PART-A: Spectral Fatigue Analysis of a ship by simplifying Structural Responses

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The Spectral Fatigue Analysis (SFA) is the comprehensive fatigue life assessment method for vessels. This analysis is to be carried out for the many critical locations of the ship structure. The spectral fatigue analysis is performed through the process of hydrodynamic response analysis, global and local structural analysis, and eventually prediction of fatigue damage using the long-term distribution models. To perform these numerically intense stages, enormous amount of computational resources are required. Considering the computational efficiency, it is not worthwhile to go for such analysis for the entire ship. Therefore, individual stages can be simplified to cut down the analysis time without upsetting the physics of the problem. This type of approach by simplifying the intermediate stages can serve as some sort of preliminary level of SFA to limit the number of cases for the detailed SFA. The present paper discussed these types of simplification in SFA though application of methods using a sample ship problem.

KEY WORDS
Spectral fatigue analysis; stress transfer functions; fatigue damage; long-term stress range distribution.

INTRODUCTION

Last two decades, fatigue damage assessment for ship structure gained a lot of interest in the shipping industry and special attention has been paid towards this failure mode. Being a compulsory requirement from the ship stakeholders, many classification societies published guidelines to carry out the detailed fatigue analysis for variety of marine structures. Shipping industry developed its concern towards accepting the fatigue assessment of critical structural elements after many bulk carriers and lives has been lost (IMO 1995). Side shell cracks were observed and found responsible for these accidents. Other ship accidents were also recorded with the cracks in the hull structure within the short period of commencement in service. Fatigue was considered to be an important contributor for these structural damages. It has been recognized that even though fatigue damage does not result complete structural failure but the estimated cost of repair and consequences to marine pollution are high. Apart from past bad experience with ship structural failure and damages, there were other reasons which contributed the inclusion of fatigue assessment as new criteria to be considered in design stage. Some of these reasons are mentioned here as:

- Optimize hull structure to improve the strength-to-weight ratio by introducing new material such as aluminium and high tensile steel
- Rise in number of ageing ships with lack of maintenance
- Growing concern towards the safety of ship, human and environment.

In general, there are two approaches which are used for performing the fatigue assessment, namely S-N approach and fracture-mechanics approach. Fracture-mechanics approach may be useful in evaluating the crack growth after a crack is spotted. This approach is used in developing the plans for inspection and repair. In practice, the S-N approach is widely used for the fatigue assessment and design. Experimentally accomplished S-N curves are used for fatigue strength characterization. The S-N curve based approach consists of three methods namely Simplified fatigue method, Deterministic fatigue method and Spectral fatigue method. In simplified fatigue life assessment method, the dominant loads which determine the stress range for the structural locations are calculated by empirical formulas provided by various ship classification societies. This method involves the long-term distribution of stress ranges to be characterized by Weibull distribution. Being a simple method to apply, this does not account for the specific ship details and operating conditions. In the deterministic method, a sea state is simply characterized using a deterministic wave height and period. In contrast to spectral method, deterministic method does not consider the spectral energy corresponding to sea state. This method is applicable for special marine structures and specific operating conditions (ABS 2018).

The spectral-based method is a frequency domain assessment method which is complex and numerically intensive technique. This method relies on the assumption of linearity between wave-induced loads with respect to waves and presumes linear relationship between structural responses and the wave-induced loads. The spectral based fatigue assessments of ship predict the fatigue life; therefore this method is referred as direct method. Fatigue assessment for ship structures are typically conducted

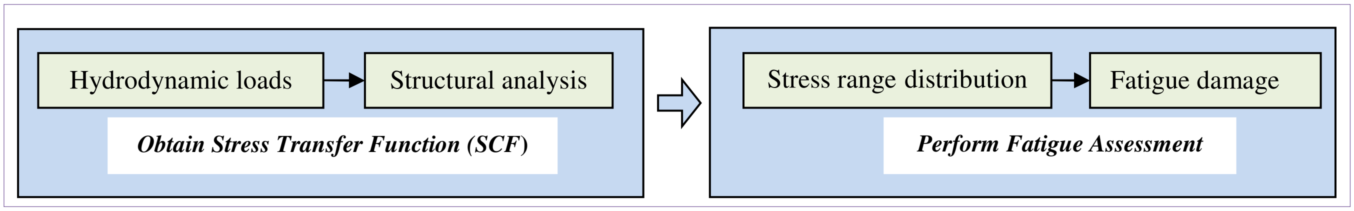

Fig.1 Schematic diagram for direct fatigue assessment

using direct calculation procedures to compute fatigue loads. On contrary to conventional-rule based design approach, the direct calculation approach includes the structural and operational details pertaining to each individual vessel. Time domain method along with rain flow counting technique can also be employed for the fatigue assessment of the structures for which the non linear responses are important and need to be considered. The applicability of time domain method is limited to specific offshore structures (ABS 2018).

In context of ship, two basic approaches have been followed for ship structural fatigue applications: rule based simplified and direct calculation approaches. DNV-GL (DNV-GL, 2015) suggested different possible fatigue analysis procedures using both approaches where intermediate results of one approach can be interchanged with other approach. Therefore, the fatigue analysis may be performed based on a combination of simplified and refined techniques such as spectral analysis. Determination of loads for the representative loading condition serves the initial step for both the approaches. Combination of stresses resulting from the action of global and local loads is to be performed according to each Society criteria and with consideration given to the probability level.

Rule based simplified approach consist of the evaluation of loads based on individual classification society's rules and Common Structural Rule (IACS 2018) defined load methodologies. However, direct calculation approach requires the numerical computation of loads based on the operational parameters and service route of the ship. Numerically evaluate stresses based on the actual ship operating conditions can also be used for the simplified approach rather than using the rule based empirical formulations. This can be achieved by evaluating Weibull parameters by fitting Weibull distribution to long-term stress range. In this manner, actual ship and operational parameters can be taken into account for classification society's simplified approach. This approach is also included in present paper to predict the damage for the sample ship in addition to SFA approach.

FATIGUE ASSESSMENT METHODS

Spectral fatigue analysis primarily consists of four different stages: Computation of hydrodynamic loads, structural analysis, long term stress distribution and damage calculation as shown in Fig. 1. The fundamental task of a spectral fatigue analysis is the determination of the stress range transfer functions or Stress Transfer Functions (STF), which express the stress response of a structural location for unit wave amplitude of specified wave frequency and heading. Once STFs are known, remaining task to perform statistical analysis can be considered post processing.

The most comprehensive method to get structural responses i.e. STF, is to perform Finite Element (FE) with the direct application of hydrodynamic loads. Where, loads are to be computed using 3D panel method. This requires enormous computation resources and time. However, authors try to simplify this step by the application of global loads calculated using 2D strip theory for FE structural application (Guedes Soares *et. el.*, 2003) or even simply using beam theory (Negi *et. el.*). Such a simplification may serve an initial level of SFA to sort out the number of critical location for full 3D hydro-structural analysis to get the STF or predict the critical locations which require immediate attention during structural survey.

In this paper work, spectral fatigue analysis of a bulk carrier has been conducted for the butt- welded plate joints at deck and side shell locations at mid-ship (0.5L). 2D strip theory and close–form semi analytical formulation for the evaluation of global loads has been used. Stress range transfer functions have been obtained in simpler manner using beam theory. However, steps and methods to perform statistical analysis based spectral fatigue assessment have been explained elaborately. Simplified method has been applied for which shape and scale parameter were obtained numerically by fitting the Weibull distribution on long-term stress range. Finally, the results were discussed with respect to the different methods used in present work and conclusions were drawn.

Table 1 Summary of the fatigue assessment approaches

Method – IDs	**Load Evaluation Method**	**Fatigue Damage Approach**
FAM-1	Semi analytical formulation	Closed form approach based on long-term response
FAM-2	2D Strip theory	Closed form approach based on long-term response
FAM-3	Semi analytical formulation	*Spectral approach Based on short term response
FAM-4	2D Strip theory	*Spectral approach Based on short term response
FAM-5	3D Panel method	*Spectral approach Based on short term response

*long term stress range distribution is defined through a short-term Rayleigh distribution within each short term sea state

Table 1 summarizes the fatigue damage prediction approaches which have been followed in the present papers (Part-A and Part-B). These approaches are the combination of the different load evaluation and damage prediction methods. Hence forth the method IDs are used when referring the various methods as mentioned in table 1.

Present paper focused on FAM-1 to FAM-4 fatigue assessment methods using beam theory based structural responses i.e. STF evaluation. FAM-5 consists of the direct application of hydrodynamic loads (Pressure and inertia) to FE model of ship and the complete description of the process has been provided in Part-B of the paper.

STRESS RANGE TRANSFER FUNCTION

The computation STF involves two steps:

- Computation of hydrodynamic loads using potential theory (2D strip or 3D panel method) based seakeeping programs or any other alternate method.
- Structural analysis to be performed to obtain STF using the hydrodynamic load application in appropriate manner.

Hydrodynamic Load

Hydrodynamic loads needs to be calculated for each representative loading condition for the ship. During voyages a vessel encounters the ocean waves from different directions and as result it undergoes through so called wave induced loads. If ship considered as flexible beam subjected to random sea environment, which bends the ship hull girder upward direction (hogging) and downward direction (sagging) depends on the position of the wave crests along the ship hull. Repetitive nature of these loads makes structure element (Plates and stiffeners) fail in fatigue mode. In case of bulk carrier the deck and side stake plates predominantly subjected to global loads under the normal operating environmental conditions. Here, following two methods has been used to obtain loads or load transfer functions.

VBM and HBM Using Strip Theory

In 2D strip theory calculations, the wave loads on a ship are found by integrating the two dimensional loads on the cross sections of an un-restrained ship over the ship length (Salvesen *et. el.* 1970). The dynamic loads (vertical and horizontal bending moments; VBM and HBM) at any section in the question is the difference between the inertia force and the sum of the external forces acting on the portion of the hull forward of that particular section at which the loads needs to be evaluated. If the external forces are separated as static restoring force/moment R_j, the exciting force/moment E_j, and hydrodynamic force/moment due to body motion D_j, we find the load eq. (1)

$$V_j = I_j - R_j - E_j - D_j \qquad (1)$$

Where, j = load index (j = 5 for VBM and 6 for HBM)

The inertia is the mass times the acceleration. Here, the inertia force is expressed in terms of the sectional inertia force. Hydrostatic moments are linear and computed by considering the actual variation of the individual sectional draft and thus accounting for the vessel motions. Since there is no resorting in horizontal plane, therefore $R_6 = 0$. For excitation forces, Froude-krylov and diffraction moments need to be evaluated. The hydrodynamic moment are caused due to the body motion. So, the D_j term in eq. (1) consists of sectional added mass and damping. All the terms of the dynamic load equation suggests that the solution for the motion of equation require beforehand. While computing dynamic loads, a critical test for consistent treatment of forces and moments is to be conducted which intended all sea loads must be equal to zero at the aft and forward of the ship. This condition needs to be satisfied through careful attention to several details such as hydrostatic balancing of forces and moments.

Semi Analytical Close-from Formulation

The most important design parameter in assessing the ship strength is the vertical bending moment. This load becomes most important at design level to estimate the section modulus of the ship. Prevailing practice to determine the wave bending moment has been remained the use of formulas issued by the classification societies. Based on the first principle and with simplifications, semi-analytical approach has been used to derive frequency response functions for the wave induced vertical bending moments for mono-hull ships (Jensen *et. el.*, 2002).

Input information require for the closed-form expression is restricted to the main dimensions: length, breadth, draught, block coefficient and water plane area together with speed and heading. The formula (eq. 2) makes it simple to obtain quick estimate of the wave-induced vertical bending and used as an alternate to numerical computation of VBM transfer function.

$$\frac{\Phi_M}{\rho g B L^2} = \kappa \frac{1-kT}{(k_e L)^2}\left[1-\cos\left(\frac{k_e L}{2}\right)-\frac{k_e L}{4}\sin\left(\frac{k_e L}{2}\right)\right] F_V(F_n) F_C(C_b) \qquad (2)$$

$$\kappa = \exp(-k_e T) \qquad k_e = | k \cos\theta |$$

Where, V is the forward speed, θ is the heading angle (180º corresponding to head sea), B and T are the breadth and drought, k is the wave number, ω is the wave frequency ($\omega^2 = kg$).

$F_C(C_b)$, $F_V(F_n)$ are the correction factors for the block coefficient ($C_b \geq 0.6$) and speed ($F_n < 0.3$) respectively. The details are provided by Jensen (Jensen *et. el.*, 2002)

Structural responses or load Response Amplitude Operators (RAOs) need to be obtained for recommended range of wave frequencies and all directional wave headings for specified average service speed. Semi analytical expression (close form) results in *VBM* load transfer functions. Whereas, other set of loads i.e. VBM and HBM loads and phases were numerically computed using strip theory.

Structural Response

Stress transfer function is found using the application of beam theory for each set of the loads obtained using the two different approaches as motioned in previous section. Vertical and Horizontal bending moment *RAO*s ($RAO_{M,V}$ *and* $RAO_{M,H}$) are converted into stress transfer function (Vertical and horizontal bending stress *RAO*) as:

$$RAO_{\sigma,h} = \frac{y}{I_{zz}} RAO_{M,H} \qquad (3)$$

$$RAO_{\sigma,v} = \frac{z - z_0}{I_{yy}} RAO_{M,V} \qquad (4)$$

Where, z is vertical distance of the structural part from the base line in meters. y is the horizontal distance of the structural part from the centre line in meters. z_0 is the distance of the neutral axis from the base line. I_{yy}, I_{xx} are midship section modulus with respect to neutral axis and the centre line axis of the vessel respectively in m^4. The combined transfer function can be derived as:

$$RAO_\sigma = \left[\left(RAO_{\sigma,v} \right)^2 + \left(RAO_{\sigma,h} \right)^2 + 2.RAO_{\sigma,v}.RAO_{\sigma,h} \cos\left(\varepsilon_v - \varepsilon_h \right) \right]^{1/2} \tag{5}$$

Where ε_v and ε_h denotes phase of the stress process due to vertical and horizontal hull girder bending respectively. Stress transfer function can be obtained

$$H_\sigma(\omega \mid \theta) = RAO_\sigma \tag{6}$$

STF calculation using semi analytical close-form load evolution approach considers the effect of vertical bending moment only.

FATIGUE DAMAGE ASSESSMENT

Operating Conditions

For fatigue damage assessment, it is require having detailed information about ship operating condition which includes:

1. Percentage time spent in each wave environment if ship is operating on specific route.
2. Fraction of time spends in each loading condition.
3. Probability of encountering for each wave heading.
4. Vessel's average speeds and time spend in each average speed when sailing in a particular sea state.

It is far more difficult to have all these details about the ship. Therefore assumptions were made at this level which may cause uncertainties in predicting the fatigue damage.

In present work, Scatter diagram for the World Wide (DNVGL, 2015) is applied for the vessel involve in worldwide trade excerpt North Atlantic voyage. Standard loading conditions for the SFA of bulk carrier are defined as homogeneous, alternate, normal ballast and heavy ballast as (IRS rules for bulk carriers and oil tankers). The fractions of time spend in each loading conditions of bulk carrier can be obtained from (IRS). Usually, an equal probability of ship heading with respect to direction of wave is considered and followed in the present paper. The vessel average speed was taken as 75% of the service speed.

Wave Environment

Ocean waves were considered to be main source of fatigue damage. The wave data usually available in the form of scatter diagram for various regions of the entire world ocean. Wave scatter diagram represents the long-term characterization of the standard environmental conditions. This contains the probability of occurrence of different sea states defined with significant wave heights (H_S) and zero crossing periods (T_Z). For each combination of H_S and T_Z, the probability of occurrence was found by dividing the observation for a sea state with total number of observations. The Pierson-Moskowitz (PM) spectrum was used to describe the short-term sea states.

$$S_\xi(\omega \mid H_s, T_z) = \frac{H_S^2}{4\pi} \left(\frac{2\pi}{T_Z} \right)^4 \omega^{-5} \exp\left(-\frac{1}{\pi} \left(\frac{2\pi}{T_z} \right)^4 \omega^{-4} \right) \tag{7}$$

Spectral Moments

The response spectrum of the ship based on the linear model is obtained directly from the wave spectrum as defined using eq. (7) and stress transfer function as obtained using eq. (6). Stress response spectrum can be obtained as

$$S_\sigma(\omega \mid H_s, T_z, \theta) = \mid H_\sigma(\omega \mid \theta) \mid^2 .S_\xi(\omega \mid H_s, T_z) \tag{8}$$

3D irregular sea way can be modeled using the spreading function. Cosine-squared spreading is assumed from +90 to –90 degrees on either side of the selected dominant wave heading. Spectral moments for each short-term sea states can be computed using following expression (eq. (9)) D

$$m_n = \int_0^\infty \int_{\theta'=\theta-90}^{\theta'=\theta+90} \left(\frac{2}{\pi} \right) \cos^2 \theta'. \left(\left(\omega - \frac{V\omega^2}{g} \cos\theta' \right)^n S_\sigma(\omega \mid H_s, T_z, \theta) \right) d\theta.d\omega \tag{9}$$

Where θ' is the spreading angle between a wave component and the dominant wave direction. From the each block of short-term description of spectral fatigue assessment, long-term stress distribution in the form of response spectrum is to be obtained. This involves certain details and calculations for number of investigated load cases in a lifetime. The following section provides the theatrical background for the same.

Short Term Response

The stress process is assumed to be stationery Gaussian and narrow banded for each short-term sea state. This assumption implies that stress ranges fit a Rayleight distribution. The probability of exceeding the stress range 'x' is given by eq. 10 (Fukuda 1967)

$$Q_S(R > x \mid \sigma_0) = \exp\left(-\frac{x^2}{2\sigma_0^2} \right) \tag{10}$$

Where, $\sigma^2 = m_0$ is the variance of the process.

Loading process in ocean environment follows wide band spectrum. A suitable wide band correction factor is required to include in the analysis to avoid conservatism due to narrow band assumption. Wrisching and Light's empirical formulation based wide band correction factor is represented by following equation

$$\lambda(m, \varepsilon) = a(m) + [1 - a(m)][1 - \varepsilon]^{b(m)} \tag{11}$$

$$a(m) = 0.926 - 0.033\, m,\ b(m) = 1.587\, m - 2.323$$

Where, ε = Spectral bandwidth

Long-Term Response

Prediction the long-term response at probability level involves summation of all of the short term responses represented by Rayleigh distributions, weighted by the frequency of occurrence of the different spectrum shapes, ship headings, and significant wave heights. Thus the probability of exceeding an stress range x in a long-term is given by eq. 13 (Fukuda 1967)

$$Q_L(R > x) = \int_0^\infty Q_S(R > x \mid \sigma) f(\sigma) d\sigma \tag{12}$$

Where, Q_S is the short term Rayleight distribution given by above eq. 12. The probability density function of peak values of response for a ship lifetime, $f(\sigma)$ can be presented as a weighted sum of the various short-term probability density functions for a given sea state, loading condition, headings and speed.

S-N Curve Fatigue Damage Approaches

This section discussed the S-N curve approaches used for the fatigue damage assessment. S-N curve gives a relationship between the applied stress amplitude (S) and number of cycle (N) to failure at that stress amplitude. In general, it illustrates the material or structural element capacity to fatigue failure at constant stress range. In practice, Palmgren-Miner summation rule which is based on the assumption that the total damage accumulated by a structural element is obtained by the linear summation of the damage in each stress block.

$$D = \frac{n_i}{N_i} \quad (13)$$

Where, n_i is the number of cycles of constant amplitude stress ranges, N_i is the total number of cycles to failure under a constant amplitude stress range.

Fatigue stress range for each load case is to be obtained and corrected for mean stress effect, thickness effect and material factor (IRS, 2016). Stress range corresponding to 10^{-2} probability level has been considered for the mean stress factor calculation. A factor of 0.85 is considered to account for the exclusion of harbor operations.

The nominal stress approach was used to determine the fatigue damage of all transverse butt-welded joints. The S-N curve 'FAT80' was selected for the assessment, which considers an axial misalignment of 10% in plate thicknesses (IACS 1999)

Closed Form approach based on long-term response

Classification society's rules for fatigue assessment are normally based on long term stress range approximated using a two parameter Weibull distribution. In present study, the Weibull shape (ξ) and scale parameters (k) were evaluated for the butt welded joint location.

$$P(x) = 1 - e^{-(x/k)^{\xi}} \quad (14)$$

The least square method was used for fitting of the Weibull distribution to the sum of Rayleigh distributions for a number of probability levels of exceedance. As a result, shape and scale parameters can be determined straight forward for each structural location. Fatigue damage can be estimated using the close form approached based on classification society rules. But, instead using classification rules to find shape and scale parameters, above fitting technique is used.

Spectral Approach Based on Short Term Response

Equation for the fatigue damage in specific sea state the stress range is normally expressed in terms of probability density functions for different short-term intervals corresponding to the individual cells of the wave scatter diagram. Linear addition of short term damages sustained over all the sea states gives the total damage for the structure element. Total fatigue damage accumulated over operational service life (T_D = 25 years) can be estimated by accounting for all sea states encountered with the different wave directions and represented loading conditions.

Total Fatigue Damage

Total fatigue damage is taken as a sum of damage occurred in a particular loading condition times the fraction of time spent in each of the loading conditions. Let us assume that D1, D2, D3 and D4 are the damages occurred in homogeneous, alternate, normal ballast and heavy ballast loading condition respectively. Therefore, combined fatigue damage is represented by eq. 16 for the case of bulk carrier having length more than 200 m. (IRS, 2016).

$$D = 0.25 D_1 + 0.25 D_2 + 0.2 D_3 + 0.3 D_4 \quad (15)$$

NUMERICAL COMPUTATION

Table 2 Ship particulars

Ship type	Bulk carrier
Length overall [m], L_{oa}	287.50
LBP [m], L_{BP}	279.00
Breadth (moulded) [m], B	45.00
Depth (moulded) [m], D	24.10
Design Draught [m], T	16.50
Scantling Draught [m], T_{sc}	17.60
Max Service speed [knots], V_s	14.60

In present study, fatigue damage assessment of transverse butt-welded plates in the two deck locations (DK1 and DK2) and side shell (SS1) structure of a bulk carrier have been carried out. Ship particulars are shown in Table -2. Four representative loading conditions and respective fraction of time spent in each loading conditions are shown in table 3.

Table 3 Ship particulars

Loading conditions	**Fraction of time**
Homogeneous	0.25
Alternate	0.25
Normal ballast	0.20
Heavy ballast	0.30

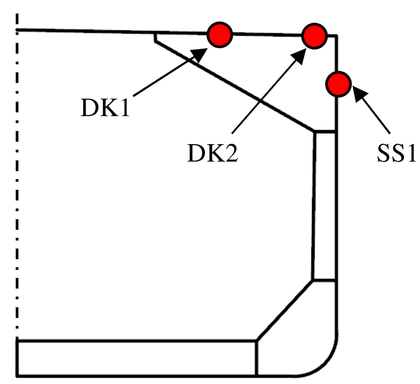

Fig. 2 Representative midship section showing the butt-welded plate joints with ids (DK1, DK2 and SS1)

Fig. 2 shows the representative midship section indicating the butt welded joint locations. Load transfer functions for the midship section was computed using strip theory (*VBM* and *HBM* amplitudes and phases) and semi analytical *VBM* formulation. Seakeeping analysis using 2D strip theory requires three main inputs namely geometry in 2D sectional format, mass distribution along the ship hull along with parameters related to loading condition and wave definition. The load transfer function is calculated for the following set of parameters:

- Frequency: λ/L = 0.2 ~ 5.0
- Wave headings: 0~330 (step of 30 deg.)
- Speed profile (75% of the service speed)

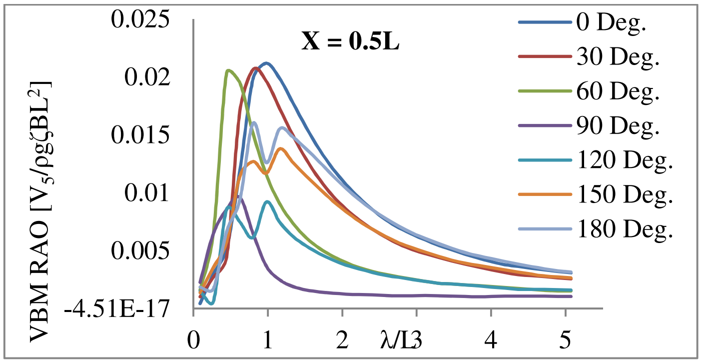

Fig. 3(a) VBM RAO (2D Strip theory) for Alternate loading

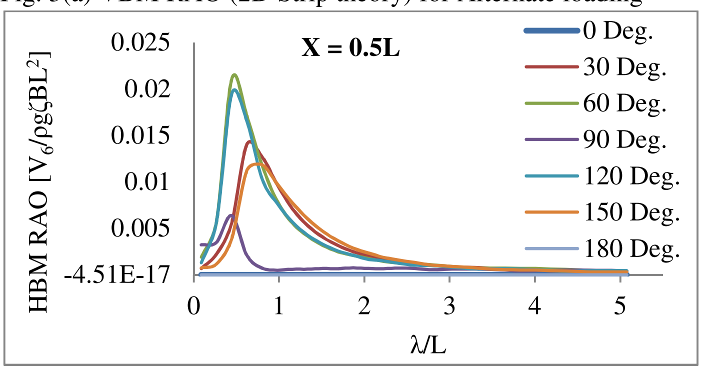

Fig. 3(b) HBM RAO (2D Strip theory) for Alternate loading

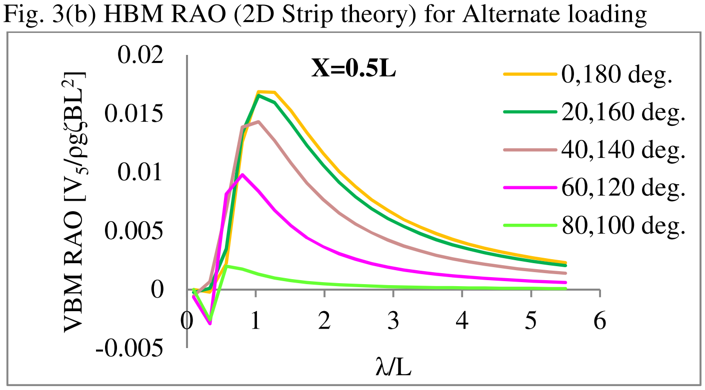

Fig. 4 VBM RAO (Semi analytical) for Alternate loading

Fig. 3(a) and 3(b) shows the *VBM* and *HBM* loads transfer function obtained for Alternate loading condition of the ship. Non-dimensional load RAOs has been plotted against the wave length to ship length ratio. It has been observed that for this loading condition, following sea (0 deg.) contributed to the maximum value of load RAO. Stern quartering seas (30 and 60 deg.) provide the larger values of RAO then the head sea. The *HBM* for the head (180 deg.) and following sea are almost zero. For the wave heading 60 deg. and 120 deg. ship experiences the higher values of *HBM* than the other headings. In same manner, load RAOs have been computed for remaining three loading conditions.

Fig. 4 shows the vertical bending moment RAO obtained for the alternate loading condition using close-form semi analytical method. This *VBM* formulation suffers the limitation due to assumption of ship's aft and forward symmetry. Therefore, it predicts the same value for a pair of equivalent headings when wave encounters from stern and head directions.

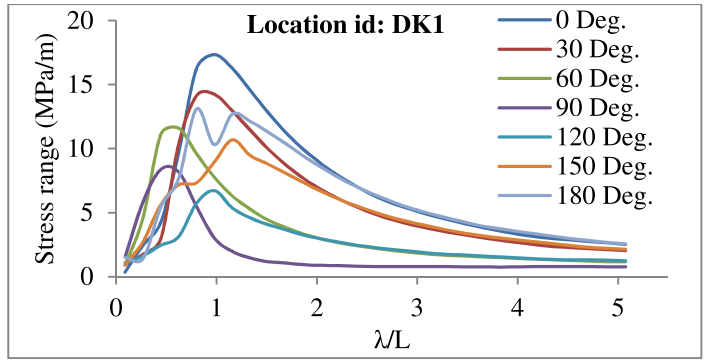

Fig. 5(a) STFs for location DK1

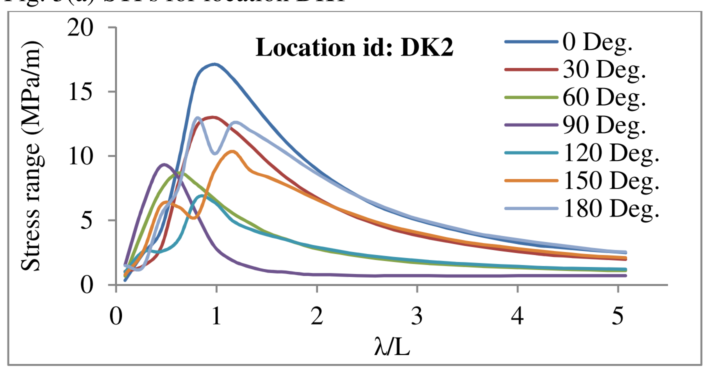

Fig. 5(b) STFs for location DK2

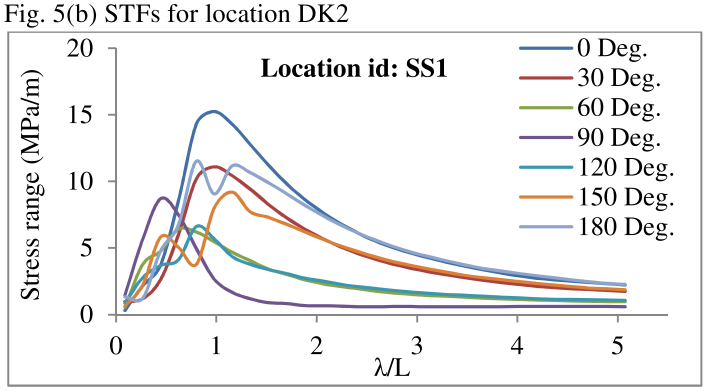

Fig. 5(c) STFs for location SS1

Sectional properties determined for the plane of butt-welded joints. Beam theory has been applied to obtain the STFs for the three specified butt-welded locations using eq. 3 and eq. 4. Figs. 5(a), 5(b), 5(c) show the STF for the all the three midship locations based on the strip theory load transfer functions for various headings. The stress transfer functions have been calculated for each load components. The structural responses have been combined using the respective phases (eq. 5). All location experienced max. stress range transfer function for the following sea condition (0^0 wave heading). Location SS3 experienced overall lesser values of stress transfer function compare to locations, DK1 and DK2. In same fashion, the STFs have been calculated using the VBM load transfer function obtained using close-form formula.

Spectral analysis was performed for the each sea states encountered by the ship described by the World wide scatter diagram (DNVGL, 2015). Two approaches close form based on Weibull long term stress distribution fitting over the long-term stress range and spectral based on short term Rayleigh distribution for each short term sea states has been followed for the fatigue damage assessment. The complete description of these two fatigue assessment methods have been already discussed in the paper. However, the two load evaluation methods were used in combination of these two fatigue assessment approaches. Refer Table 1 for the complete summary of the different fatigue assessment approaches used in this paper except FAM-5.

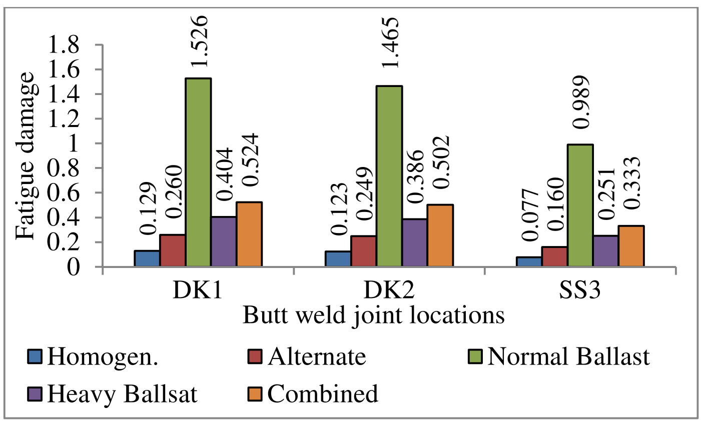

Fig. 6(a) Fatigue damage using FAM-1

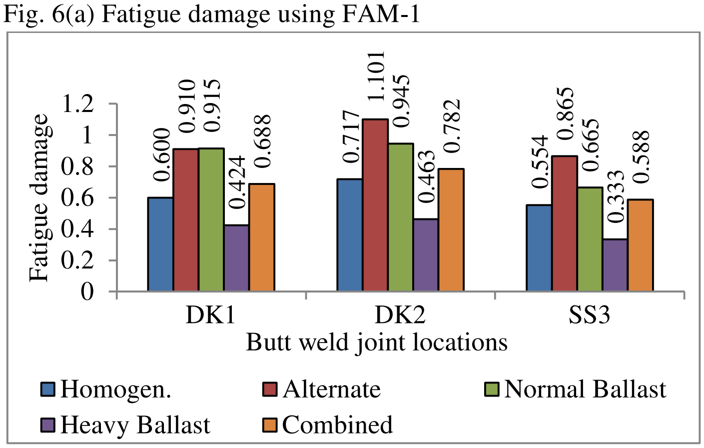

Fig. 6(b) Fatigue damage using FAM-2

For each individual methods and structural locations, fatigue damage is shown using Fig. 6(a) ~ 6(d). Fatigue damage is shown for all four loading conditions of the ship including the combined one (refer eq. 15) for the same location. A large scatter in fatigue damage values can be noticed for all the loading conditions which are quite obvious primarily due to different hydrodynamic loads and mean stress effect consideration. FAM-1 and FAM-3 (Fig. 6(a) and 6(c)) predict the maximum fatigue damage for normal ballast loading condition as compare to other load cases. This is mainly due to larger VBM load transfer function values obtained using semi analytical formulation. These results the large value of stress transfer functions for normal ballast condition and therefore predicted damage is higher.

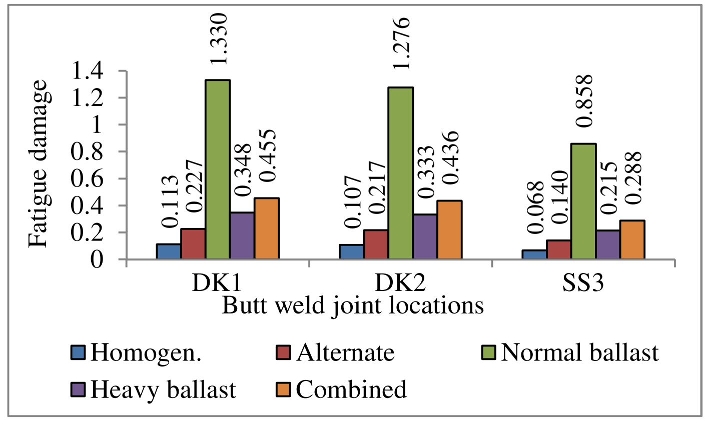

Fig. 6(c) Fatigue damage using FAM-3

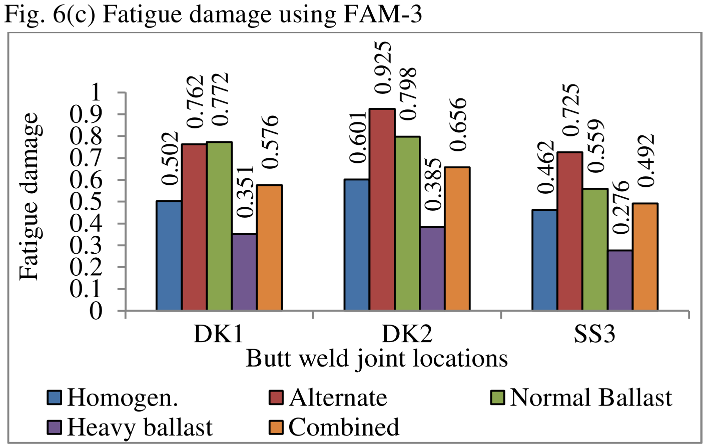

Fig. 6(d) Fatigue damage using FAM-4

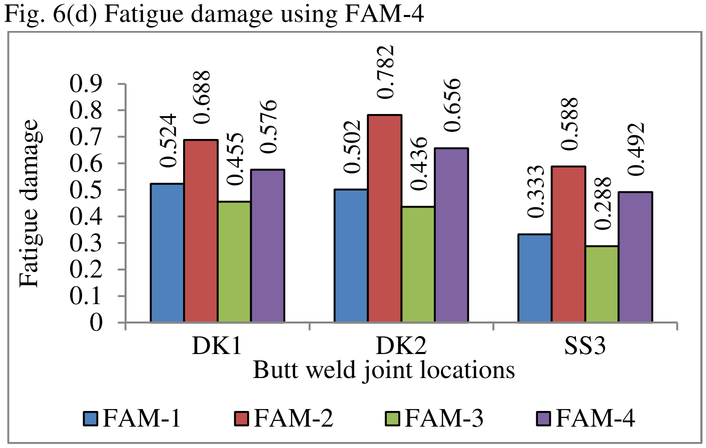

Fig. 7 Combined fatigue damage using different methods

Despite scattering of damage values for each individual loading condition, the final combined damage values are comparable at some level, refer to Fig. 7. In general, the closed form approach produces the larger fatigue damage than the spectral approach when comparing the load evaluation method-wise (FAM-1 and FAM-3) and (FAM-2 and FAM-4). For FAM-2 and FAM-4 strip theory was used for the estimation of loads. Therefore, influence of the *HBM* can be seen for the location DK2 where the fatigue damage is more than for location DK1 and SS1 using combined stress range due to *VBM* and *HBM*. This sort of effect is completely missing across all the results (FAM-1 and FAM-3) which used close-form semi analytical formulation to consider the load effect due to *VBM* only.

CONCLUSION

In this paper, the fatigue analysis of butt-welded joints in the deck and side shell of a bulk carrier has been carried out using four different method of the fatigue assessment. These methods comprised the combination of two different loads evaluation methods and two different fatigue assessment approaches. Actual ship operational and environmental details have been considered to predict fatigue damage using both the fatigue assessment methods. However, spectral based fatigue assessment approach the simplifications were made in obtaining the structural responses.

All methods were demonstrated using a sample ship problem. The fatigue damage was obtained for the three different butt-welded location of a bulk carrier. For fatigue analysis using direct methods, evaluation of STF is one of the elementary requirements. STFs have been obtained for three different locations of the ship using beam theory. All in all, the structural responses have been obtained in simplistic manner.

Due to its massive structural size, performing direct FE based structural analysis for each structure element is time consuming process. However, entire ship structural elements can be analyzed for the fatigue failure using the methodologies explained in this paper which may provide an initial level of investigation for the fatigue failure. The outcome of this initial fatigue assessment can drastically reduced the number of critical locations to perform a comprehensive structural analysis such as using FE methods. Fatigue predictions based on FE methods cannot be ignored for the more realistic results and has been discussed in our paper part-B.

The fatigue assessment for the three butt-welded joints of bulk carrier shows that

- Large variation of fatigue damage for individual loading condition is pertaining to the differences in the load response transfer function level and determination of mean stress effect.
- For the common load evaluation method, closed form approach based on long-term response predicts higher fatigue damage than spectral approach based on short term response for all the three butt plate joints.
- Notable influence on combined fatigue damage can be observe using *HBM*.
- Though in some of the loading the fatigue damage is more than 1.0, but the combined fatigue damage compensated due to fraction of time spent by ship in each loading conditions.

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