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Research Article

Study on Spectral Fatigue Assessment of Trimaran Structure

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Abstract: This study presents fatigue strength assessment of the trimaran platform by the spectral approach. Spectral fatigue calculations are based on complex stress transfer functions established through direct wave load analysis combined with stress response analysis. In this study, ANSYS software with 3 dimensional linear sea-keeping code AQWA is used to compute frequency response functions of the vessel at zero forward speed. Finite element analysis of global trimaran structure is performed in ANSYS software utilizing hydrodynamic wave loads. Hot spot stress approach is used to compute stress transfer functions of the selected critical details. A MATLAB program, based on direct calculation procedure of spectral fatigue is developed to calculate total fatigue damage using wave scatter data of North Atlantic. Damage incurred during individual heading direction is also calculated and presented by means of polar diagrams to study its contribution towards cumulative fatigue damage.

Keywords: Finite element, hot spot, spectral fatigue, stress response, trimaran

INTRODUCTION

Trimaran platform design has gained enormous attention in recent years owing to its superior seagoing performance. The trimaran offers significant advantages in terms of low resistance at high speed, excellent sea-keeping characteristics, massive deck space and stealth (Blanchard and Ge, 2007). Due to its unique configuration and high operating speed, trimaran experiences severe structural loads, which include splitting moment, wet deck slamming and stress concentration in the cross deck region. These loads accelerate fatigue damage; hence, evaluation of fatigue strength is vital for trimaran design.

The research work focusing on sea keeping aspects of the novel trimaran platform emerged after launching of RV Triton in 2000, being the world's largest trimaran of that time (Pei-Yong *et al*., 2002; Varyanik *et al*., 2002; Xiao-Ping *et al*., 2005; Fang and Too, 2006; Fang and Chen, 2008; Kang *et al*., 2008). However, very little material is available on fatigue strength assessment of trimaran structure (Chun-Bo *et al*., 2012). The fatigue strength of a ship structure is generally assessed either by simplified method or spectral based Method (Bai, 2003). These techniques are categorized based on the method used for determination of stress distribution. In simplified method, long-term stress distribution in structure is specified by Weibull probability distribution, whereas, short term stress range distribution in spectral method is defined by Rayleigh probability density functions for each short term sea state. Application of simplified method for trimaran is complex, since guidelines of the classification societies for fatigue loads, load cases and loading conditions are not available. Moreover, excessive sensitivity of the estimated fatigue damage to the Weibull shape parameters and selection of basic design SN curve confine the use of simplified approach to novel ship structures.

Spectral fatigue analysis is a direct calculation method based on linear theory in the frequency domain of a stationary and ergodic but not necessarily narrow banded Gaussian random process with zero mean (Kukkanen and Mikkola, 2004). Spectral method is considered as the most reliable method for fatigue life estimation of ship structure due to its ability to cater different sea states as well as their probabilities of occurrence. This research is focused on fatigue strength assessment of trimaran by spectral method.

In this study, frequency response functions representing the ship response to a sinusoidal wave with unit amplitude for different frequencies and wave headings are computed using linear sea keeping code ANSYS AQWA utilizing 3-dimensional potential flow based diffraction-radiation theory. Considering hot spot stress approach, stress transfer functions are calculated by global FE analysis of the trimaran. Finally direct calculation procedure of spectral based fatigue is employed to estimate cumulative fatigue damage of the hot spots. The study also investigates the effect of Wirsching's rain flow cycle correction factor and contribution of fatigue damage caused by individual

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heading direction towards cumulative fatigue damage of the hot spots.

LITRETURE REVIEW

Spectral-based fatigue analysis is a complex and numerically intensive technique. Theoretical background and method of spectral fatigue are presented in detail in numerous publications (Wirsching and Chen *et al*., 1988; Sarkani, 1990; Pittaluga *et al*., 1991; Wang, 2010). In spectral approach, wave loads in regular waves or Response Amplitude Operators (RAOs) and corresponding wave induced stresses in ship structural components are computed for a specific range of frequencies and headings to obtain stress transfer functions at the hot spots. Each transfer function is valid for a specified ship velocity, wave heading angle and loading condition.

Wave data in terms of a wave scatter diagram and a wave energy spectrum are incorporated to generate stress-range response spectra, which is used to define the magnitude and frequency of occurrence of local stress ranges at hot spots in a probabilistic manner. Fatigue damage from individual sea state is calculated using Rayleigh's probability density function describing the short-term stress range distribution, spectral moments of various orders, S-N curve of the structural detail and zero crossing frequency of the response. Based on Palmgren-Miner linear damage accumulation hypothesis with occurrence probabilities of the different operational and environmental conditions, total or cumulative fatigue damage is determined by combining the short-term damages over all the applicable sea states (Siddiqui and Ahmad, 2001). The analysis procedure of spectral based fatigue is shown in Fig. 1.

Mathematically, spectral-based fatigue analysis begins after the determination of the stress transfer function. Wave energy distribution S_η in short term sea state over various frequencies, is modeled by parametric Pierson-Moskowitzwave energy spectrum (DNV, 2010) and expressed as:

$$S_\eta(\omega|H_s,T_z) = \frac{H_S^2}{4\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-5}\, exp\left(-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-4}\right) \quad (1)$$

where,
H_s : Significant wave height
T_z : Zero crossing period
ω : Wave frequency

Stress energy spectrum S_σ is obtained by scaling Pierson-Moskowitz wave energy spectrum in the following manner:

$$S_\sigma(\omega|H_s,T_z,\theta) = |H_\sigma(\omega|\theta)|^2 \,.\, S_\eta(\omega|H_s,T_z) \quad (2)$$

where,
$H_\sigma(\omega/\theta)$: The stress transfer function
θ : The heading angle

The n^{th} spectral moment m_n of the stress response process for a given heading is calculated as follows:

$$m_n = \int_w \omega^n \,.S_\sigma(\omega|H_s,T_z,\theta)\, d\omega \quad (3)$$

Effect of directional spreading can be included in spectral moment calculation using cosine squared approach $(2/\pi)\cos^2\theta$ to model confused short crested sea conditions. Spreading limitation of the cosine squared function is generally assumed from +90 to -90°C on either side of the selected wave heading. Revised spectral moment formulation after inclusion of wave spreading function is as follows:

$$m_n = \int_w \omega^n \sum_{\theta'=\theta-90}^{\theta'=\theta+90}\left(\frac{2}{\pi}\right)\cos^2\theta'.\ S_\sigma(\omega|H_s,T_z,\theta)\, d\omega \quad (4)$$

Assuming the short-term stress response to be narrow-banded, then stress ranges follow the Rayleigh probability distribution (ABS, 2004). Using spectral moments of various orders, Rayleigh probability density function *g(s)* describing the short term stress-range distribution and zero up-crossing frequency of the stress response f and the bandwidth parameter ε of Wirsching's rain flow correction are calculated as follows:

$$g(s) = \frac{s}{4m_0}\, exp\left(-\frac{s^2}{8m_0}\right) \quad (5)$$

$$f = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}} \quad (6)$$

$$\varepsilon_i = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \quad (7)$$

where,
s : Stress range
m_0, m_2, m_4 : Spectral moments

Using SN curve of the form $N = AS^m$, the short term fatigue damage D_{ij} incurred in the ith sea-state is given by the relation:

$$D_i = \left(\frac{T}{A}\right)\int_0^\infty s^m f_{0i} p_i g_i(s)\, ds \quad (8)$$

where,
f_{0ij} : Zero-up crossing frequency of stress response in Hz
T : Design life in sec
m & A : Constants of SN curve
p_i : The probability of occurrence of individual sea state

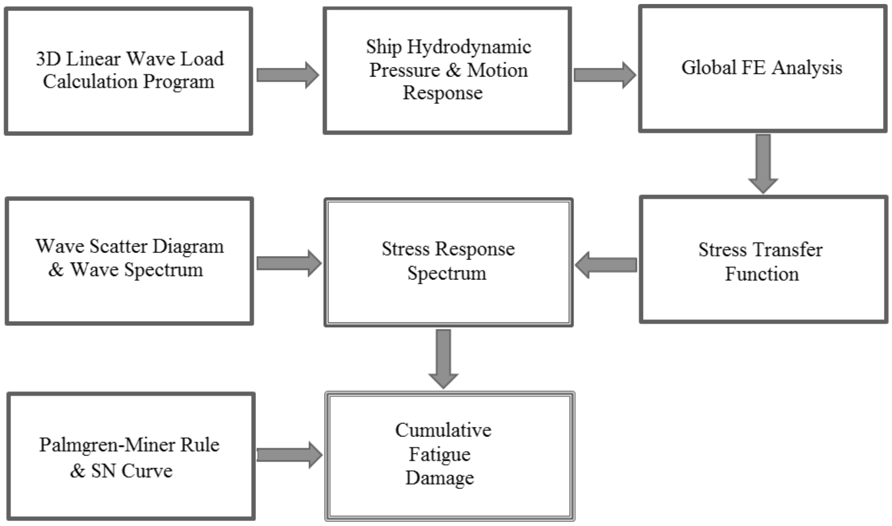

Fig. 1: Spectral based fatigue analysis flowchart

Table 1: Main characteristics of trimaran platform

Parameters	Main hull	Side hull
Length (m)	154.6	41.16
Draught at mid ship (m)	5.330	2.940
Breadth at waterline (m)	10.15	1.760
Moulded depth (m)	14.94	12.50
Displacement (m^3)	3491	68
Cross deck Height (m)	2	
Dead weight (tons)	3627	

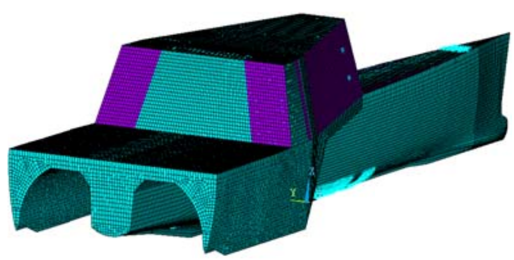

Fig. 2: Global FE model of trimran

Substituting the value of *g(s)* from Eq. (5) and after mathematical manipulations, above equation takes the form as:

$$D_i = \left(\frac{T}{A}\right)\left(2\sqrt{2m_{0i}}\right)^m \Gamma\left(1+\frac{m}{2}\right) p_i f_{0i} \quad (9)$$

where, Γ represents gamma function. Based on Palmgren Miner rule, the total or cumulative fatigue damage D is calculated by the linear summation of the damage in individual sea state and is expressed as:

$$D = \frac{T}{A}\,\Gamma\left(1+\frac{m}{2}\right)$$

$$\sum_{n=1}^{N_{Load}} p_n \cdot \sum_{i=1}^{n_s}\sum_{j=1}^{n_h} p_i\, p_j f_{ijn}\left(2\sqrt{2m_{0ijn}}\right)^m \quad (10)$$

where,

N_{load} : Total number of loading conditions considered
p_n : Fraction of design life in loading condition n
n_s : Total number of sea states
n_h : Total number of headings
p_j : Occurrence probability of heading j
f_{ijn} : The zero crossing frequency in short term stress condition i, j combined with loading condition n

Effects of swell are not accounted for in above calculation, as the wave scatter diagram is used to represent the wave environment. Wirsching's rainflow correction factor is used to cater swell effects in short-term fatigue damage calculation (Wirsching and Light, 1980).

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

where,

$a(m)$ = 0.926 - 0.033 m
$b(m)$ = 1.587 m - 2.323
ε_i = Bandwidth parameter calculated by Eq. (7)

Addition of Wirsching's rain flow correction factor modifies Eq. (9) and (10) as:

$$\mathrm{D_i} = \left(\frac{\mathrm{T}}{\mathrm{A}}\right)\left(2\sqrt{2\mathrm{m_{0i}}}\right)^{\mathrm{m}} \Gamma\left(1+\frac{\mathrm{m}}{2}\right) \lambda(\mathrm{m},\varepsilon_i)\mathrm{p_i f_{0i}} \quad (12)$$

$$D = \frac{T}{A}\,\Gamma\left(1+\frac{m}{2}\right)$$

$$\sum_{n=1}^{N_{Load}} p_n \sum_{i=1}^{n_s}\sum_{j=1}^{n_h} \lambda(m,\varepsilon_i)\, p_i\, p_j f_{ijn}\left(2\sqrt{2m_{0ijn}}\right)^m \quad (13)$$

Both Eq. (9) and (12) can be employed to compute accumulated fatigue damage in a specific sea state.

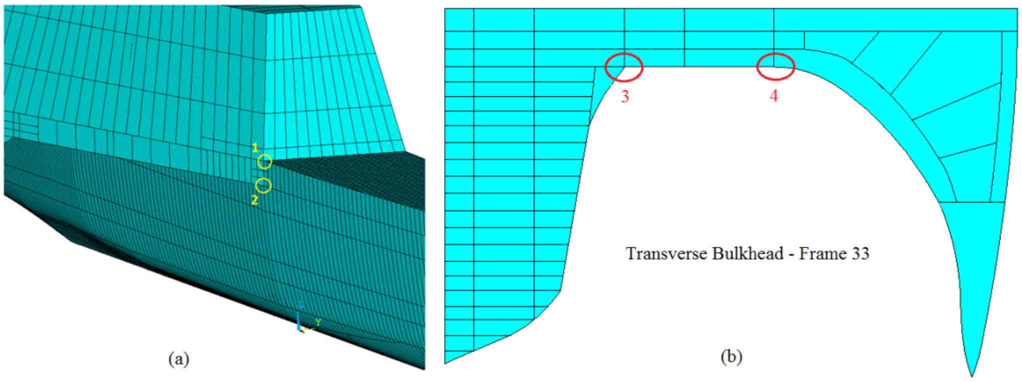

Fig. 3: Location of hot spots (a) Connection of main hull with cross deck and wet deck at front (b) Connection of wet deck with main hull and side hull

Cumulative fatigue damage is converted to expected fatigue life T_f by the expression:

$$T_f = \frac{T_d}{D}$$

where, T_d is the design life of the ship.

METHODOLOGY

FE model and hot spots location: Main particulars of trimaran ship analyzed in this study are presented in Table 1. A 3D FE model of trimaran based on net thickness approach is generated in ANSYS software as shown in Fig. 2. Structure analysis of trimaran based on direct calculation procedure of Lloyd's Register Rules for Classification of Trimaran is performed to identify location of maximum stress concentrations or hot spots (Shehzad *et al*., 2012). Following locations are selected to perform spectral fatigue assessment (Fig. 3):

- **Hot Spot 1:** Starting connection of cross deck with main hull at front
- **Hot Spot 2:** Starting connection of wet deck with main hull at front
- **Hot Spot 3:** Connection of main hull with wet deck at transverse bulk head
- **Hot Spot 4:** Connection of side hull with wet deck at transverse bulk head

Considering the intricacy of trimaran structure, hot spot stress approach is used to calculate stress transfer function. Therefore, local fine mesh of size‘t *x t’* is used at hot spots, whereas remaining model is coarse meshed with element size equal to stiffener spacing (Fig. 4).

Response Amplitude Operator (RAOs): The main objective of motion and load calculations in spectral based fatigue analysis is the determination of RAOs, which are mathematical representations of the vessel

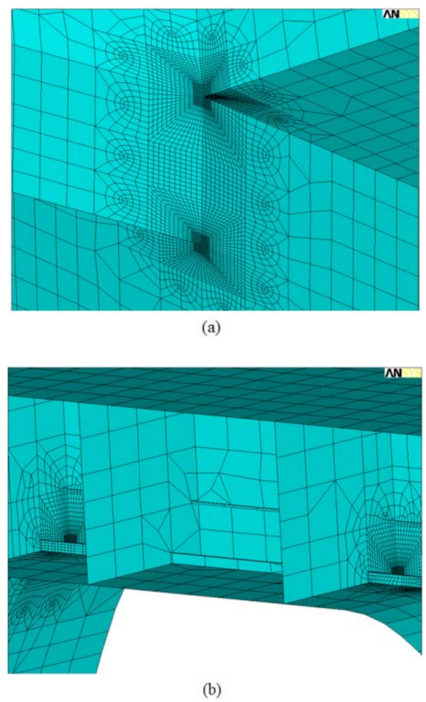

Fig. 4: Fine mesh at hot spots, (a) Hotspot 1 and 2, (b) Hotspot 3 and 4

Table 2: Wave load calculation parameters

S. No	Parameter	Range	Increment
1	Frequency ω	0.2~2.0	0.1
2	Heading angle θ	0^0~330^0	30^0
3	Heading probability p_j	1/12	-

responses and load effects to unit amplitude sinusoidal waves. In this study, wave induced motions and hydrodynamic pressure loads at zero forward speed are calculated using linear sea-keeping code ANSYS-AQWA, utilizing 3 dimensional and potential flow-based diffraction-radiation theory. Parameters used in wave load calculation are summarized in Table 2.

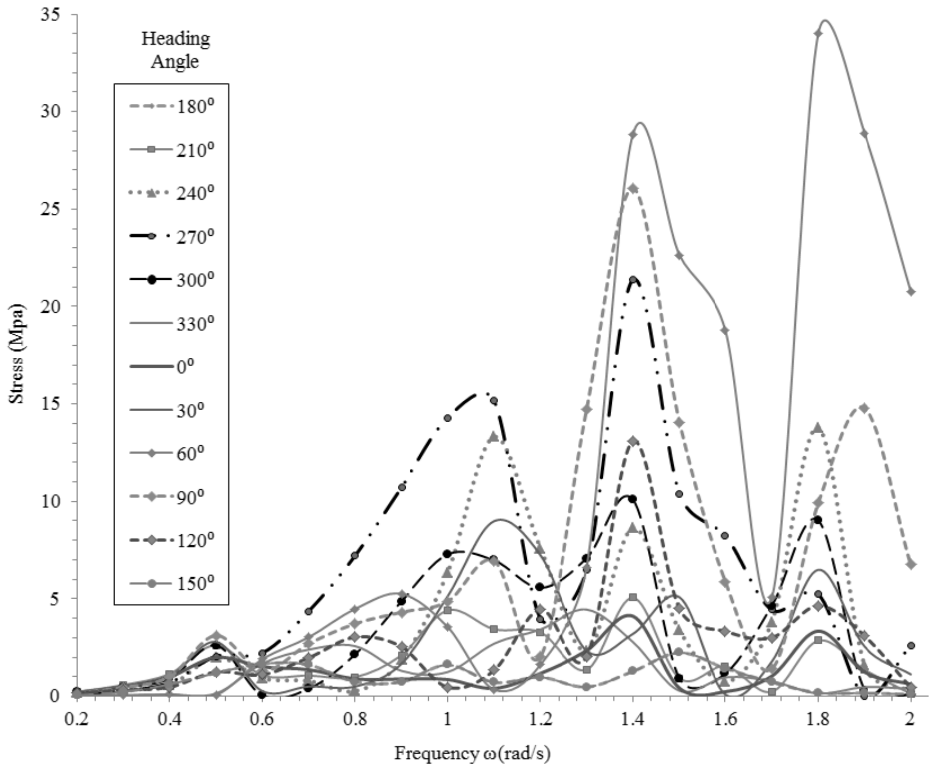

Fig. 5**:** Stress transfer function of hotspot 4

Table 3: Cumulative fatigue damage and expected fatigue life

	Without correction factor		With rain flow correction factor		
Hot spot	Damage	Fatigue life (years)	Damage	Fatigue life (years)	Increase (%)
1	4.5299	4.4100	3.9240	5.1000	15.65
2	1.9708	10.150	1.6858	11.860	16.85
3	1.4396	13.900	1.2236	16.340	17.55
4	0.0790	253.16	0.0683	292.83	15.67

Stress transfer function: Determination of stress transfer function is the key step in spectral fatigue analysis. Stress range transfer function represents the relationship between the stress at a particular structural location, wave frequency and heading. Stress transfer functions at hot spots are determined by FE analysis of global structure model by applying inertial load of ship motion and hydrodynamic pressure on hull surface. In this study, AQWA WAVE is used for mapping of hydrodynamic loads from hydrodynamic model to global FE model and structure analysis is performed for 228 load cases corresponding to 19 frequencies and 12 headings. Stress transfer function of hotspot 4 is shown in Fig. 5.

Fatigue damage calculation: A MATLAB code is developed to calculate spectral fatigue damage according to the mathematical formulations explained earlier in this study. The program uses stress transfer function obtained by finite element analysis and wave scatter diagram data as input. In this study, fatigue damage is calculated for one base vessel loading condition using wave scatter data of north Atlantic and SN curve E of CCS rules. Only long crested waves are taken into account with the assumption of equal probability of vessel heading relative to the direction of the waves. Design life of the ship is taken as 20 years with 85% duration at sea. The factor of 0.85 corresponds to the non-operational time of the ship at harbor.

RESULTS AND DISCUSSION

Fatigue damage calculation results of hot spots and a comparison of expected fatigue life by applying Wirsching's rain flow correction are summarized in Table 3. Cumulative fatigue damage values of hotspots 1, 2 and 3 are greater than one, indicating structural nonconformance of fatigue strength criteria at these locations. Also, addition of Wirsching's rain flow

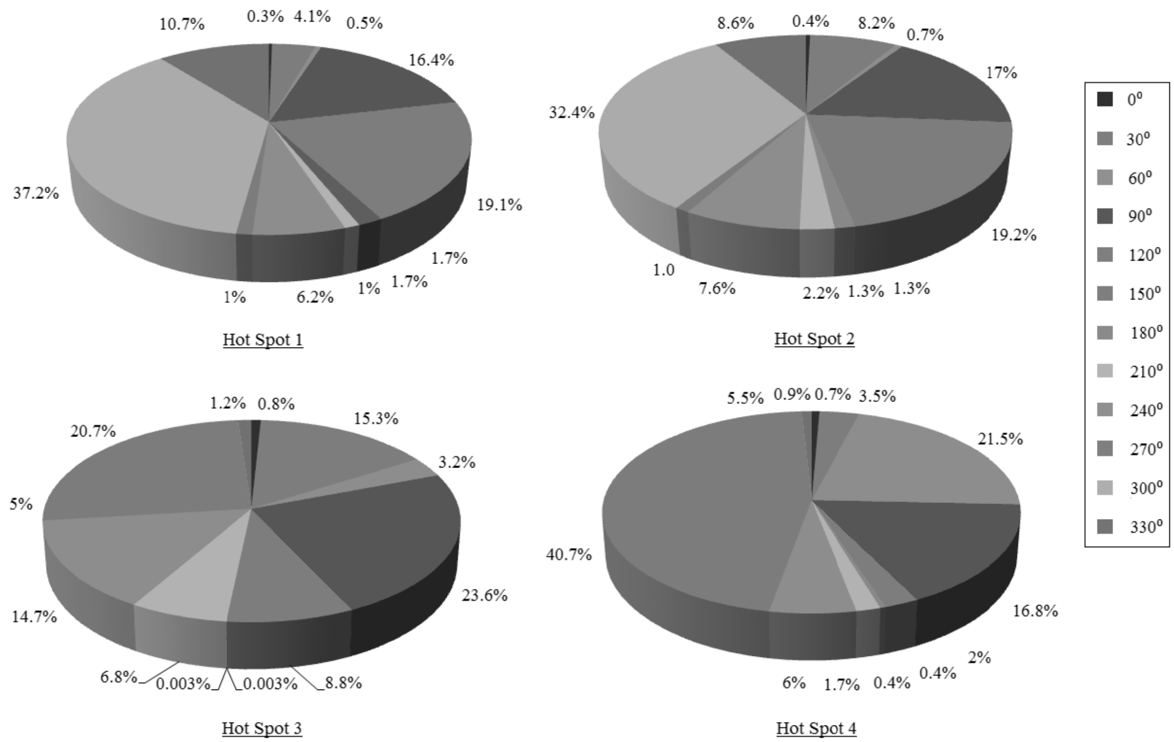

Fig. 6: Fatigue damage distribution caused by waves at different heading angle

correction factor in spectral fatigue calculation increases the predicted fatigue life of the hot spots.

Figure 6 demonstrates the contribution of damage incurred during individual heading direction towards cumulative fatigue damage for all hot spots. Statistical damage results of hotspot 1 reveals that waves inclined at 270, 300 and 330°C, respectively cause maximum damage approximately equal to the damage caused by waves at other inclination angles. Damage distribution plot of hot spot 2 nearly exhibits the same response as that of hot spot 1. For hotspot 3, transverse waves and neighboring 30°C waves account for the major proportion of fatigue damage. In case of hot spot 4, waves inclined at 60, 90 and 270°C, respectively contribute 75% of the total fatigue damage.

CONCLUSION

This study presents fatigue assessment of trimaran structure by spectral based method. Wirsching's rain flow cycle correction factor is applied to include swell's effects in fatigue damage calculation. According to the calculation results it is found that front connection of cross deck and wet deck with main hull and connection of main hull with wet deck at transverse bulk head suffer maximum fatigue damage. Moreover, predicted fatigue life is considerably less than the design life of the vessel, which indicates the requirement to enhance structure design at these particular locations. Therefore, fatigue strength assessment of trimaran cross structure is recommended at initial design stage.

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