The role of ship motions on green water and the probabilities

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1 Introduction

Waves interact with ships, sometimes in ways that lead to impacts. Green water is one of these impact types. Green water is water that crashes on the deck or against superstructures and can lead to large impact pressures. They are extreme events, which means that they do not occur often. Knowing how often these green water events occur during a ship's lifetime is helpful for ship design.

In literature, the probability of water exceeding the deck has been used as an analogy for the probability of green water. The exceedance probability is obtained from setups with mainly fixed, ship-like models in irregular waves [1, 2, 3]. All these methods are based on the probability of a water elevation exceeding the deck elevation, but in order to consider events green water a considerable volume of water has to flow on deck [4, 5]. Exceedance events are not always green water events, as white water and spray events also occur, but these events do not induce the large pressures and subsequent damage that is associated with green water [6]. Also, Greco [7] found green water events where deck exceedance was not measured before green water: hammer-fist type events. The assumption in previous research that exceedance and green water are the same has resulted in the already complex green water problem being made more complex as now conclusions have to hold for not only green water, and also for exceedance events as no differentiation is made between these different event types. This has for instance led to the probability of green water occurrence, in the strict definition that it needs to lead to a considerable volume of flow on deck, not yet being quantified to the authors' knowledge.

Besides the occurrence of green water, also the expected pressures caused by green water events are needed to design for green water. For the pressures much research focuses on the pressure and pressure development during an event, using static box shapes in regular or breaking waves [8, 9, 10, 11, 12, 13]. From a design perspective, however, also the distribution of the maximum pressures over a range of green water events is of interest as this would give the expected pressures on a ship during a green water event.

The first goal of the present work is to differentiate between exceedance that is not followed by a large volume of flow on deck and green water by finding for which motions and waves only exceedance occurs and for which motions exceedance becomes the flow on deck associated with green water. Also, the probability of green water occurrence and the distribution of the pressures is found. Lastly, a calculation method for the expected maximum pressures during a ship's lifetime is shown.

2 Methodology

Data from experiments modelling 1945 full-scale sailing hours in irregular head waves and with forward speed is used, also used in Boon and Wellens [14]. The data set is available on https://doi.org/10.4121/21031981 [15]. The data is from experiments in a wave-current tank where the model is kept stationary while the water flows.

Green water (GW) and exceedance that did not become green water (EX) are differentiated using the distance of flow onto deck as an identifier. If the flow on deck is limited but water is measured to exceed the deck level it is classified as exceedance. A flow of water on the deck from the stem to at least 8% of the ship's length between perpendiculars (L_{pp}) is classified as green

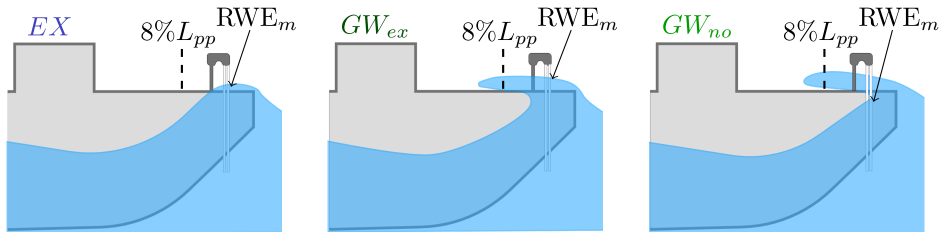


Figure 1: Schematic of the different event types. From left to right exceedance without green water (EX), green water with exceedance (GW_{ex}) and green water without exceedance (GW_{no}). RWE$_m$ indicates the measured relative wave elevation

water. This limit was chosen based on the green water events shown by Buchner [1] and Pham [16] which all reached over 8% L_{pp}. Green water events for which no exceedance was measured (GW_{no}) were also found. In total 409 green water events were identified. Figure 1 shows schematics for the different event types and figure 2 actual events from the experiments.

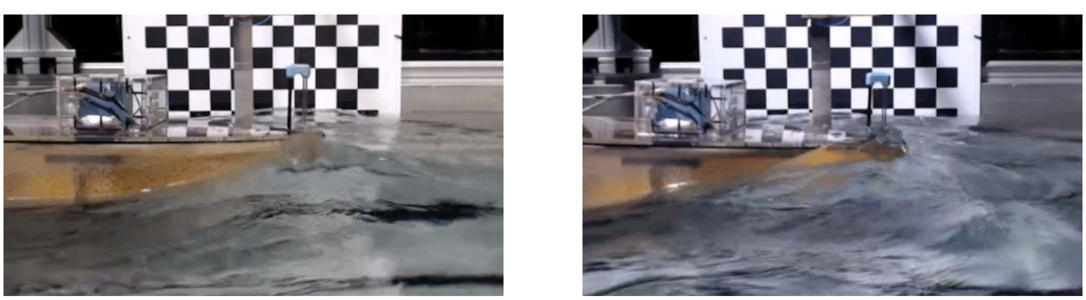
3 Results

The number of events that occurred for GW and EX event types are investigated. The number of green water events (n_{GW}) is found to be 0.85 times the number of exceedances without green water. The number of green water events without measured exceedance is 0.17 times the total number of green water events.

Figure 3 shows RWE$_m$ over significant wave height (H_{m0}) for the different data sets. The figure shows that the average RWE$_m$ for exceedance events is consistently lower than the average RWE$_m$ for green water events. A similar increase in RWE$_m$ over H_{m0} for $GW_{ex} \cup EX$ was found in the present study as was found by Soares et al. [3]. The increase in RWE$_m$ for $GW_{ex} \cup EX$ is mostly caused by an increase in RWE$_m$ for GW_{ex}, as figure 3 shows. This indicates a difference between the mechanisms that lead to either a GW or EX event.

Not only the relative wave elevation is different, but also the pitch motions during an event differ for GW and EX, as green water events only occur with a large forward pitch, while exceedance events also occur when the pitch is neutral. Figure 4 visualizes the difference with histograms. Similar heave positions and wave heights are found during GW and EX events.

From the large data set the probability of specifically a green water event occurring and the distribution of occurrence, as well as the maximum local and global pressures per event, are found.



(a) EX event

(b) GW event

Figure 2: Stills from footage of GW and EX events

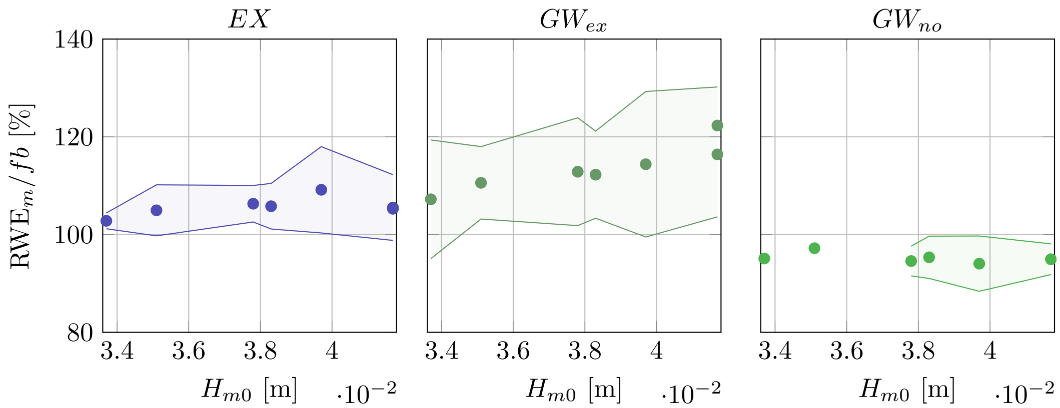


Figure 3: Difference in RWE$_m$ for EX, GW_{ex} and GW_{no} shown from left to right. The shaded area indicates the standard deviation of RWE$_m$. As for $H_{m0} < 0.036$ m the GW_{no} set has one event per case no standard deviation is shown. The values as a percentage of the freeboard (fb).

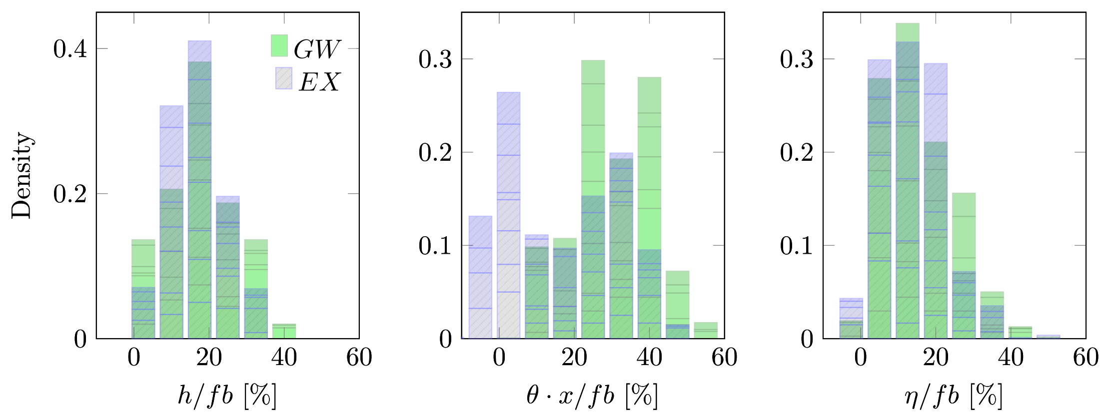


Figure 4: Visualizing the differences and similarities between EX and GW with RWE$_m$, heave (h), pitch (θ) times the distance from the centre of buoyancy to the stem (x) and wave height (η) as percentage of freeboard in stacked density histograms.

The distribution for the times between both GW and EX events is the exponential. The global and local maximum pressures are distributed according to the Fréchet distribution, also referred to as extreme value distribution II.

The probability of a certain limit pressure (p_{lim}) being exceeded during an event can be calculated with the cumulative distribution function of the Fréchet distribution.

$$Pr(p_{max} > p_{lim}) = 1 - exp(-\frac{p_{lim} - m}{c})^{\alpha}. \quad (1)$$

Here p_{max} is the pressure on deck, m is the location parameter, c the shape parameter and α the scale parameter. Combining equation 1 with the number of events occurring over a ship's lifetime, using compound probability theory, gives the probability of a pressure being exceeded during a ship's lifetime.

$$\begin{aligned} Pr(p > p_{lim}) &= 1 - (1 - Pr(p_{max} > p_{lim}))^{n_{GW}} \\ &= 1 - (exp(-\frac{p_{lim} - m}{c})^{\alpha})^{\frac{t}{\lambda_{GW}}} \end{aligned} \quad (2)$$

4 Conclusion

Green water and exceedance event types are compared to find for which motions and waves exceedance events occur and for which motions and waves they develop into the considerable volume of flow on deck associated with green water. Less than half of the exceedance events develop into green water. Differences between the relative wave elevation for EX and GW events indicate that different mechanisms are at play. This is also indicated from the difference in pitches that is found during green water events and exceedance events without green water. Green water events consistently occurred with large forward pitch motions, while exceedance also occurs when the pitch is neutral.

The distributions of the time between green water events and the pressures during the events have been identified and an equation for the probability of a pressure being exceeded during a ship's lifetime is given.

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