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# Experimental investigation of the influence of floodwater due to ship grounding on motions and global loads

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ABSTRACT

High profile collision and grounding incidents show that safety standards for ships need improvement to ensure ship survivability and reduce the potential for loss of life. An experimental investigation into the influence of floodwater, and transient flooding on the motions and structural response of a ship hull following a grounding incident is presented. Results show that floodwater can have a significant effect on the magnitude of ship responses; testing of the transient flooding case provides the opportunity to quantify the magnitude of these changes as well as the time to flood by provision of intact and flooded data during a single test. The movement of the floodwater free surface shows some substantial second order sloshing effects close to the ship peak response, but little movement in higher frequency waves. Comparisons to classification design rules indicate that there is scope for further assessment of safety margins, including investigation of global responses in conjunction with any local loading due to the presence of floodwater. Future work will look at improving the modelling of the floodwater free surface and carrying out further transient flooding testing in order to better quantify the effect of a ship grounding incident on the survivability of a vessel.

## 1. Introduction

Ship safety is of paramount importance to a vessel's operator and crew in order to ensure confidence in the operation and survivability of the ship. In an ideal situation a ship should be able to act as its own lifeboat and return to port safely following a damage incident. High profile collision and grounding incidents in the last two decades, such as those given in Table 1, have shown that there is scope to enhance safety standards for ships (Lois et al., 2004). Severe accidents can cause major economic, social and environmental problems (Zhu et al., 2002) including significant structural damage to a vessel, loss of life and environmental pollution (Pedersen, 2010). Research shows that severe accidents at sea involve over 1.5% of ocean-going vessels annually and incidents involving collision, contact and grounding damage dominate (Pedersen, 2010). Eleftheria et al. (2016) further review safety levels of ship accidents and find that the frequency of accidents has increased in the last decade. This statistic, and the associated casualties, can be considered unacceptable given modern navigation technologies available.

Vanem and Ellis (2010) assessed 826 accidents involving passenger ships (including Ro-Ro ferries) between 1990 and 2006, finding that collision (15%) and groundings (16%) were the most common causes of accident after fire and explosion, and machinery and hull damage. For passenger vessels, fatalities are more likely with a grounding than collision incident; 5% of fatalities (including missing) associated with the 826 incidents were due to collision whilst 17% occurred during groundings (Vanem and Ellis, 2010). Evacuation times, and therefore whether the vessel capsizes, also significantly affect fatality rates. This can be seen in the incident between Eifuku Maru No. 18 and Jia Hui detailed in Table 1, where all fatalities were from the capsized Eifuku Maru (gCaptain, 2013a). If less than 5 minutes are available for evacuation the fatality rate can be as high as 96% compared to 7% if the vessel remains afloat for 90 minutes or more; the equivalent statistics for groundings are 88% and 5% (Vanem and Ellis, 2010). Further, a disparity in size between vessels involved in a collision is also more likely to result in fatalities (e.g. the 2013 collision between the 161 m long Sima Sapphire and a fishing vessel).

Further statistical studies have been performed to establish the most likely location of occurrence of damage for particular incidents; the results of these studies can be used to inform experimental and numerical modelling of vessels subject to damage. In particular, the extent of the damage (in terms of length and girth) will have significant

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**Table 1**
Collision and damage incidents in the last 5 years.

| Year | Ship | Incident | Result | Casualties |
|---|---|---|---|---|
| 2015 | Thorco Cloud cargo ship/Stolt Commitment | Collision | Afloat/sank | 6 out of 12 crew missing from Thorco Cloud |
| 2015 | Norwegian Dawn cruise ship | Grounding | Refloated | None |
| 2015 | Hoegh Osaka | Grounding | Refloated and repaired | 1 injured |
| 2014 | Vectis Eagle general cargo ship | Grounding | Refloated and repaired | None |
| 2014 | MV Colombo Express/MV Maersk Tanjong | Collision | Afloat | None |
| 2013 | Maria security vessel/Texal 68 trawler | Collision | Sunk/afloat | 3 missing |
| 2013 | Sima Sapphire/Fishing vessel | Collision | Afloat/sunk | 8 missing |
| 2013 | Eifuku Maru No. 18/Jia Hui | Collision | Capsize/afloat | 6 missing |
| 2013 | MV Smart coal cargo ship | Grounding | Structure compromised | None |
| 2013 | MV Danio cargo vessel | Grounding | Refloated and repaired | None |
| 2012 | Costa Concordia cruise ship | Grounding | Sunk | 2 missing<br>32 deaths |

strength implications for a vessel, particularly if located in the amidships region where the global hull strength is concentrated (Zhu et al., 2002); hence it will affect the global loads measured during testing. Zhu et al. (2002) find that the majority of grounding damage occurs at, or just forward of amidships with a girth less than 50% the ship breadth and a length generally less than 5% the ship length (and unlikely to be greater than 20% the ship length). Furthermore, a larger vessel will experience significantly greater damage extent and hull girder loads than a smaller vessel during grounding (Pedersen and Zhang, 2000). Collision incidents are more complicated as the damage location and extent will depend on the relative angle between the colliding vessels (bow-bow or bow-side for example), as well as the relative sizes of the colliding vessels. Pedersen and Zhang (2000) show that there is a 25% probability of damage extending for more than 15% of the ship length for vessels longer than 100 m, and 17% for vessels shorter than 100 m. Severe damage incidents have been known to cause a vessel to split in half, more common when grounding or structural failure is being considered (e.g. the MV Rena in 2011 or the MV Smart in 2012); a colliding vessel is more likely to be vulnerable to sinking due to hull penetration.

The relatively high frequency of damage incidents, and the structural implications associated with them, makes it important to better understand the survivability of ships subject to damage – not only the motions, but also the global loads (specifically the vertical bending moment) that a ship hull is subject to when damage occurs. Kim et al. (2013) for example use a risk-based approach to investigate safety guidelines for the ultimate hull girder strength of a grounded containership with a view to developing acceptable damage criteria and salvage or rescue techniques. However, further effects due to damage such as water influx, movement of floodwater within the hull (hence free surface effect) and the abnormal load distribution created within the hull by the ingress of floodwater, will have a significant effect on ship structural response. As a first stage, these are aspects that need to be investigated experimentally in order to gain an understanding of the interaction between the interaction between the ingress of floodwater into the hull and the associated change in ship responses (ITTC, 2011).

To date, experimental investigations into damaged ship responses are somewhat limited. Those that have been conducted focus on either the vessel response (motions and global loads) or the behaviour of floodwater inside a damaged compartment but not the interaction between these effects.

One of the most extensive investigations into ship response is that by Korkut et al. (2004) and Korkut et al. (2005) into the six degree of freedom motions and global loads of a Ro-Ro ferry subject to symmetric, two compartment damage. A flexible model hull was used and results found that the motions and vertical and horizontal bending moments are less in the damaged than intact condition for a Ro-Ro in beam seas. Palazzi and de Kat (2004) investigated the motions of a damaged frigate and the potential for capsize following damage using a rigid model. Lee et al. (2007) presented experimental results for the motions of a damaged Ro-Ro vessel subject to three different damage locations – bottom, side shell and bow visor damage. The model was flexibly moored, and the damage extent in each case was based on the analysis of maritime casualties and measurements were taken of the six degree of freedom motions, accelerations and the floodwater height within the damage compartment. Time histories were obtained of the change in ship motions during floodwater ingress into each damaged compartment. Lee et al. (2012) used a passenger ship hull to assess vessel motions and the free surface of floodwater inside a damaged compartment. Begovic et al. (2013) investigated the motions of an intact and damaged frigate in head, beam and quartering seas at zero speed including the effect of having the model either freely drifting and restrained. Six degree of freedom motions were measured using a motion capture technique and two-compartment, symmetric flooding was assumed. In general the model was in a steady flooded state prior to commencement of the test, although for the beam seas case tests were conducted with the damage aperture open to the waves (note that the damage aperture was positioned on the side of the vessel, making it representative of collision damage). Manderbacka et al. (2015) conducted an investigation into the transient flooding of a box shaped barge. The investigation focused on the change in roll damping with and without the inclusion of flooded water, and the effect of division of the flooded compartment (both symmetric and antisymmetric). Video imagery was used to measure the flooded water surface within the barge. A recent publication is that of Acanfora and De Luca (2016) which assesses the influence of the location of damage (side or bottom damage) on the roll decay, and the sway, roll and heave RAOs of a stationary passenger ferry in still water and beam on to regular waves. Results show that the different damage conditions significantly affect the motions experienced and highlight the need for further research, as presented in this paper.

There are clear indications here that more research is required into ship safety and whether vessels meet current safety standards. Although previous research has looked at ship motions during transient flooding at zero speed, assessing the structural response is considered by the authors to be particularly important as ship flexibility will change substantially when a damage opening occurs. Furthermore, recent events such as the sinking of Costa Concordia in 2012 demonstrate that a ship does not automatically become stationary as soon as damage occurs and therefore the influence of forward speed should also be addressed. How the floodwater behaves inside the ship following damage will indicate the relative impact of the additional mass due to floodwater in the vessel versus the free surface effect of the moving floodwater on the ship responses during a damage incident. With the number of damage incidents increasing in the last decade, it is also imperative to obtain an indication of the ability of a vessel to meet current design standards following damage.

The focus of this paper is therefore to investigate the influence of floodwater, transient flooding and forward speed on the motions and structural response of a ship hull travelling in regular waves. The