, the tie-down members are assumed to experience both of tension and compression forces. Skid beams and tiltbeams are modelled by box section and neutral axes are located 6 feet above the barge deck. Finally, the barge plate model was combined with the jacket space frame model through the tie-downs, skid beams and tiltbeams (Fig. 4).

6. Motion Responses

In order to calculate the inertia load RAOs acting on the jacket/barge system, motion responses in unit amplitude regular waves, which are called motion RAO, were computed on the basis of the well-established strip theory. The computational procedure is outlined as follows.

First, the submerged portions of the barge are represented by two dimensional contour lines at a number of longitudinal locations. Each of the contour lines is then approximately represented by straight line segments.

Second, after computing two dimensional (2-D) hydrodynamic properties at each section, three dimensional (3-D) hydrodynamic properties-added mass, damping coefficients, hydrostatic restoring forces and wave exciting forces are computed.

Third, six-degree-of freedom system motions are computed for various wave frequencies and headings by solving the following equation of motion.

$$([M]+[A])\{\ddot{\eta}\}+[B]\{\dot{\eta}\}+[C]\{\eta\}=\{F\}e^{i\omega t}$$

where

$[M]$: the generalized 6×6 mass matrix of the jacket/barge system

$[A]$: the generalized 6×6 added mass matrix

$[B]$: the generalized 6×6 damping coefficients

$[C]$: the 6×6 hydrostatic restoring force matrix

$[F]$: the vector indicating the complex amplitude of the wave excitation forces

$[\eta]$: the vector indicating the complex amplitude of the six-degree-of freedom motions

ω : the frequency of the wave

$\cdot$: time derivative

To perform motion analysis, the mass properties of the jacket/barge system are calculated from each mass properties of the jacket and the barge. Because of the lack of data such as the ballasting plan of barge, the mass properties of the barge was calculated on the assumption that the mass of the barge including ballast water is appropriately distributed along the barge length and breadth. Although the ballasting condition of the barge may have an effect on the maximum member stresses, the fatigue damages of the jacket members are relatvely insensitive to the ballast distribution. Therefore, this assumption may not lead to significantly wrong results in fatigue analysis.¹⁰⁾

In this analysis, the towing speed was assumed to be zero because the used computer program "OTTO"11) which has the integrated functions of the motion, structural analysis and finally fatigue analysis during sea transportation, does not have the capability of considering the tow speed effect. However, because the tow speed is relatively low and unsteady generally, the speed effect may be neglected.

7. Loads Generation

7.1 Inertia Loads

7.1.1 Inertia Loads due to Rigid Motion

As previously described, the motion responses of the system to a series of unit amplitude regular waves were determined. These motions, in the form of accelerations, are in turn used to compute the inertia loads on the system. And then, the inertia loads on the system are transformed into the form of complex variables to preserve the phase relationships between the different loads acting on the system. This computational procedure applies throughout the structural analysis, so that even the stress results appear per unit wave amplitude in the form of complex variables.

If the acceleration at the center of gravity of the system are known, the accelerations of each member can be obtained as follows.

$$\vec{a}=\vec{a}_0+\vec{\omega}\times(\vec{\omega}\times\vec{r})+\vec{\alpha}\times\vec{r}$$

where

$\vec{a}$: the translational acceleration at a given field point on the structure

$\vec{a}_0$: the translational acceleration vector at the center of gravity of the jacket/barge system

$\vec{\omega}$: the angular velocity vector

$\vec{\alpha}$: the angular acceleration vector

$\vec{r}$: the position vector of the field point w.r.t. the center of gravity of the jacket/barge system

Consequently, member inertial loads are calculated by multiplying each member mass by the member acceleration. These member forces are, also, complex form.

7.1.2 Gravitational Loads due to Eccentricity

The gravitational load caused by the static weight eccentricity due to large rotational angles are dynamic ones and should be included in the structural analysis. In the local body fixed moving coordinate system, the gravitational accelerations can be computed as follows.

Gravitational acceleration component in the direction of sway $=g\cdot\sin(\phi)$

Gravitational acceleration component in the direction of surge $= g \cdot \sin(\theta)$

where

g : gravitational acceleration

ϕ : roll angle in the form of real or imaginary value

θ : pitch angle in the form of real or imaginary value

Consequently, the loads are calculated by multiplying each member mass by the acceleration. These loads are, also, in the form of complex variables.

7.2 Hydrodynamic Loads

For the same waves used in motion analysis, hydrodynamic pressure loads on the barge hull due to the combined effects of the incident waves, the diffracted waves, and the six-degree-of-freedom motions are computed as follows.

$$\{f_H\} = \{f_W\} - [a]\{\ddot{\eta}\} - [b]\{\dot{\eta}\} - [c]\{\eta\}$$

where

$\{f_H\}$: the complex $N \times 1$ nodal force vector indicating the total hydrodynamic pressure load

$\{f_W\}$: the complex $N \times 1$ nodal force vector indicating the wave exciting load

$\{\eta\}$: the complex 6×1 vector indicating the six-degree-of-freedom rigid body motions in surge, sway, heave, roll, pitch, and yaw.

$\cdot$: time derivative

$[a]$: the $N \times 6$ nodal added mass matrix

$[b]$: the $N \times 6$ nodal damping coefficient matrix

$[c]$: the $N \times 6$ nodal restoring force matrix

8. Computation of Fatigue Damage Ratio and Results

8.1. Nominal Stress Transfer Function

For the jacket/barge system in a given direction, the inertia loads acting on the system and the distribution of the pressure loads on the barge were computed for unit wave amplitudes as described in the previous sections. Notice that each of the response quantities(inertia loads and pressure loads) were represented by the complex variables. At this point, the global equilibrium of the system should be verified for each load condition. After significant unballances are deleted, the structural analysis can be performed. Furthermore, accepting the fact that the natural frequencies of the jacket are much higher than those of the dominant waves, there is little, if any, dynamic amplification effect. Therefore, the structural responses (nominal stress transfer functions) can be obtained from the quasi-static structural analysis.

The nominal stress transfer function, $Hn(\omega)$, is simply the stress amplitudes resulting from the application of unit amplitude regular waves with various frequencies to the system. Therefore,

$$|Hn(\omega)| = [(\sigma_R(\omega))^2 + (\sigma_I(\omega))^2]^{\frac{1}{2}}$$

σ_R : the real part of complex stress amplitude (axial + bending)

σ_I : the imaginary part of complex stress amplitude (axial + bending)

8.2 Stress Concentration Factor

Fatigue damage occurs predominantly at the member intersections (joints) of a structure. The nominal member stresses, which were obtained from a stress analysis of the jacket as described above, do not represent the true states of stresses at the member intersection. The true stresses (hot spot stress) are generally estimated by multiplying the nominal stress by a appropriate stress concentration factor.

There are many formulas for *SCF* calculation which were obtained by analytically or experimentally. But, the formulas are applicable to the joints with simple geometries such as T, Y, K, or TK. Therefore, for the accurate determination of *SCFs* at critical joints whose forms are complex, i.e. over lapped, multiplanar or multibranch, etc., the additional finite element analysis should be performed for each joint.

As an alternative method, the formulas for joints with simple geometries can be used for the joints under the common practice described below.[13)]

For the *SCF* estimation of the complex tubular joints, the joints are treated as consisting of a simple T and K connection components without provision for these connections to interact. And the concentration effects associated with a combined loading are accounted for by estimating and adding the peak stress contributions of the component loadings at the 8 circumferential points. Generally, this method gives quite conservative estimates.

Because there are 663 joints and 1905 members in the Exxon's Harmony jacket, it takes quite a much time to determine every *SCF* for all member ends. In this analysis, the *SCFs* at all joints and member ends are assumed to be 3 for both axial and bending stresses(DnV min. required value).

8.3 Stress Spectrum

To obtain the hot spot stress history such as the number and magnitudes of stress peaks, the hot spot stress spectrum is generated using the following relation.

$$S_\sigma(\omega)=\{SCF\cdot|Hn(\omega)|\}^2\cdot S_\xi(\omega)$$

$S_\sigma(\omega)$: the hot spot stress spectrum

$Hn(\omega)$: the nominal stress transfer function

$S_\xi(\omega)$: the wave spectrum

The hot spot stress spectrums are obtained for all seastates, in all directions of incident waves, at 8 points of all member ends of the jacket and tie-downs.

8.4 Cumulative Fatigue Damage Ratio

Once the hot spot stress spectrum is generated, the stress statistics such as the stress range density function and average mean period can be obtained. If the stress peaks follow a Rayleigh distribution, the stress range density function, $P(\sigma)$, and the average mean period, T_{av}, for a seastate are computed as follows.

$$P(\sigma_r)=\frac{2\sigma_r}{8m_0}Exp\left(\frac{-\sigma^2{}_r}{8m_0}\right)$$

$$T_{av}=2\pi\frac{m_0}{m_1}$$

where the i-th spectral moment m_i is defined as

$$m_i=\int_0^\infty \omega^i S_\sigma(\omega)d\omega$$

The fatigue damage ratio is computed using the well-known Palmgren-Miner's rule which assumes that fatigue damage accumulates linearly. With the stress range density function and the average mean period, the total cumulative damage ratios during transportation, *CDR*, at the 8 points per member end are computed by summing the damage ratios at all seastates for three headings.

$$CDR=\sum_{i=1}^{3}\sum_{j=1}^{m}\frac{T_{ij}}{Tav_{ij}}\int_0^\infty\frac{P_{ij}(\partial_r)}{N(\partial_r)}d\partial_r$$

i : the index denoting the heading

j : the index denoting the seastate

T_{ij} : the exposure time in $'i'$ th heading at $'j'$ th seastate

Tav_{ij} : the average mean period in $'i'$ th heading at $'j'$th seastate

$P_{ij}(\partial_r)$: the stress range density function in $'i'$th heading at $'j'$ th seastate

m : number of seastate

$N(\partial_r)$: number of stress range wich cause fatigue failure

There are 68 jacket members and 38 tie-downs whose fatigue damage ratios exceed 0.1 in the case of route Ⅰ and 40 jacket members and 38 tie-downs in the case of route Ⅱ.

Table 1 and 2 list the largest cumulative damage ratios among those at 8 points of the most highly

Table 1 Cumulative damage ratio-jacket members

Route Ⅰ			Route Ⅱ		
Member		Damage ratio	Member		Damage ratio
Joint	Joint		Joint	Joint	
J1161	J1133	0.44	J1161	J1133	0.33
J0322	J0332	0.38	J0322	J0332	0.28
J0332	J0322	0.35	J0332	J0322	0.25
J1165	J1137	0.32	J1165	J1137	0.23
J0410	J0457	0.30	J0325	J0339	0.20
J0411	J0457	0.29	J0410	J0457	0.20
J0325	J0338	0.29	J0411	J0457	0.20
J0338	J0325	0.28	J0338	J0365	0.19
J0462	J0442	0.27	J9462	J0442	0.18
J0464	J0444	0.26	J0464	J0444	0.18
J0362	J0316	0.25	J0310	J0350	0.16
J0562	J0542	0.25	J0362	J0316	0.16
J0564	J0544	0.25	J0562	J0542	0.16
J0310	J0350	0.24	J0564	J0544	0.16
J0311	J0350	0.23	J1265	J1242	0.16
J0364	J0360	0.23	J0311	J0350	0.15
J0364	J0314	0.23	J0362	J0360	0.15
J0362	J0360	0.22	J0364	J0360	0.15
J0711	J0766	0.22	J0364	J0314	0.15
J0710	J0768	0.21	J0710	J0768	0.14

Table 2 Cumulative damage ratio-tiedowna

Route I			Route II		
Member		Damage ratio	Member		Damage ratio
Joint	Joint		Joint	Joint	
J0303	B0142	0.59	J0303	B0142	0.46
J0302	B0142	0.51	J0302	B0142	0.40
I0302	B0132	0.50	J0302	B0132	0.39
J0303	B0142	0.49	J0303	B0142	0.37
J0303	B0252	0.48	J0303	B0252	0.36
J0302	B0132	0.45	J0302	B0132	0.33
J0303	B0252	0.45	J0302	B0232	0.33
J0302	B0142	0.44	J0303	B0252	0.33
J0302	B0332	0.43	J0302	B0142	0.32
J0303	B0262	0.43	J0303	B0152	0.32
J0302	B0222	0.42	J0303	B0262	0.31
J0303	B0151	0.42	J0302	B0222	0.30
J0303	B0151	0.42	J0303	B0152	0.30
J0302	B0232	0.41	J0302	B0232	0.29
J0303	B0242	0.41	J0303	B0242	0.29
J0302	B0242	0.39	J0302	B0242	0.28
J0403	B0232	0.36	J0402	B0342	0.28
J0302	B0242	0.36	J0403	B0342	0.28
J0302	B0242	0.36	J0302	B0242	0.27
J0403	B0342	0.33	J0302	B0242	0.26

impaired 20 jacket member ends and 20 tie-down member ends for two routes respectively.

9. Conclusions

In spite of some limitations described previously, the analysis results lead to some remarkable conclusions as follows.

(1) For two routes selected in this analysis, the jacket members can be less impaired by fatigue by adopting the transportation route as the south route via Hawaii(Route II).

(2) The results show relatively high damage ratios at the jacket member ends and tie-downs which are in the vicinity of the barge ends in the consequence of neglecting the barge flexibility.

(3) The transverse members of the jacket are more vulnerable to fatigue damage during transportation than the longitudinal members.

(4) Some jacket members are somewhat highly damaged by fatigue under the assumption made in the analysis.

(5) Tie-down members may be safe enough to withstand the fatigue under the assumption made in this analysis.

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