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Global wave-induced loads in abnormal waves: Comparison between experimental results and classification society rules

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ABSTRACT

It is important to assess the consequences of ship encounters with abnormal waves due to the perceived dangers of such encounters. A starting point for this is the assessment of global loads, with a focus on examining how the design rules fare with respect to loads induced by abnormal wave encounters. This paper presents the results of an experimental investigation into the global wave induced loads experienced in a range of abnormal sea states. Results are obtained for a segmented, flexible backbone model of a typical naval frigate. Abnormal wave encounters result in a significant increase in the global wave-induced loads compared to the equivalent random sea, with slamming becoming considerably more severe. Through comparisons with the experimental measurements it is concluded that the design rules which allow for an extreme wave encounter provide a reasonable safety margin for the global loads in abnormal waves, although discrepancies occur towards the aft of the vessel. Further investigation of the amount and conditions in which the design rules may be exceeded by an abnormal wave encounter is required.

1. Introduction

Abnormal, freak or rogue waves are a dangerous phenomenon which causes severe structural damage and operation disruption to the encountering vessel and, in some cases, loss of the vessel and crew. The passenger ship *Voyager* experienced severe roll motion, control room flooding and a loss of electrical systems in 2005 (Bertotti and Cavaleri, 2008). FPSO *Schiehallion* suffered deformation damage to plating 15–20 m above the waterline from severe bow slamming (Stansberg, 2000). Both of these examples are documented encounters with abnormal waves. Unexplained losses of the M/V *Munchen* in 1978 (Liang, 2007) and the M/V *Norse Varient* and M/V *Anita* simultaneously in 1973 (Kjeldsen, 2000) are attributed to abnormal wave encounters.

The aforementioned examples illustrate the importance of assessing the risks associated with encountering abnormal waves from a structural viewpoint and investigating the consequences for the ship structural design; hence, by implication, ship design rules. Global loads, especially when slamming is involved, should be assessed using a hydroelastic analysis, which accounts for the inherent coupling between the hydrodynamic actions on a ship and the distortions of the ship due to the waves present. Such an analysis is conducted experimentally in this paper using a flexible model hull.

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Flexible models can be wholly elastic or constructed of rigid hull segments connected by either a flexible backbone or flexible hinges (Denchfield, 2011) and have been used for investigations of ships in severe wave conditions. Drummen et al. (2009) use a hinged model of a containership to measure vertical bending moments in steep regular and random waves. Wu et al. (2003) use a wholly elastic model of an S175 containership in steep random waves to assess vertical bending moments. The results are used to provide further detail on the nature of the vertical bending moments, as well as verify predictions from hydroelasticity theories. Dessi and Mariani (2008) and Lavroff et al. (2010) analyse slamming induced loads of high speed monohull and catamaran hulls. A backbone model with a non-uniform cross-section backbone is used by Dessi and Mariani (2008) whereas Lavroff et al. (2010) use a hinged model. Miyaki et al. (2009) perform an experimental study of the response of a mega containership in regular and irregular waves. Analysis looks at the influence of springing and whipping events on the magnitude of the vertical bending moment in a range of wave heights and frequencies.

The experimental investigations of a ship in abnormal waves to date tend to have used a rigid model. The majority of investigations have taken place at zero speed, for example Guedes-Soares et al. (2006) measure the vertical bending moment and two degree of freedom motions (heave and pitch) of an FPSO in abnormal seas constructed of three segments joined by instrumented steel plates to measure bending. In a similar manner, Clauss (2008) investigates a semi-submersible in abnormal waves to look at heave and splitting forces. Only limited investigations have been carried out that involve a vessel in abnormal waves at forward speed. Clauss (2009) investigates one speed and measures vertical bending moment at only one location along the vessel whilst Kinoshita et al. (2006) investigate a fully flexible model of a containership in transient waves at two speeds.

This paper presents experimental results for the vertical bending moments at various positions along a naval frigate, travelling at its service speed in a range of head regular and long-crested irregular (random and abnormal) waves, obtained using a segmented, flexible backbone model. Probability of exceedence calculations are carried out for the ship responses and an analysis of the whipping response is presented. The results are compared to naval ship design rules from classification societies, namely Lloyd's Register (LR), Det Norske Veritas (DNV) and Bureau Veritas (BV). The suitability of current ship design rules for producing ship designs capable of withstanding abnormal waves is discussed.

2. Experimental set-up

2.1. Test facility

Tests were conducted in a towing tank 60 m long, 3.7 m wide and 1.86 m deep with a maximum carriage speed of 4.5 ms^{-1}. Unidirectional (long-crested) waves were generated using a single, motor-driven paddle wavemaker. Wave reflections from the absorption beach measured using the technique of Isaacson (1991) were less than 10%.

2.2. Flexible model hull

A typical naval frigate hull with the principal particulars in Table 1 was tested. The hull was a segmented, flexible backbone model constructed of four rigid segments attached to a uniform, aluminium backbone beam. The aluminium backbone beam was carefully selected to ensure that the natural frequency and the bending stiffness of the model hull correctly represented those of the full scale vessel, represented as a uniform backbone beam. Based on literature four segments is sufficient to obtain the lower vertical bending modes whilst a uniform cross-section backbone allows the correct scaling of the 1st vertical bending mode (Denchfield, 2011). It is considered that the flexible backbone technique is sufficient to approximate the bending stiffness of the full scale ship appropriately; hence flexible backbone models have been used in previous research (e.g. Takaoka et al., 2012) allowing the modelling of vertical bending moment, whipping and slamming response. Fig. 1(a) is a schematic of the hull arrangement whilst Fig. 1(b) is the body plan.

The uniform backbone of the model, with a thin-walled rectangular cross section, was designed to match the predicted natural frequency of the 2-node vertical bending mode (obtained from non-uniform Timoshenko beam theory). Table 2 gives the predicted and measured (from an impact hammer test) dry 2-node natural frequencies at full scale. Fig. 2 presents

Table 1
Principal particulars of typical naval frigate at model and full scale.

Parameter	Model	Ship
Length overall, L_{OA} (m)	2.60	113.40
Length between perpendiculars, L_{BP} (m)	2.52	109.72
Breadth, B (m)	0.29	12.36
Draft at amidships, T (m)	0.096	4.19
Displacement, Δ (kg, Tonnes)	29.40	2921
LCG aft amidships (m)	0.091	3.96
Pitch gyradius, k_{yy} (%L_{OA})	23.21	24.0
Ship service speed, V_s (ms^{-1}, knots)	1.40	18.0
Scale	43.62	1