A Relationship Between Breaking Wave Characteristics and Slamming Forces Acting on Jacket Structures

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ABSTRACT

The goal of this study was to investigate and describe the relationship between breaking wave characteristics and total slamming forces acting on a jacket structure in shallow water, based on the experimental data collected during the WaveSlam experiment. Total slamming forces were filtered from the measurement, using Empirical Mode Decomposition (EMD). From these results impulse slamming forces, peak slamming forces, slamming coefficients, rising time and duration time were calculated. The transformation of the breaking wave parameters along the flume was analysed. Then, breaking points for each wave were identified, based on parameter changes along the flume, combined with visual analysis of video recordings of slamming events. The relationship between slamming forces and geometrical parameters at breaking was investigated. It was found that the breaking wave forces and breaking wave forces' parameters depend most strongly on breaking point location, breaking wave height, wave front steepness and horizontal wave asymmetry.

KEYWORDS: Breaking Waves, Slamming Force, Wave Forces, Jacket Structure, Breaking Wave Characteristics

INTRODUCTION

In recent decades, Europe has become a leader in wind energy production. Starting from 2001, the market has seen an exponential growth in the number of offshore wind investments. In 2017, only along the European coast, 560 new offshore wind turbines across 17 wind farms were installed, doubling the number of investments in the previous year and exceeding the record from 2015 by 4% (Remy, Mbistrova and Pineda, 2018). The substructures of wind turbines can be either fixed-type structures (monopiles, gravity-based, tripod and jacket structures) or floating-type structures (semi-sub, spar or TLP (tension-leg platform)). Due to the simplicity of the design and installation, monopiles are widely used. However, their operating water depths, as well as turbine capacity and size, are limited.

On the other hand, the jacket structures can hold larger turbines, which is why the share of jacket type substructures in offshore wind applications rises every year. Due to the lower costs of installation, maintenance and grid connectivity, the majority of offshore wind farms are installed in relatively shallow water depths. Currently, most of the offshore wind investments have been developed at 5- to 30-m water depths. The integrity, stability and longevity of the offshore structures depend strongly on an understanding of the interactions between those structures and the waves acting on them.

In shallow water regions, where waves undergo nonlinear transformations, such as wave shoaling and breaking, the offshore structures are subjected to highly varying hydrodynamic loads, occasionally from plunging breaking waves (Chaplin, Flintham, Greater and Skyner, 1992). Shallow water hydrodynamics is far more complicated, compared to breaking wave processes in deep water, and understanding the wave structure interactions in shallow water regions is particularly challenging. The impulsive breaking wave forces are considered a key design criterion for substructures in shallow water, and it is of great importance to estimate them accurately. The truss structures offer advantages, compared to the monopiles in many design situations, as they are more transparent to the waves and have a larger load-bearing capacity. Slamming have been researched thoroughly in recent years (Dias, Ghidaglia, 2018; Tu, Cheng, Muskulus, 2018; Peeringa, Hermans, 2017). Number of studies investigated the impact forces on the jacket structures in shallow water (Arntsen, Obhrai and Gudmestad, 2013; Arntsen and Gudmestad, 2014; Jose, Podrażka, Obhrai, Gudmestad and Cieślikiewicz, 2015; Jose, Podrażka, Gudmestad and Cieślikiewicz, 2016; Jose, Podrażka, Gudmestad and Cieślikiewicz, 2017), nevertheless the uncertainties regarding breaking wave-offshore structure interactions still exist.

During wave propagation in shallow water regions, with increasing wave height and steepness, the forward momentum of the wave front rises as well. The slope of the wave front increases until the wave breaks. Therefore, the wave becomes nearly vertical at the breaking point, especially for the plunging breaker. The energy from the plunging breaking waves dissipates over a relatively small impact area. When a nearly vertical front of the wave hits the surface of the structure, it causes a sudden drop in momentum, which exerts high local pressures and a high impulsive load of short duration, of the order of milliseconds (Goda, Haranaka and Kitahata, 1966). The additional term, called slamming force, must be added to quasi-static Morison forces (Morison, Johnson and Schaaf, 1950) to estimate the effects of breaking waves acting on offshore structures:

$$F_T = F_I + F_D + F_S \quad (1)$$

As a result, the total force (F_T) is a sum inertia (F_I), drag (F_D) and slamming forces (F_S). of Wave particle velocity, breaking position and the shape of the wave surface at breaking play a significant role in describing the impact force. As a wave propagates over a uniform seabed slope, it interacts with the seabed, which results in a steepened wave crest and a flattened wave trough. Thus, the wave reaches the breaking point with an asymmetric profile. The wave steepness, described as the ratio between wave height and length, is the most commonly used parameter to describe the wave's asymmetric profile, in both deep (Bonmarin, 1989; Kjeldsen and Myrhaug, 1978) and shallow water (Adeyemo, 1969 Ischida and Iwagaki, 1978). However, wave steepness is not sufficient for the geometrical description of the local wave profile at breaking. Kjeldsen and Myrhaug (1978) investigated the geometry of the wave profile at breaking in deep water, using steepness and asymmetry factors. In previous studies (Jose, Podrażka, Gudmestad and Cieślikiewicz, 2016; Jose, Podrażka, Gudmestad and Cieślikiewicz, 2017), the authors investigated the relation between front crest asymmetry and breaking wave height and total and local slamming forces acting on the jacket structure in shallow water for selected cases. This study focuses on the steepness and the asymmetry characteristics of a breaking wave in shallow water and tries to shed some light on the relationship between those parameters and total slamming force characteristics. A comprehensive study of wave breaking on the jacket structure is performed, based on the data obtained during the three days of a large-scale experiment, in which a wide range of breaking wave cases was measured. The desired total wave slamming forces from the measured forces were computed with the empirical mode decomposition (EMD) method (Cieślikiewicz, Gudmestad and Podrażka, 2013; Jose, Podrażka, Obhrai, Gudmestad and Cieślikiewicz, 2015; Jose, Podrażka, Gudmestad and Cieślikiewicz, 2016; Jose, Podrażka, Gudmestad and Cieślikiewicz, 2017a,b).

There is a limited number of studies dealing with interactions between breaking waves and jacket structures in shallow water. Most were conducted on a small laboratory scale, which introduced problems with scale effects. Since jacket structures are much more complicated than monopiles, the analysis of the wave forces acting on them is more complicated. The empirical models that are found very useful for calculating forces on monopiles (Wienke and Oumeraci, 2005; Goda, Haranaka and Kitahata, 1966) cannot be easily transferred to jacket structures, due to members' orientation, size and interactions between them.

Gaps in knowledge about wave-jacket structure interactions and numerous uncertainties in this area inspired the realisation of the WaveSlam (Wave Slamming Forces on Truss Structures in Shallow Water) project, a joint initiative of the University of Stavanger, the Norwegian University of Science and Technology, Trondheim, Norway, (NTNU) and a number of industry and scientific partners. The objective of the research was to investigate the slamming forces from plunging breaking waves acting on truss structures in shallow water regions and to improve the method to calculate those forces through model tests on a large scale. The experiment was conducted in 2013 in the Large Wave Flume in Hannover, in the Coastal Research Center, a Joint Central Institution of the Leibniz Universität, Hannover, and the Technical University of Braunschweig, and was one of the first attempts to study breaking wave forces on the jacket structures on a large scale (Arntsen, Obhrai and Gudmestad, 2013).

EXPERIMENTAL STUDY

The truss structure's model, designed at a scale of 1:8, was tested for a wide range of breaking wave conditions. The experimental setup is presented in Fig. 1.

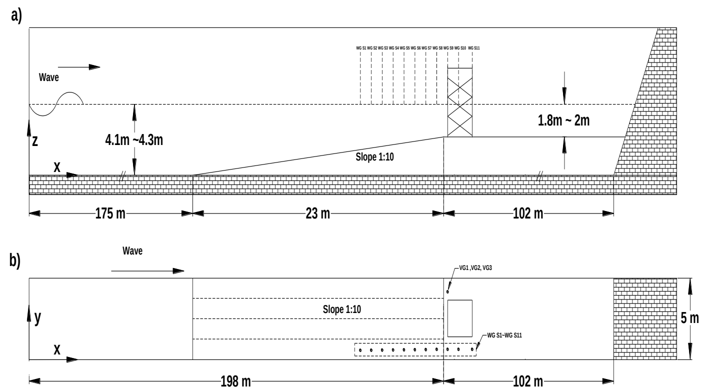

Fig. 1 Schematic representation of experimental set-up a) side view b) top view (Jose, Podrażka, Gudmestad and Cieślikiewicz, 2017).

The wave flume is 300 m long, 5 m wide and 7 m deep. The piston type wave generator generated the waves, and an upper flap movement superimposed the horizontal movement of a wave paddle to simulate the water wave kinematics more accurately. A 1:10 slope was created to produce depth-limited wave breaking. The tested truss structure was installed immediately behind the slope on the berm. It was suspended from the girder fixed across the frame, approximately 200 m from the wave paddle. The legs of the structure were hanging freely 4 cm above the bottom. Eight wire wave gauges (WG S1-S8), distributed along the flume with 1 m resolution, to track wave transformation along the slope, and three additional ones located at the front, middle and back of the jacket structure (WG S9-S11), recorded the water surface elevations (see Fig. 1). For reflection analysis and incident wave measurements, additional gauges were installed above the flat bottom, approximately 100 m from the wave paddle.

Additionally, three Acoustic Doppler Velocity meters (ADVs), positioned in line with the front leg of the structure, measured three-dimensional flow velocities. Total and local force transducers recorded the response force of the structure under the wave action, and the structure's natural frequency was identified during impulse hammer tests. The wave channel (GWK) data acquisition system, with real-time recording, allowed readings from all instruments to be logged simultaneously. Furthermore, one high-speed and two normal-speed cameras captured the slamming events on the structure.

During the experiment, the truss structure was tested for an extensive range of wave conditions, with the majority of tests carried out for regular waves with different wave heights and periods (H=0.75 m-1.9 m; T=3 s-5.55 s), as well as for irregular waves, based on the JONSWAP spectrum. String wave gauges recorded water surface elevation data with a 200-Hz sampling frequency. At first, the water depth during the testing was set to 4.3 m, in the vicinity of the wave generator, but an additional set of tests was performed with a lower water level (4.1 m), to create conditions for the wave to break at the front of the structure. In the presented study, only regular waves were taken into consideration. Wave cases from three days (14.06.2013, 17.06.2013 and 19.06.2013) were analysed. The waves with initial wave periods between 4.1 to 5.55 s and wave heights between 1.6 to 1.8 m were chosen for the analysis, as those were the cases for which wave breaking occurred. Each regular wave train consisted of 20 individual waves; however, for wave-structure interaction analysis, only waves causing slamming were considered. Four transducers (Model/Type: HBM/S9M), installed at the back of the structure: two on the top (FTTF02 and FTTF04) and two on the bottom (FTTF01 and FTTF03), measured the total response of the structure to the wave action (see Fig. 2). Twelve dual axis transducers (FTBF01-FTBF12) measured the response forces on the bracings, and ten local force transducers (FTLF01-FTLF10), mounted in 40-mm-high sections on the front legs, provided information on the vertical distribution of the forces. The transducers recorded response forces with a 10000-Hz sampling rate.

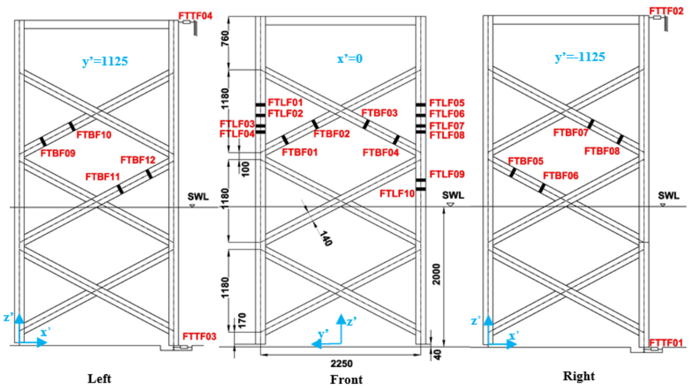

Fig. 2 Location of the force transducers (FTTF01-FTTF04, FTBF01-FTBF12, FTLF01-FTLF10) and dimensions of the structure in mm (Jose, Podrażka, Obhrai, Gudmestad and Cieślikiewicz, 2015).

METHODOLOGY

The total wave forces acting on offshore structures in shallow water are the superposition of slowly varying, quasi-static Morison forces and large impulsive slamming forces, due to wave breaking. The force recorded by the force transducers has a dynamic amplification component, which is the result of the structure's excitation at or close to its natural frequency. As the primary interest of this paper lies in the slamming force and its relationship with breaking wave parameters, a separation procedure was used to remove the Morison force and the effect of dynamic amplification from the measured response force. The EMD method, previously described by the authors (Jose, Podrażka, Gudmestad, Cieślikiwecz, 2016), was employed. The resulting slamming forces were then analysed, and force parameters were computed. The geometrical wave parameters were computed, based on the wave gauge measurements recorded during the WaveSlam experiment. Based on those parameters, the breaking point, in relation to the jacket structure's position in the wave channel, was calculated. Further, the relationship between breaking wave parameters and slamming characteristics was analysed.

Estimation of total slamming force and force characteristics

In this study, EMD (Huang, Shen and Long, 1999) was used to separate total slamming forces from the recorded global response force of the jacket structure to the wave action. The EMD method decomposes the signal into intrinsic mode function (IMF): the dynamic amplification component due to the structure's vibration and the residue: the net breaking force. The net breaking force is a sum of the Morison force and the slamming wave force. The total global response of the structure was computed as a sum of the responses recorded by four total force transducers. A detailed description of the method used and its applicability can be found in the authors' previous work (Jose, Podrażka, Obhrai, Gudmestad and Cieślikiewicz, 2015; 2016). From the resulting slamming force, the following parameters were obtained:

- Peak slamming force (maximum slamming force);
- Force rise time, defined as the time taken by the signal to change from zero to its maximum value;
- Duration time, which is the time of an impact;
- Impulse slamming force, which is defined as the integral of the impact (slamming) force over duration time.

For the majority of the analysed cases, a double hit of the wave on the structure was observed. This means that, after the front crest of the breaking wave impacted the front of the structure, only part of the energy dissipated, causing a second, in most cases less severe, impact on the back of the structure. The abovementioned parameters were computed for both impacts.

Estimation of breaking wave parameters

The distance of the breaking point from the structure, breaking wave height and the shape of the breaker play a significant role in describing the wave impact force. The geometrical parameters: wave crest front steepness (S_f) and wave crest back steepness (S_b), wave horizontal asymmetry (A_h) and wave vertical asymmetry (A_v), as well as wave height (H), as defined in Fig. 3 and Eqs. 2~5, were computed based on the wave gauge measurements, for all locations along the flume.

$$S_f = \eta'/L' \tag{2}$$
$$S_b = \eta'/L'' \tag{3}$$
$$A_h = L''/L' \tag{4}$$
$$A_v = \eta''/\eta' \tag{5}$$

The same procedure as that incorporated by Jose et al. (2016; 2017b), who computed the wave's crest front steepness and breaking wave height, was used here to calculate the extended wave characteristics. The zero-downcrossing method was used to calculate wave height (H), wave crest amplitude (η') and wave trough amplitude (η'') (Massel, 1996). The wave crest front and back periods were estimated based on the wave gauge measurement, and then an approximation of dispersion relation for shallow water waves (see Eqs. 6~8) was used to compute wave lengths associated with those periods. Dispersion relation is expressed as:

$$\omega(k) = c(k)\,k \tag{6}$$

where ω is phase velocity, k is a wave number and c is a wave phase velocity, which in shallow water depends only on water depth (h) and gravitational acceleration (g), and is calculated as :

$$c = \sqrt{g\,h} \tag{7}$$

hence the wave length is shallow water can be calculated as:

$$L = \sqrt{g\,h}\,T \tag{8}$$

During wave propagation in shallow water, with the decreasing depth, the wave profile becomes steeper, resulting in an increase in wave front crest steepness and wave height values. When both parameters reach a critical value, the wave breaks, and those parameters' values suddenly drop. Knowledge about these properties, combined with the analysis of video recordings of wave propagation in the vicinity of the jacket structure, was used to compute the breaking point location for each wave. Further, the wave characteristics at breaking location were identified and used to analyse the relationship between breaking wave properties and the total slamming force acting on the structure, as explained by Jose et al. (2017b).

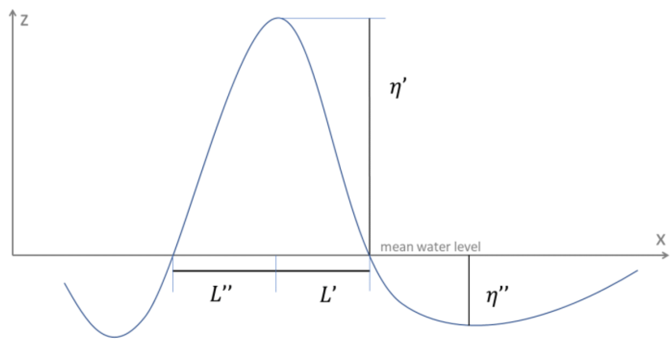

Fig. 3 Definition sketch of geometrical wave parameters.

RESULTS

In this study, all the data collected for regular waves during the WaveSlam experiment are analysed. Fig. 4 shows the typical slamming force exerted by one individual breaking wave acting on the jacket structure. The red line represents the wave impact on the front of the structure, and the black line represents the second impact of the same wave while hitting the back of the structure. In about 70% of the analysed cases, a double hit on the structure was identified. In most of the slamming events, the second hit was 50 to 70% lower than the initial slamming force value.

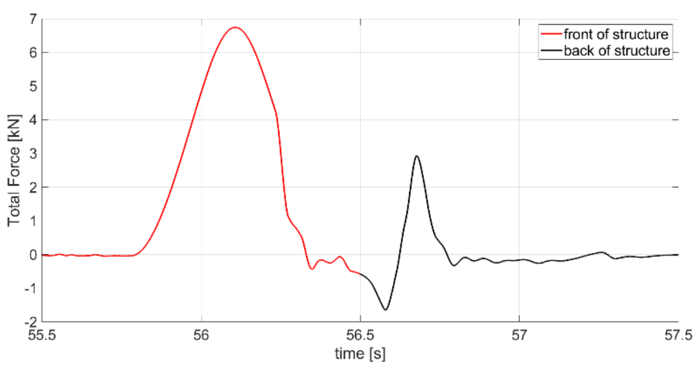

Fig. 4 Total slamming force on the structure.

Fig. 5 shows the relationship between the maximum value of the slamming force acting on the structure and the position of the breaking point with regard to the location of the structure. The location of the structure in the flume is marked as position 0 on the x-axis. Red dots represent the maximum slamming force acting on the front of the jacket structure, and the black dots represent the maximum value recorded for the second hit, on the back of the structure. As stated in the previous paragraph, for the majority of analysed cases, the second impact is significantly lower than the first one. It is also observed that the breaking wave location affects the magnitude of the slamming force acting on the front of the structure more than the force acting on the back of the structure. The maximum value of the second impact force for each breaker location, even for the most severe wave conditions, does not exceed 4 kN. On the other hand, the total slamming force on the front structure is strongly affected by the breaker's location. The highest values are registered for waves which are breaking just in front of the structure, 0 and 1 m from the jacket structure.

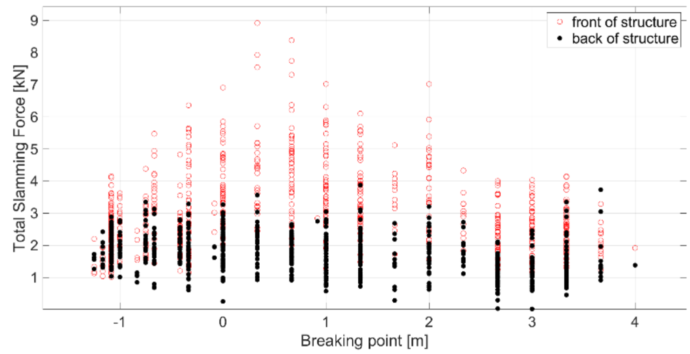

Fig. 5 The dependency between breaking point location and total slamming force acting on front and back of the structure.

The relationship between the maximum slamming force registered during each wave slamming event and the location of the breaking point, regardless of whether the greater impact force was exerted on the front or back of the structure, was also analysed. It can be seen from Fig. 6 that the front of the structure had to withstand the greatest impact, for the majority of the slamming events. However, the second impact force was greater if the wave broke in the middle or at the back of the structure. Most probably, in those cases, the wave breaking was forced by the presence of the structure itself, not the slope, as in the cases when the wave broke at some distance in front of the structure.

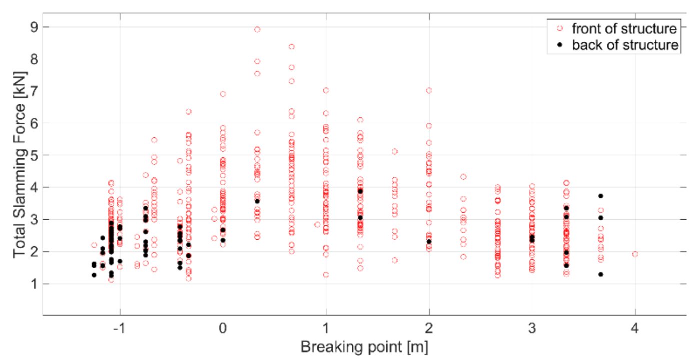

Fig. 6 The relationship between breaking point location and maximum slamming force acting on the structure.

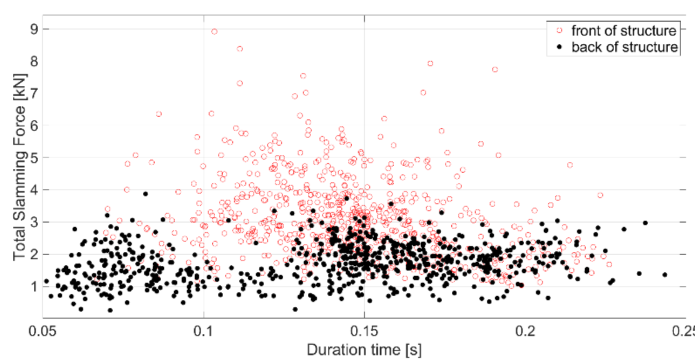

Fig. 7 The relationship between total slamming force magnitude and duration time.

The results of all recorded slamming forces are presented in Figs. 7~8.

Fig. 7 shows the relationship between the total slamming duration time and the magnitude of the slamming force. One can see that, in the case of slamming at the front of the structure, the highest magnitudes appear for duration times between 0.1 and 0.2 s. For the second hit, the increase in the force is observed in two distinct time intervals. The first increase lies between 0.05 s and 0.1s, and the second, between 0.12 and 0.22s.

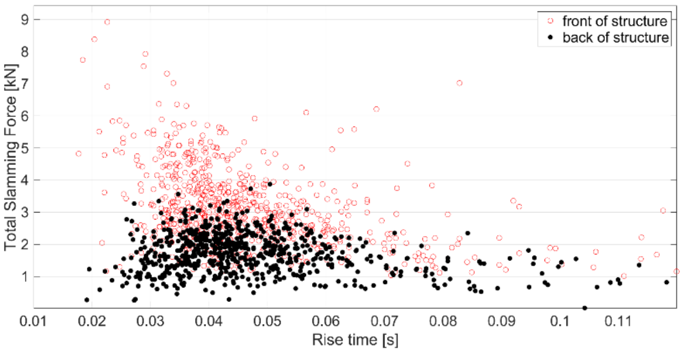

Fig. 8 The relationship between total slamming force magnitude and rise time.

The relationship between peak total slamming force and force rise time is shown in Fig. 8. It can be seen that the highest magnitudes are related to short rise times in the range between 0.03-0.05 s. The waves which break just in front of the structure act as an impulse on the structure. They exert the greatest slamming forces in very short duration times, and this impact creates the highest risks for the structures and can lead to their failure.

The results in Figs. 9~14 are presented for maximum slamming force recorded during each slamming event, regardless of whether the maximum impact occurred on the back or front of the structure. It is apparent that the breaking point location strongly governs the total slamming forces. Nevertheless, the wave front shape and the wave height at breaking play essential roles in impact-force generation, as proved in previous studies (Jose, Podrażka, Gudmestad, Cieślkiewicz, 2017).

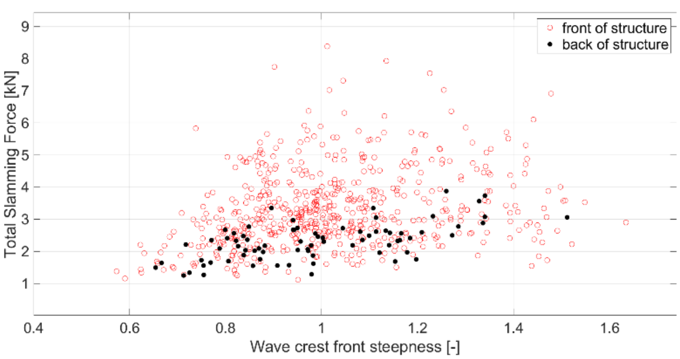

Fig. 9 The relationship between wave crest front steepness and maximum total slamming force.

Fig. 9 presents the relationship between wave crest front steepness and total slamming force, exerted on the front and the back of the structure. The results are presented for all available cases with different initial wave periods and initial wave heights. The process of wave breaking is strongly nonlinear. Thus, geometrical properties at breaking differ from wave to wave, even for the same wave train generated with the same initial conditions. Nonetheless, it is clear that the peak slamming force value increases with the increasing wave crest front steepness. The same relationship is observed for slamming on the front and back of the structure.

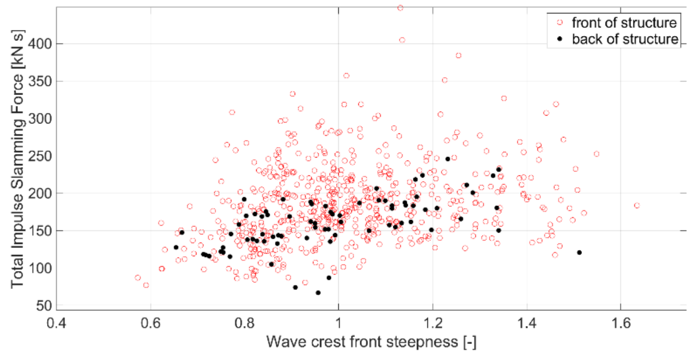

Fig. 10 The relationship between wave crest front steepness and maximum total impulse slamming force.

Fig. 10 shows the dependency between wave crest front steepness and maximum total impulse slamming force. As explained in the previous section, impulse force was calculated as the integral of slamming force over time. Impulse slamming forces show less variation than the peak slamming force. Thus, the dependency between the wave parameter and slamming force is even more evident. Moreover, even though the slamming forces acting on the back of the structure have lower magnitudes, they have longer duration times compared to the slamming forces acting on the front of the jacket structure. As a result, impulse force on the back of the structure is equal to about 50% of impulse force on the front.

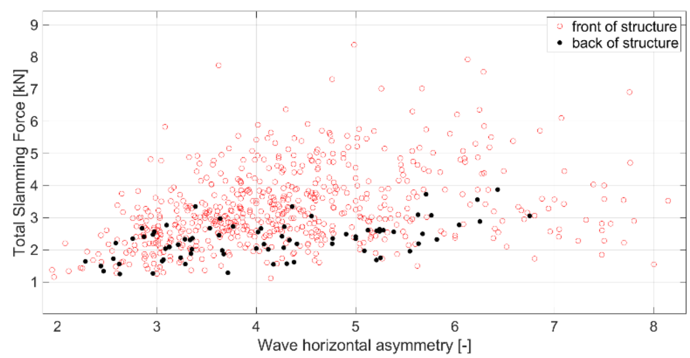

Fig. 11 The relationship between wave crest horizontal asymmetry and maximum total slamming force.

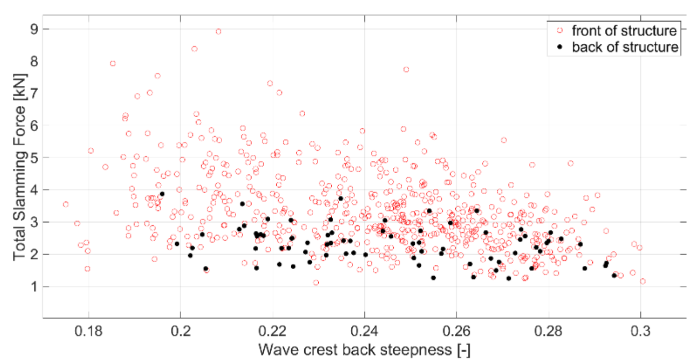

Fig. 12 The relationship between wave crest back steepness and maximum total slamming force.

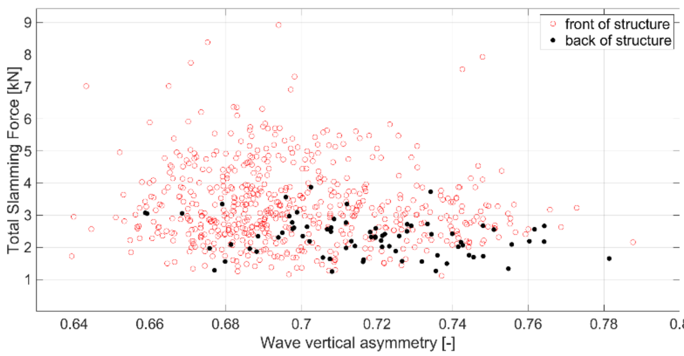

Fig. 13 The relationship between wave vertical asymmetry and maximum total slamming force.

As seen in Fig. 13, no correlation between the total slamming force magnitude and the wave vertical asymmetry was observed. It is the result of a very small variation in this parameter for different individual waves. This means that, for the range of cases analysed in this study, the ratio between wave crest and wave trough remains in the range of 0.65 to 0.75. Fig. 14 shows the relation between breaking wave height and the total slamming force. The increase in breaking wave height results in an increase in the total slamming force. The highest waves create the most severe impacts on the jacket structure.

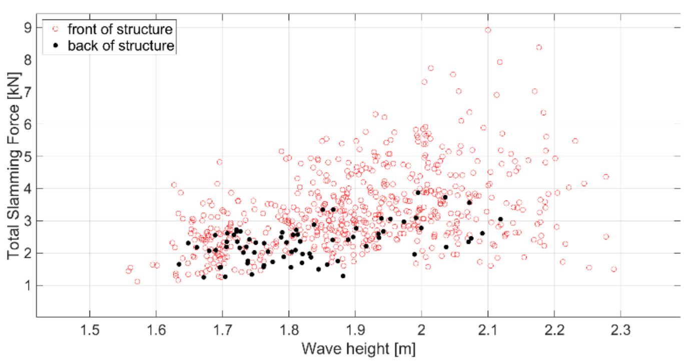

Fig. 14 The relationship between breaking wave height and maximum total slamming force.

CONCLUSIONS

This paper presents a comprehensive study on the interactions between breaking waves and the jacket structure in shallow water. The analysis and the results presented in the study are based on the wave and force data recorded during a large-scale experiment, conducted within the WaveSlam project. One thousand slamming events, associated with regular waves breaking, were registered during the three days of the experiment. During the experiment, the global response of the structure to the wave action was recorded. Total slamming forces were obtained from the measurements, using the EMD method. Breaking wave position along the flume and breaking wave parameters were computed, based on recordings from wave gauges distributed along the flume. Four geometrical parameters: wave crest front steepness, wave crest back steepness, wave vertical asymmetry and wave horizontal asymmetry, as well as breaking wave height, were calculated. The relationship between those parameters and the total slamming forces on the structure was analysed.
In the majority of the analysed cases, wave breaking in the vicinity of the jacket structure caused a double impact on the structure: on the front and back parts of the structure. The greatest total slamming forces were exerted on the structure by waves breaking at 0 to 1 m in front of the structure. Excluding the cases where waves broke in the middle or at the back of the structure, the magnitude of the second hit was significantly lower than that of the first one.
The strong dependencies between breakers' position, wave crest front steepness, wave horizontal asymmetry and breaking wave height were observed. It was concluded that the greatest total slamming forces were exerted by high waves with a steep crest front but relatively long crest back. In such cases, the large part of the jacket structure is impacted by nearly vertical wave front, which carries a significant mass of water.

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