Wave Loads

8. Introduction

The evaluation of structural responses is key element in ship design. Fundamental to this is the determination of the wave loads to support the Classification Rule requirements and for application in direct calculations (Hirdaris et al., 2014). To date, the current design philosophy for the prediction of ship motions and wave-induced loads has been driven by empirical or first-principles calculation procedures based on well proven applications such as ship motion prediction programs employing the strip theory and panel methods explained in Lecture 7. In recent years, the software, engineering and computer technology available improved dramatically. Thus, a trend that may utilize the latest technologies to assess the influence of wave loads on ship strength emerged. This lecture reviews some of the key methods that may be used for the assessment of wave loads on ships. The emphasis is on empirical methods and rigid body structural dynamics. Hydroelastic methods for the prediction of springing and whipping loads are briefly introduced.

9. Classification of wave loads

A prime category of **static loads** that involve hydrodynamic actions and are frequently used in the structural analysis are **still water loads**. They may be attributed to (a) the variation of buoyancy distribution along ship length and (b) the non - uniform longitudinal distribution of light and dead weights (see

Figure 0-1). The longitudinal uneven distribution of the net load causes vertical shear forces and bending moments. Still water loads may be either sagging or hogging depending on the resultant distribution of the net load. Cargo weights have the largest impact on the bending moments and shear forces as they may vary rapidly during loading, unloading and seaway operations. To avoid hull splitting due to bending and shear effects the cargo should be spread out and interspersed. The maximum longitudinal shear force is at the neutral axis and decreases towards the deck and bottom (see Figure 0-2).

Slowly varying loads are bending moments and shear forces in seaway. Waves may cause high variation in the buoyancy distribution throughout the ship length that significantly increases the bending moment and shear force. The largest effect occurs when the ship is balanced on the peak of a wave that has the same length as the ship with crest amidship. The wave crest at amidships increases the buoyancy forces and leads to hogging vertical bending moments. Conversely, when the ship is on a wave trough amidship sagging vertical bending moments prevail (see Figure 0-3).

Horizontal bending around the ship's vertical axis (say the Z-axis) occurs when the ship is in an inclined condition due to roll. This moment arises when the ship has a wave crest on one side that phases a trough on the other side in oblique or beam seas. Based on engineering experience it is noteworthy to mention that this type of moment for most small mono-hull ships is usually less than

20% of the vertical bending moment of most for large tankers and mega-containerships, it can rise to as high as 50% of the vertical bending moment.

Torsion becomes important in oblique seas where the ship may be subject to opposite direction righting moments at her forward and aft parts. Ships with large deck openings, like containerships and mega bulk carriers, can experience significant torsion moments. Racking loads arise from ship rolling and they are of practical significance for "shoe box type hulls", i.e. ships without transverse bulkheads (e.g., ro-ro ships and car ferries). During racking, the deck tends to move laterally relative to the bottom, while the side shell moves vertically relative to the other side (see Figures 8-4 and 8-5).

(a) Weight, VSF, VBM diagrams (b) Still water VSF and VBM for various cargo distributions

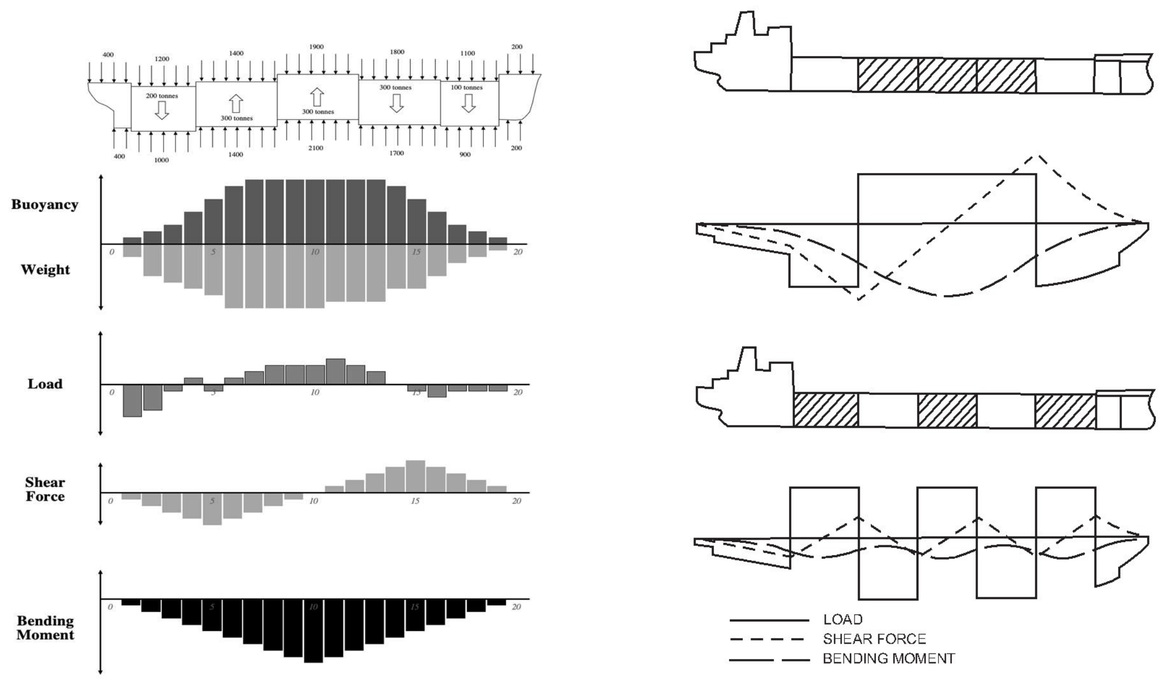

Figure 0-1. Overview of load distributions (Shama, 2013)

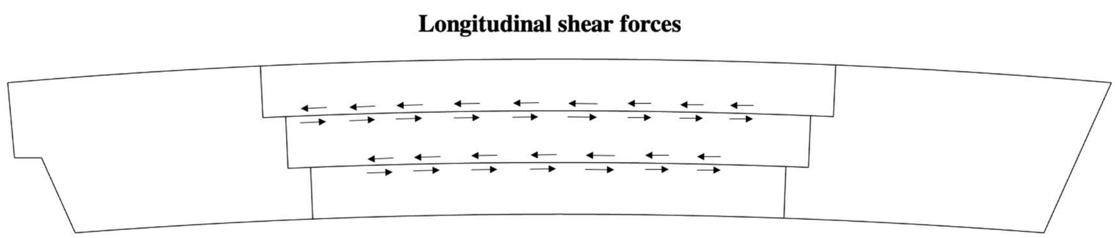

Figure 0-2. Longitudinal shear forces (Shama, 2013)

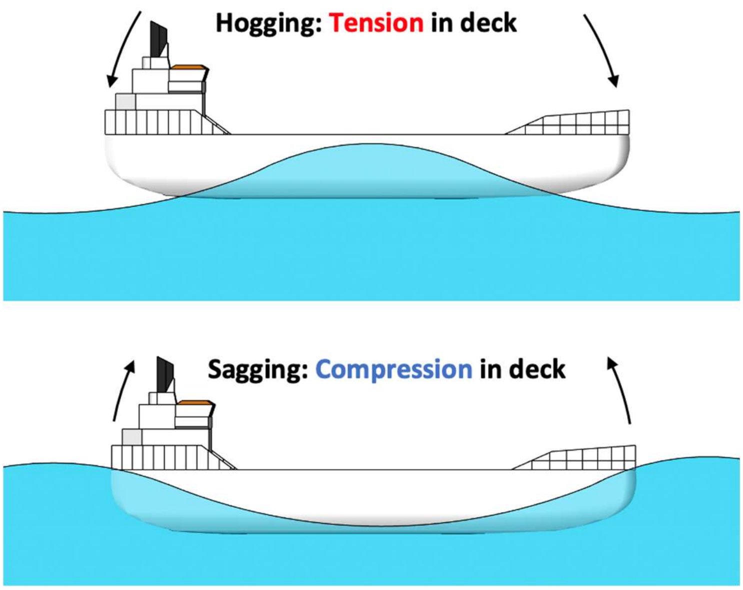

Figure 0-3. hogging and sagging condition in a regular wave

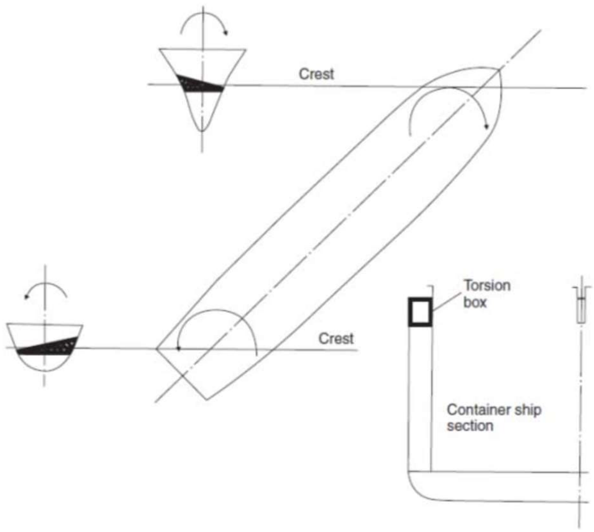

Figure 0-4. Torsion moment in oblique seas

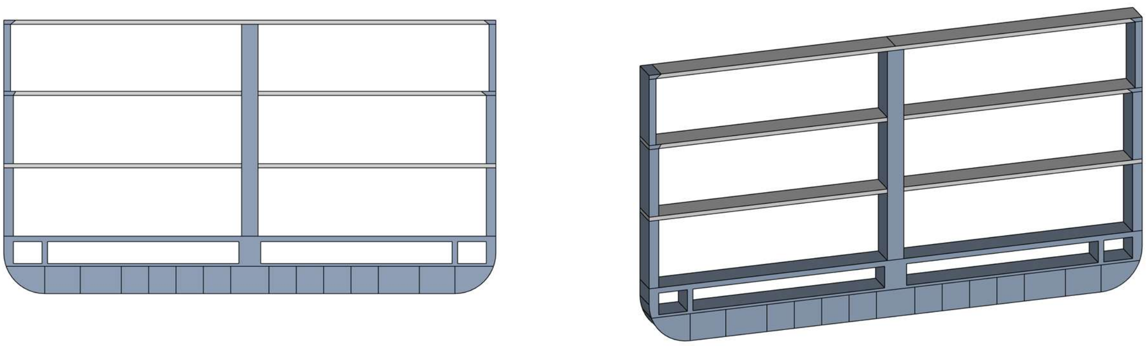

Figure 0-5. Racking deformation

Rapidly varying loads have short periods. For example, shipping of **green seas on deck** is an impact load that mostly affects the forecastle deck. On the other hand, **panting** originates by the variable external water pressure from waves which causes the shell plating to bellow-in and out continuously. The pitching motion of the ship in waves highly affects this type of load. **Slamming loads** originate from heaving and pitching motions. During slamming events the forward vessel speed in a wave trough may lead to emergence of the forward portion of the vessel. Consequently, the ship experiences a severe hydrodynamic impact on water re-entry. Slamming loads are rapid and intense and are usually accompanied by a loud booming or slamming sound. They may be critical for monohull ships with large bow flare and broad stern but also influence multi-hull vessels like catamarans (see Figure 0-6).

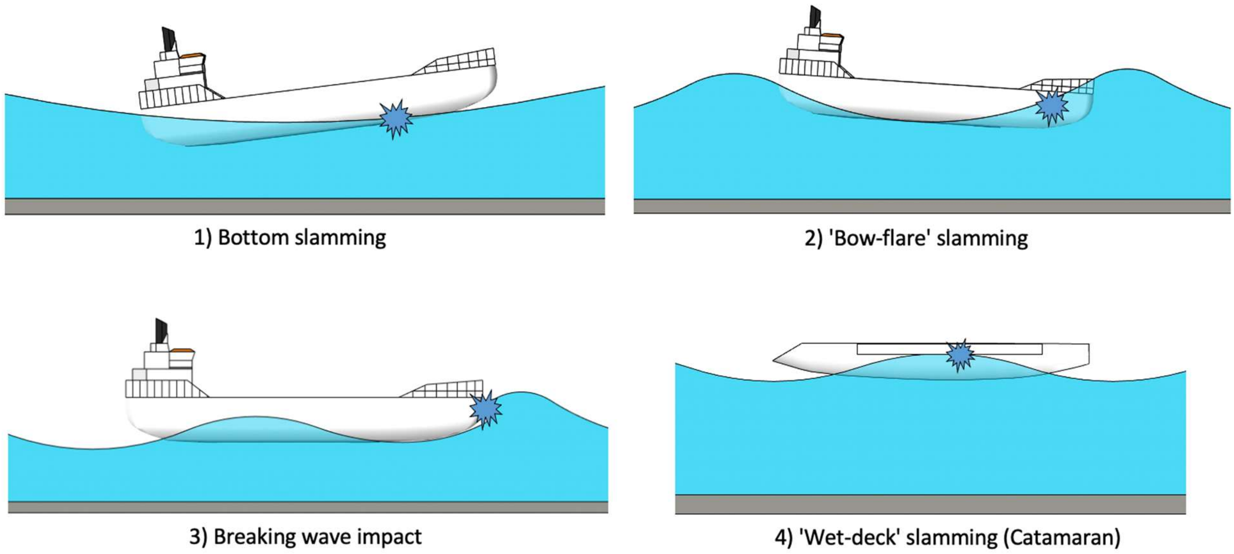

Figure 0-6 Types of ship slamming loads

3. Murray's method

Murray's Method can be employed to estimate the longitudinal bending moment amidships which arises when the ship is stabilized on the so called standard wave defined as a wave of length equal to the length of the ship (L) and height $0.607\sqrt{\mathrm{L}}$ (see Figure 0-7). This method can be categorized as static analysis because it does not consider the dynamic load components induced by the waves. The total bending moment can be divided into two parts namely the still water and wave induced bending moments. The latter is defined as a function of ship breadth (B) and Length (L) as follows

$$\mathrm{M_w} = \mathrm{b} \cdot \mathrm{B} \cdot \mathrm{L}^{2.5} \times 10^{-3} \text{ tonnes metres} \qquad (0\text{-}1)$$

where *b* is a constant based on the ship block coefficient C_b and whether the ship is sagging or hogging (see

Table 0-1).

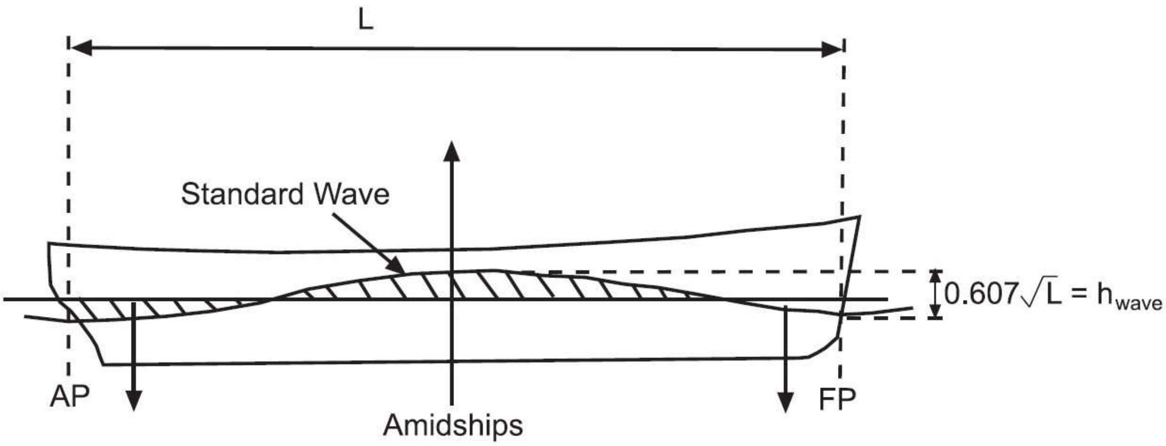

Figure 0-7. Standard wave (Barrass and Derrett 2011)

Table 0-1 Murray's coefficients 'b'

	Values of b	
C_b	Hogging	Sagging
0.80	10.555	11.821
0.78	10.238	11.505
0.76	9.943	11.188
0.74	9.647	10.850
0.72	9.329	10.513
0.70	9.014	10.175
0.68	8.716	9.858
0.66	8.402	9.541
0.64	8.106	9.204
0.62	7.790	8.887
0.60	7.494	8.571

If the still water bending moment is not available it can be obtained using the following approximation

$$M_s = \frac{W_F + W_A}{2} - \frac{W}{2} \cdot LCB \qquad (0\text{-}2)$$

where W is the total ship weight, W_F is the moment of the weight forward of amidships and W_A is the moment of the weight aft of amidships. The first term of equation (0-2) represents the mean weight bending moment while the second term represents the mean buoyancy moment. If the mean weight moment is greater than the mean buoyancy moment at amidships the ship hogs in still water (+ve M_s) and vice versa. The total bending moment from still water and waves can be obtained by summing up the still water bending moment M_s and the wave bending moment M_w when the ship sags and/or hogs. In addition to the static forces acting on the body when the ship is balanced on a stationary wave, an inertia component that originates from the ship's motion should be added to the ship's weight distribution, while the buoyancy distribution varies. Finally, motions generate outgoing waves that cause oscillating pressures on the wetted hull surface. Integrating these pressures over the wetted surface yields the forces and moments acting on the ship from waves.

4. Wave induced responses

Wave induced responses are classified as **static**, **quasi-static** and **dynamic**. The evaluation of static responses does not consider any wave actions. In quasi-static analysis some motion effects are considered. In dynamic analysis the effects of hydrodynamic actions and time variation of loads are considered. In those cases that vibratory actions arising from waves may lead to local or global resonance phenomena known as springing and slamming induced whipping loads. In these cases wave induced resonances are evident and therefore hydroelasticity may be considered important. Figure 0-8 illustrates the topology of responses from global hull girder to local response. The following sections discuss aspects of relevance to the influence of nonlinear hydrodynamics on wave load predictions and the evaluation of rigid body wave loads in irregular waves. Considering the highly mathematical nature of the subject the emphasis is on qualitative aspects, methods and tools available for use in ship design.

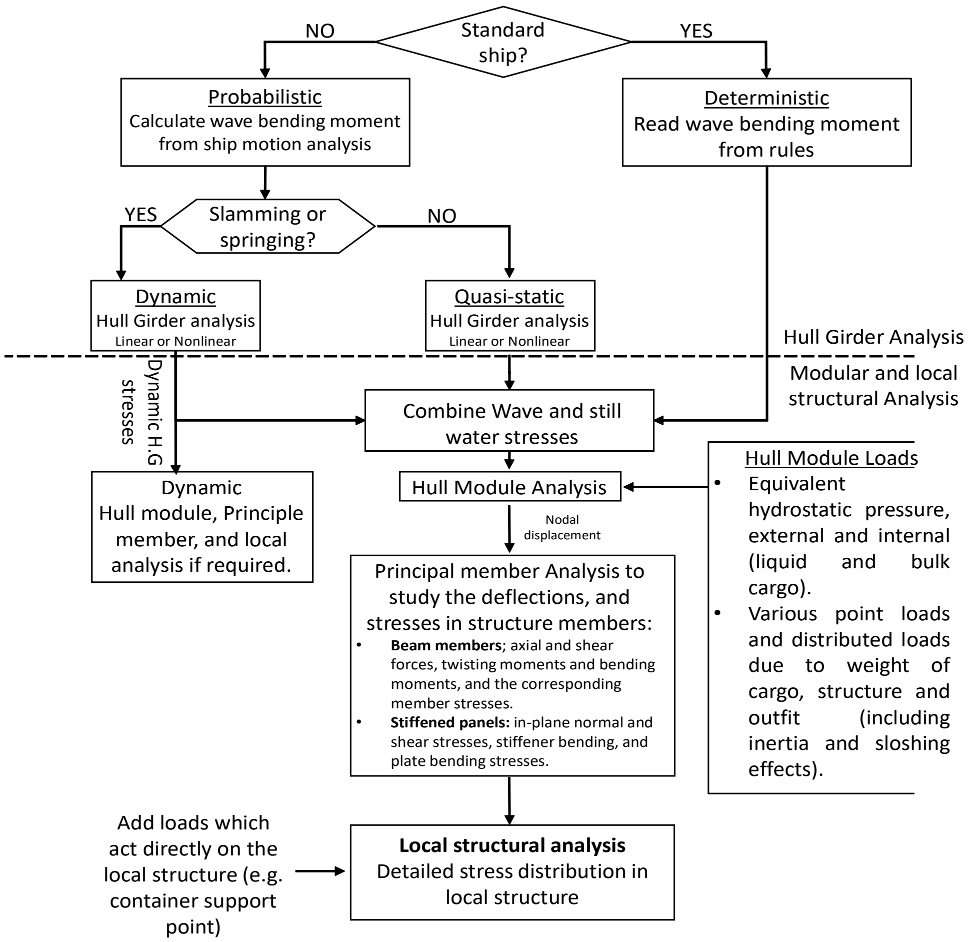

Figure 0-8 Wave induced loads and their link with ship responses

5. The influence of nonlinear hydrodynamic actions

Wave induced loads on large ships and / or modern innovative vessels that may have unusual hull form proportions are usually nonlinear. This is because of variations of the waterplane below and above the waterline. Analysis of these loads using empirical approaches is limited by simplified hydrodynamic assumptions or rule of thumb rules. In recent years the advances in computer software, speed and ship science lead to the development of direct hydrodynamic analysis methods that may be used to address nonlinear effects associated with wave elevation in way of the free surface, variations of the waterplane area, forward speed effects etc. Such methods are developed primarily by academics or Classification Societies and they are progressively implemented in Classification notes (e.g. DNV, 2010) It is noted that implementation of nonlinear hydrodynamic actions can provide revised hogging and sagging correction factors to be applied in the linear analysis of the ship global loads. Whereas some of these developments are already evident in modern IACS unified requirements, as the theoretical background of implementation is complex they are not considered part of this course and hence not explicitly explained here (IACS, 2015). Instead, this section presents the basis of calculation of linear and nonlinear calculation of the shear force and bending moment for the case of a rigid ship (see Figure 0-). In linear analysis, the net load $q(x)$ (force / unit length) in waves is obtained by summing the ship weight $m(x)g$, buoyancy at each section of area $A(x)$, inertia from the heave $m(x)\ddot{\eta}_3$ and pitch $m(x)x\ddot{\eta}_5$ and the hydrodynamic forces $F(x)$ as follows:

$$q(x) = -m(x)g + \rho g A(x) - m(x)(\ddot{\eta}_3 - x\ddot{\eta}_5) + F(x) \quad (0\text{-}3)$$

The shear force at each section x'_p is obtained by integrating the net load throughout the ship length

$$Q(x'_p) = \int_0^{x'p} q(x')dx' \quad (0\text{-}4)$$

The bending moment is evaluated by integrating the shear force along the ship length

$$M(x'_p) = \int_0^{x'p} x'q(x')dx' \quad (0\text{-}5)$$

As the model is linear, we can employ it to get the RAO of the vessel in different operating conditions (wave heading, forward speed and loading condition). Notwithstanding this, it is important to note that linear assumptions do not help us distinguish between hogging and sagging induced by the waves. For example, linear assumptions have been employed by (Kukkanen, 2012) to evaluate the shear force and bending moment RAOs of the "*Seatech-D*" Ro-Pax vessel as illustrated in Figure 0-10. Further work at Aalto university towing tank revealed considerable amount of **nonlinearity** in the shear force and the bending moment RAOs obtained using different wave amplitudes (see Figure 0-). The impact of hydrodynamic nonlinearities has been more obvious at frequencies close to resonance. An obvious difference in the maximum and minimum loads in sagging and hogging conditions(see Figure 0-). The bending moment is remarkably large in sagging condition. The geometry of the ship's hull and the waves generated by her forward speed have large contribution in this un-symmetry.

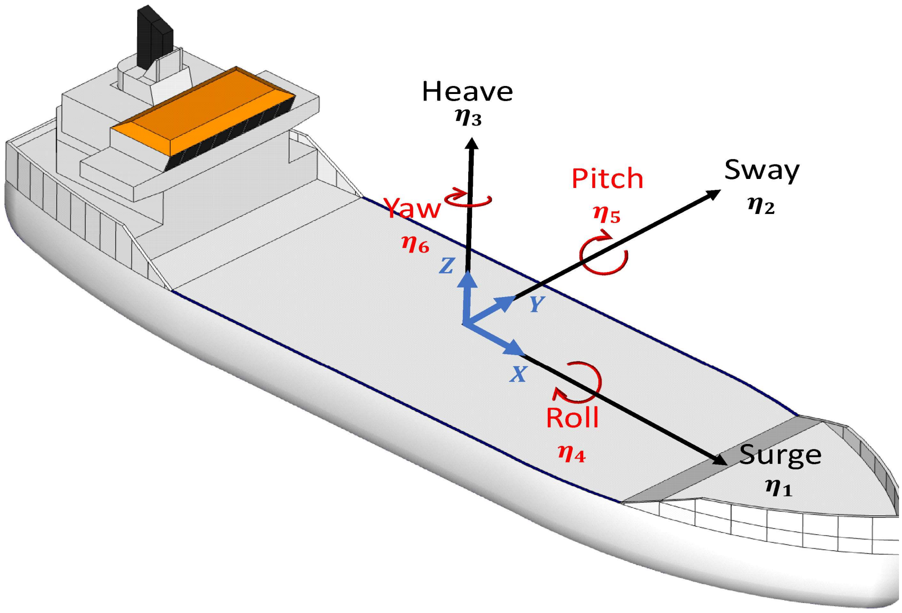

Figure 0-9 Ship-fixed co-ordinate system and motion components employed in the linear and nonlinear analysis

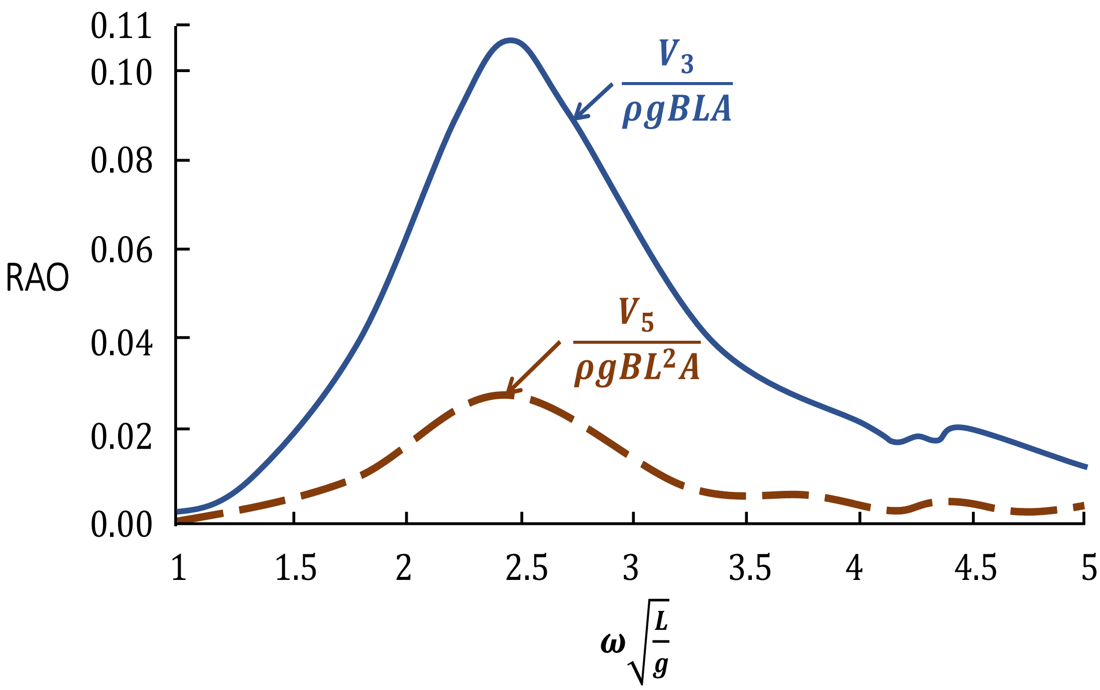

Figure 0-10 Seatech-D Ro-Pax vessel shear force and bending moment RAOs near amidships using linear theory for Fn= 0.25 in head seas (Kukkanen 2012)

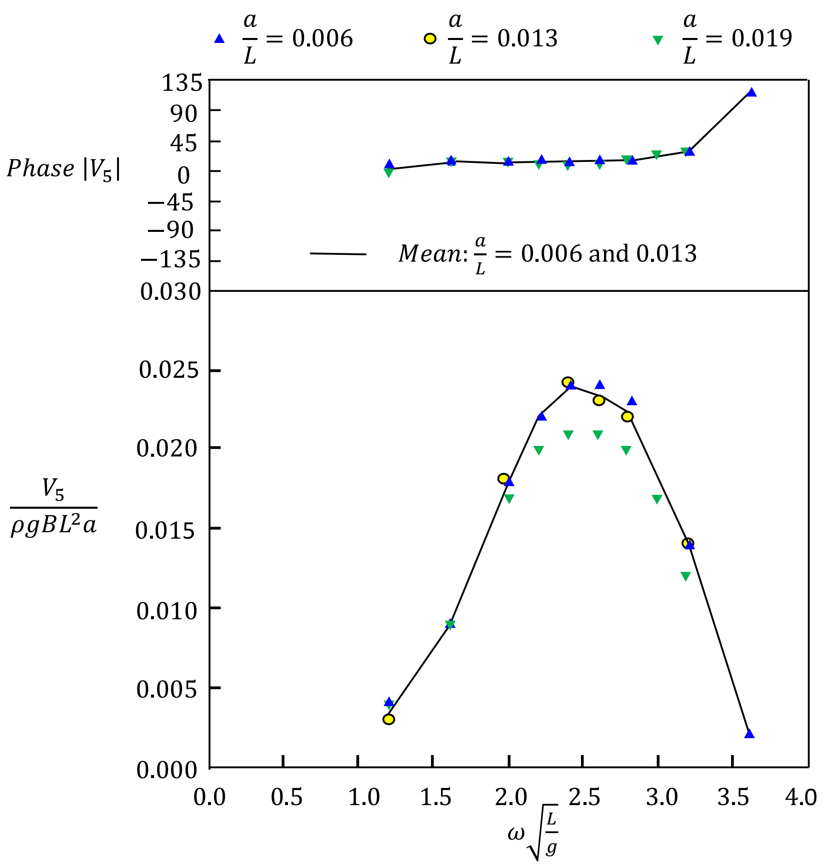

Figure 0-11 model test results of the bending moment RAO obtained using different wave amplitudes in head seas and $Fn = 0.25$ (Kukkanen 2012).

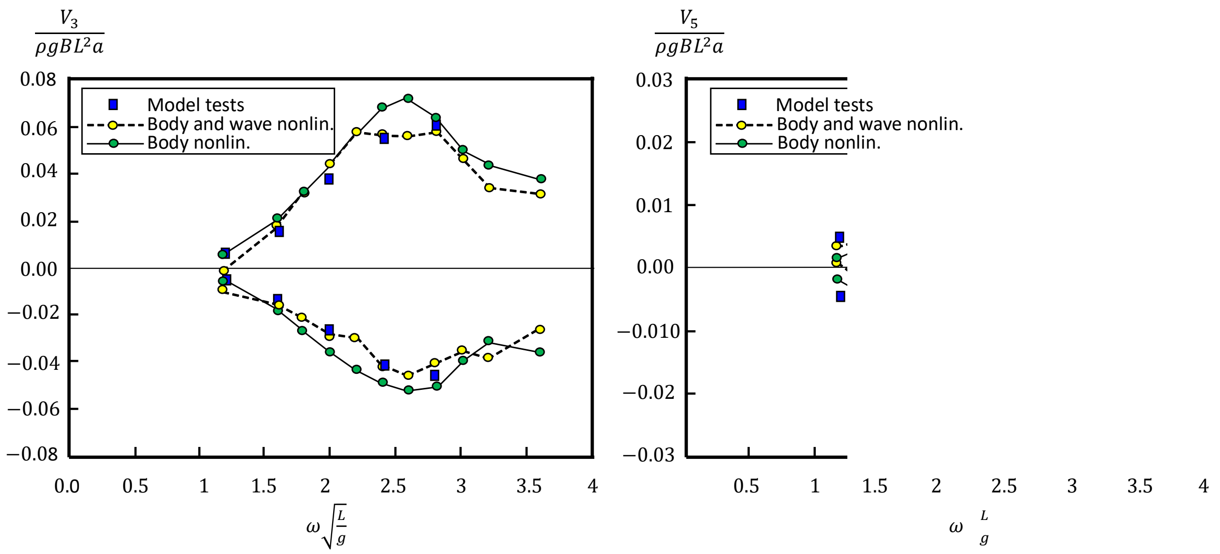

Figure 0-12 maximum and minimum loads in sagging and hogging condition (left) shear forces (right) bending moment for Fn=0 and a/L =0.013 (Kukkanen 2012).

6. Ship responses in irregular waves

Wave induced dynamic loads are stochastic and difficult to be determined precisely. If the correlation between these loads and a ship's displacement is linear or weakly nonlinear irregular responses can be evaluated via the aggregation of regular responses, i.e., based on Rayleigh's superposition principle (see Lectures 3,4) in the "*frequency domain*". In case the correlation between the force and displacement is remarkably non-linear then the structure should be solved using time as an independent variable (i.e., in the "time domain"). Response in waves considers the following assumptions:

- The irregularity of the ocean's waves can be represented by linear summation of a huge number of individual regular waves with different heights and periods;
- The total hydrodynamic forces are the summation hydrodynamic actions calculated on each transverse section separately;
- In typical analysis the ship may be considered wall sided and the wave forces acting on her may be considered linearly proportional to the wave height (linear analysis).

The accuracy of the first two of the above-mentioned assumptions are generally satisfactory. The third one gives satisfactory results for box like wall sided ships (e.g., tankers or bulk carriers) at the waterline region. however, it can be challenged for monohull slender ships with large flare operating at moderate to high speed or multihull vessels and high speed craft. In any case, the principal steps that should be involved in stochastic analysis are summarized as follows:

- **Seakeeping response analysis** is carried out for individual regular waves having different frequencies and unit wave amplitudes. The range of frequencies used in the analysis should cover all the expected encounter wave frequencies that the ship may experience. That yields to smooth definitions of the transfer function (RAO) of motions, wave-induced hull girder bending moments, shear forces and stresses. The analysis can be carried out using seakeeping software based on strip theory or a 3D potential flow. Various commercial solvers can be used in this area of work. Examples are :
    1) NAPA (https://www.napa.fi/)
    2) MAXSURF (https://maxsurf.net/)
    3) MOSES (https://bentley.ultramarine.com/),
    4) ANSYS AQWA (https://www.ansys.com/products/structures/ansys-aqwa)
    5) BV HYDROSTAR (https://marine-offshore.bureauveritas.com/hydrostar-software-powerful-hydrodynamic).
- As explained in Lecture 3, the energy contained in each short-term sea state is defined by a wave spectrum $S_\eta(\omega|H_s,T_z)$ (e.g., Pierson–Moskowitz, Jonswap etc.).
- Each RAO is then used to calculate the response spectrum, $S\,(\omega|H_s,T_z,\theta)$, by scaling the wave energy spectrum as

$$S\,(\omega|H_s,T_z,\theta) = |H\,(\omega|\theta)|^2\, S_\eta(\omega|H_s,T_z) \quad (0\text{-}6)$$

- The extreme response occurs when the peak of the wave spectrum matches the peak of the RAO. In case the sea state is represented by different wave spectra, results are combined by taking into account the proportion of each spectrum on RAO.
- The above analysis is repeated for different sea states with different headings and forward speeds. Each iteration represents the short-term response, while the statistical combination of these short-term responses, based on the wave scatter diagram, represents the long-term response.
- The long-term response can be used for probability analysis of different failures limit states. The mathematical background and process on how to achieve this within the context of both rigid and flexible ship dynamics is explained by (Wu and Moan 2006) and (Tilander et al., 2020).

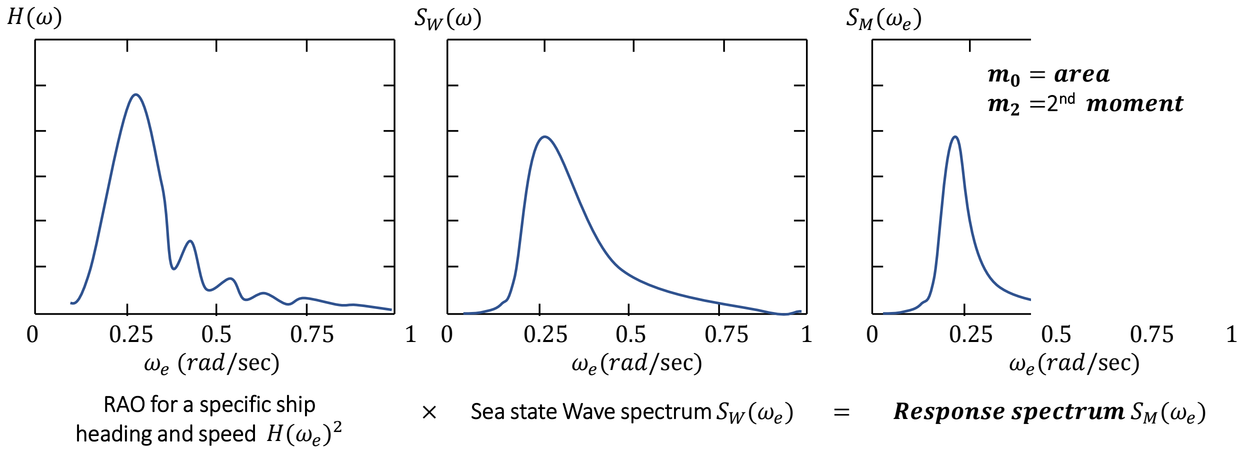

Figure 0-13 Stochastic ship dynamics (Hughes 2010)

7. Introduction to Hydroelasticity of Ships

Traditional ship dynamics assume that ships behave as rigid bodies. In reality, long slender ships are flexible structures. The influence of flexible ship hull dynamics is addressed by hydroelasticity theory; a method which assumes that ships in waves experience symmetric (vertical bending induced) and antisymmetric (coupled horizontal bending and torsion) flexible distortions. The method was introduced originally by Bishop and Price (1979) and developed by various contributors to the field over the last 30 years (e.g. Hirdaris and Temarel, 2009).

When a hull experiences motions and distortions in water the resultant hydrostatic and hydrodynamic pressures influence her dynamic characteristics (natural frequencies and mode shapes) of the hull. As we explained in Lecture 7 the hydrodynamic effects associated with ship seakeeping are frequency dependent. The concept of mode shapes and natural frequencies is based on time (and frequency) independent properties of the hull. This means that the influence of the surrounding water is treated as frequency independent. This is known as the **wet approach**. Alternatively, one can consider the hull in vacuo, with the influence of the surrounding water treated as external action. This is known as the **modal approach** and it allows for the influence of the hydrodynamic effects to be treated as frequency dependent, as they do not contribute to the calculation of the natural frequencies and mode shapes of the **dry hull**. In 2D linear hydroelastic analysis the dry ship hull is idealised as a beam and the fluid actions use the concept of strip theory. The method is applicable to slender mono-hull vessels only and the hull is assumed to possess port-starboard symmetry.

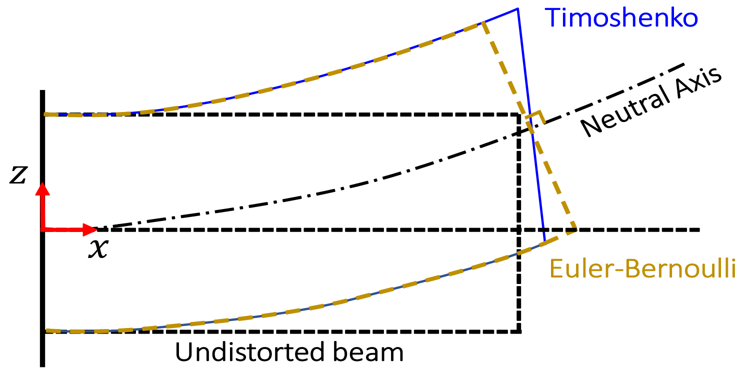

Figure 0-14 Illustration of differences between Euler and Timoshenko beams used in 2D hydroelasticity analysis

The 3D form of the method was developed to include the non-beamlike structures as offshore and multihull structures. The numerical studies of the hydroelasticity employing CFD, potential flow theories and finite element methods have become common due to the wide availability of the software used in this analysis. Typically, application of the method requires the application of a structural FEA model and a potential flow seakeeping theory making use of a Boundary Element Method (BEM). Further details on the significance and application of the method is included in a recent publication by (Tilander et al., 2020). In both 2D and 3D hydroelasticity methods the analysis usually aims to investigate the vessel natural frequencies and transfer functions or RAOs. Figure 0- indicates key results from 3D hydroelastic analysis of a container ship in regular waves when using BV Hydrostar computer program (BV, 2006). In recent years, hydroelastic predictions have been validated by segmented model tests with elastic backbone (see Figure 0-). Extensive discussion of the methods available are give by Jiao et al (2017) and they are considered beyond the scope of this course.

Hydroelasticity assessment focuses on the prediction of springing and whipping loads. **Springing** is a continual vibration (flexing) of the hull girder that may last for several hours once initiated. This phenomenon occurs when waves excite the resonant hull girder frequencies. Springing may have a great impact on vessels with high forward speed (typically above 20 knots) and low natural vibration frequencies of bending and torsional modes, usually less than 3rad/sec or 0.5 Hz. Typically, large container ships, Great Lake Carriers are more prone to springing (Hirdaris and Temarel, 2009). Typically, the number of springing cycles is 4-8 times the number of wave cycles and can influence the fatigue strength ships (Ren et al., 2018).

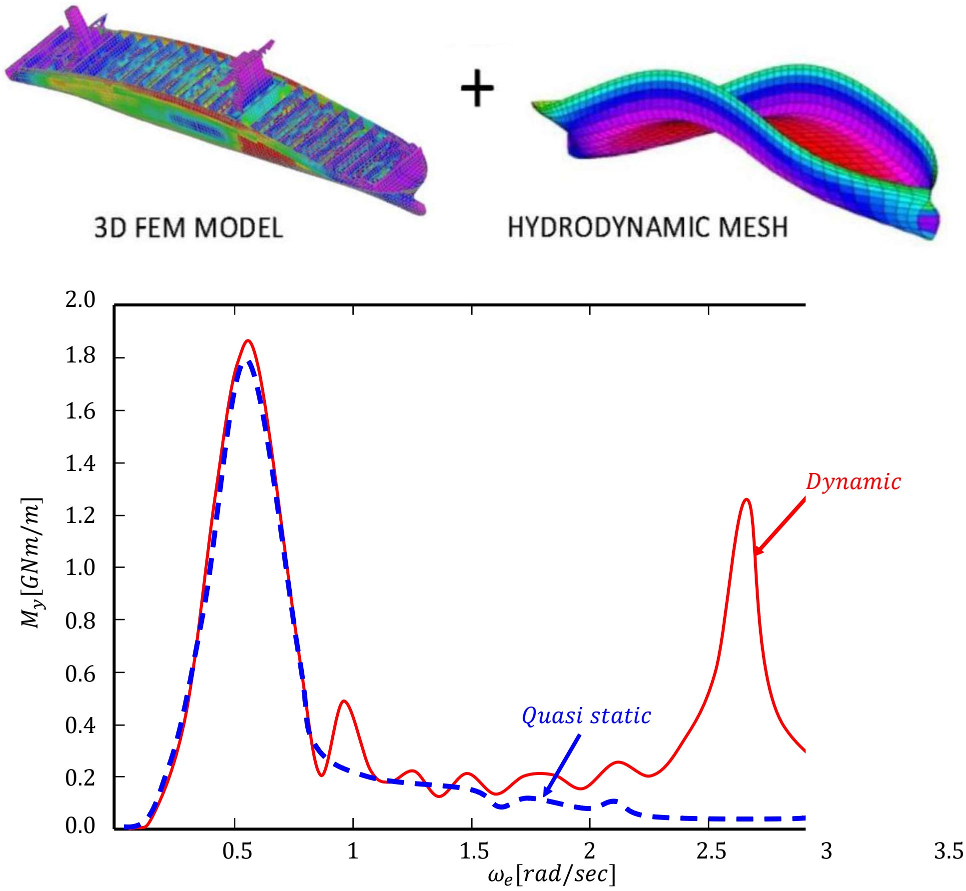

Figure 0-15 Springing analysis using BV Hydrostar software

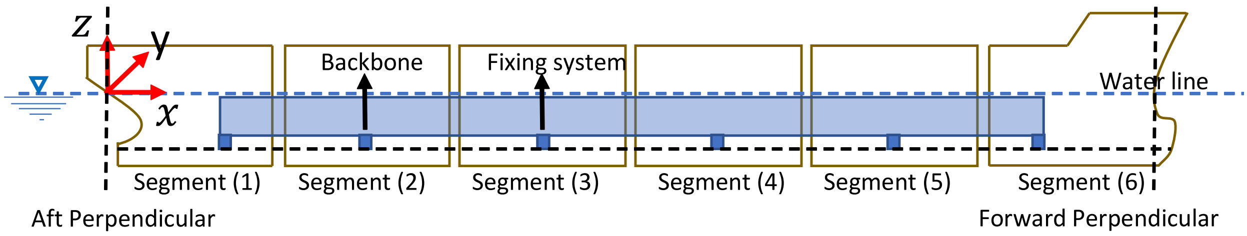

Figure 0-16 Hydroelasticity test of a segmented model of 10,000 TEU containership

Whipping induced wave loads are excited by the rapid flexing of the hull girder due to slamming and induce the propagation of high-frequency oscillations on the hull girder (see Figure 0-). Based on in service experience it is believed that the dominant oscillation mode of whipping loads is the vertical hull girder vibration. This mode causes a remarkable increment of the vertical bending moments and shear forces which affects the ultimate strength of the ship. Whipping loads decay fast, so the cycles of vibration are usually small and flexible hull dynamics are not considered important from a fatigue strength perspective (Hirdaris et al., 2010).

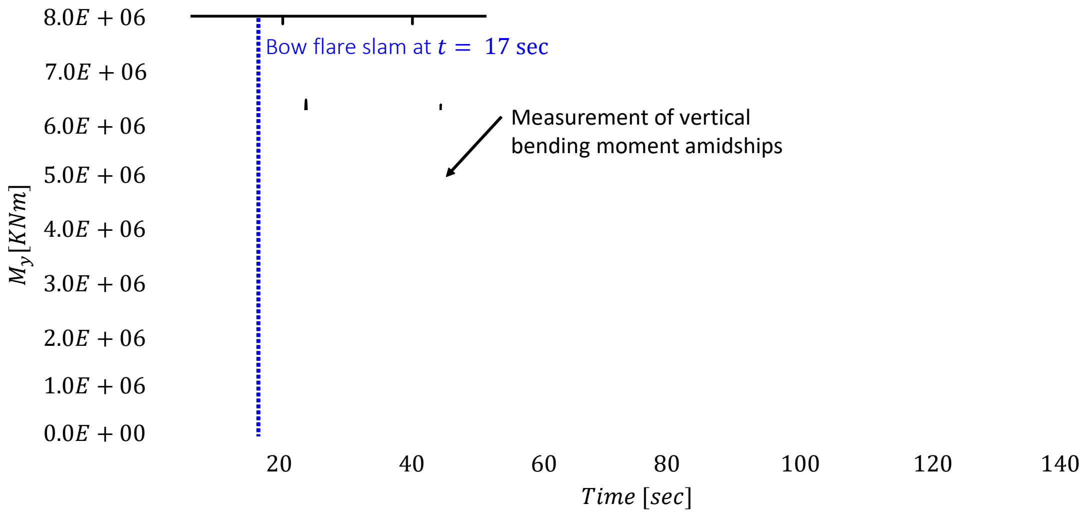

Figure 0-17 Full-scale measurements of vertical wave bending moment including whipping loads for an 8,500 TEU container ship (Lloyd's Register, 2018)

Classification societies provide guidelines for the prediction of the vertical bending moment including the critical vibrational whipping loads (Lloyd’s Register, 2018). Equation (0-7) illustrates how the linear bending moment M_{Linear} should be calculated and then multiplied by the whipping enhancement factor f_{f-W} and the longitudinal distribution factor $f_{\text{WDA}-1}$

$$\begin{aligned} \text{VBM}_{\text{WH}-S} &= f_{\text{fS}-W} f_{\text{WDA}-1} M_{\text{Linear}} \quad \text{for sagging} \\ \text{VBM}_{\text{WH}-H} &= f_{\text{fH-W}} f_{\text{WDA}-1} M_{\text{Linear}} \quad \text{for hogging} \end{aligned} \tag{0-7}$$

It is noted that the whipping enhancement factor depends on the bow flare shape, ship length, area waterline, area amidships, critical wave frequency and the natural frequency of the 2-node hull girder vertical bending mode. Figure 0-3 illustrates a comparison between the predicted and measured wave induced vertical bending moment amidships an 8,500 TEU container ship. The analysis is conducted in head seas, and the load is calculated using Jonswap wave spectrum. The oscillations in the responses corresponding to full scale measurements can be attributed to whipping loads. Springing occurs around a wave encounter frequency of 3.5 rad/sec and this is well confirmed by both full scale measurements and the numerical analysis. A similar study carried out for a passenger ship of 200 m length and 23,000 tonnes displacement (see Figure 0-) demonstrated that the rigid body dominant response occurs at lower frequencies below 1 rad/sec. In this range the response of the ship is entirely dominated by the quasi-static analysis and performs like a rigid body. The springing induced elastic behavior of the ship occurs at 8 – 12 rad/s encounter frequencies.

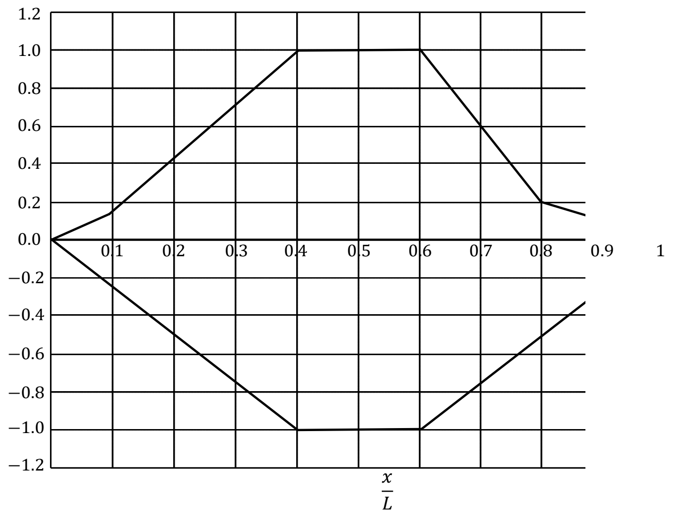

Figure 0-18 Longitudinal distribution factor f_{WDA-1} (Lloyds Register, 2018)

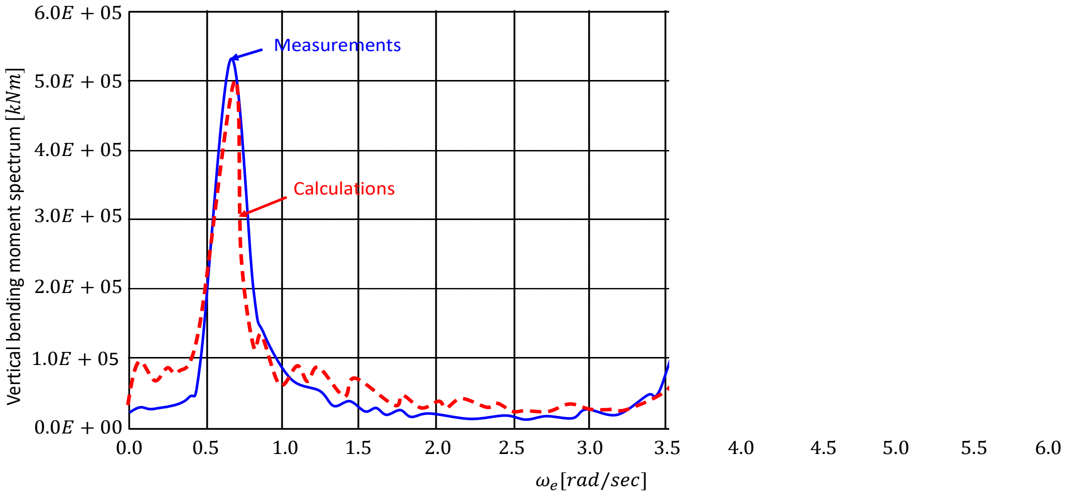

Figure 0-3 Calibration of the numerically calculated vertical bending moment using Jonswap wave spectrum against full-scale measurements (Lloyd's Register, 2018).

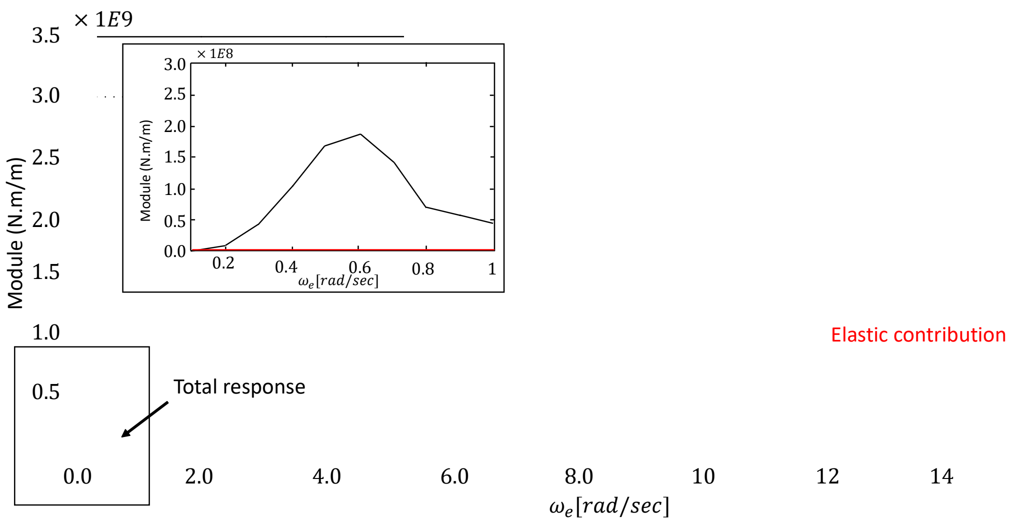

Figure 0-20 Vertical bending moment at amidship of 200 m passenger ship (Tilander et al.,2020)

8. Questions

1- Explain the classification of wave loads. what is the difference between slowly varying and rapidly varying loads? give examples and use sketches to elaborate your answers.

2- Calculate the wave bending moment using Murray's method of a ship encountering a standard wave. Assume ship length = 248 m; ship breadth = 38 m and block coefficient = 0.8. Then calculate the maximum total bending moment if the still water bending moment is 130523 tonnes meter sagging.

3- Discuss briefly the structural response analysis and the different methods/alternatives involved.

4- List the situations when the implementation of non-linear analysis is essential. In which frequency the effect of non-linearity is usually significant?

5- Explain the difference between wave induced sagging and hogging moments, which one usually has a higher value and why.

6- What are the principal assumptions and steps of frequency domain analysis?

7- Discuss briefly the hydroelasticity theory, what are the differences between dry and wet approach?

8- Compare the traditional hydrodynamic analysis and hydroelasticity analysis in terms of ship response in low and very high wave frequencies; use sketches to elaborate your answers.

9- What are the springing and whipping loads; how they can be aroused and what theories are used to evaluate them?

10- Use neat sketches to distinguish between whipping and springing loads, which one is more significant in fatigue analysis and why?

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