Methods for Analysing Wave Slamming Loads on Truss Structures used in Offshore Wind Applications based on Experimental Data

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ABSTRACT

Offshore wind turbines installed in shallow water regions are subjected to highly varying hydrodynamic loads, also from plunging breaking waves. Many investigations have been made regarding the wave slamming forces acting on both vertical and inclined piles, on flat and sloping bottoms. However, very few studies have been carried out to study the slamming forces on truss structures. In this paper, the wave slamming loads on the truss structure are analysed based on the experimental studies carried out on a 1:8 truss model. The total force and the forces on local members were registered during the experiment. The total and local forces on the structure have been analysed using two different methods. The total slamming loads on the truss structure were analysed using the Empirical Mode Decomposition (EMD) method and for the local forces on the truss structure, the Frequency Response Function (FRF) method was used. The EMD method is based on time series decomposition of the measured force and the FRF method is on the hammer tests performed on the local force members during the experiments. The relative strengths and weaknesses of both the methods have been discussed and conclusions on optimum analysis method for those data set have been proposed. In addition, the slamming forces calculated from the measurements are compared with the values obtained using the existing force models.

KEY WORDS: Jacket, Truss Structures, Wave Slamming load, Breaking Wave Load, Empirical Mode Decomposition, Frequency Response Function, Hammer Test.

INTRODUCTION

Due to the depletion of conventional energy sources and growing energy demands, wind energy is becoming more popular. Offshore-based wind turbines have started to become popular because of the specific nature of the wind field over maritime areas. Wind turbines can be placed in shallow water regions, where they are subjected to highly varying hydrodynamic loads, also from plunging breaking waves (Chella et al., 2012, Navaratnam et al., 2013, Arntsen and Gudmestad, 2014). The total forces acting on such structures can be divided into the quasi-static force (Morison force) and the slamming force due to breaking waves. The wave slamming forces are very large forces acting for a short period of time. Many investigations have been made regarding the wave slamming forces acting on both vertical and inclined piles, on flat and sloping bottom (Goda et al., 1966; Sawaragi and Nachino, 1984; Wienke and Oumeraci, 2005); also monopile and tripod structures have been taken into consideration (Goda, 1973; Hanssen and Tørum, 1999). There are however a limited number of experimental studies on slamming loads on truss structures. The wave slamming force F_S caused by the breaking wave can be treated as an addition to the drag F_D and inertia F_M Morison forces. The total loading force F_T can be written as,

$$F_T = F_D + F_M + F_S \tag{1}$$

where, slamming force is given by Goda et al. (1966) as,

$$F_S = \frac{1}{2}\rho_w C_s D C_b{}^2 \lambda \eta_b \tag{2}$$

F_D and F_M are drag and inertia force respectively. F_S is the slamming force, C_S is the slamming coefficient, C_b is the breaking wave celerity and λ is the curling factor. According to Goda et al. (1966), the slamming coefficient C_S is π and curling factor λ is 0.4. Wienke and Oumeraci (2005) calculated higher slamming forces than those predicted by Goda et al. (1966) with a slamming coefficient C_S, 2π and curling factor λ, 0.46.

The WaveSlam project (Arntsen and Gudmestad, 2014; Arntsen et al., 2013) was carried out in 2013, with the aim to investigate the wave slamming forces from plunging breaking waves on a truss structure in shallow water. The large-scale truss model was tested for plunging breaking waves. During the experiment, unique data sets were collected and recorded.

The total wave forces on the truss structure and the local forces on the members of the truss structure were recorded during the experiment. One of the difficulties with analysis of the measured data is the separation of the quasi-static and the dynamic part of the response force and the removal of the effect of structure's natural frequency. The purpose of this paper is to determine the optimum method to calculate the slamming forces on the truss structure under plunging breakers in large-scale experiment. The total wave forces acting on the structure are analysed using the Empirical Mode Decomposition (EMD) method and the local forces on the truss members are analysed using the Frequency Response Function (FRF) method. The wave slamming force from the experimental results were compared with the existing models.

WAVESLAM PROJECT

Within the WaveSlam project, large-scale tests were carried out in 2013 at the Large Wave Channel, Coastal Research Centre, Joint Central Institution of the University of Hannover and the Technical University of Braunschweig. The truss structure was modelled in a scale of 1:8. The experimental set-up is shown in Figs. 1~2.

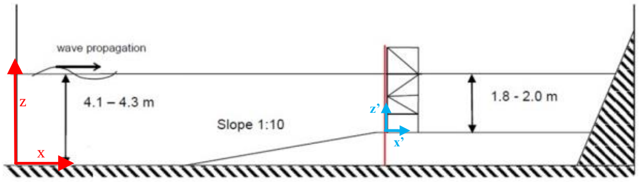

Fig. 1 Experimental set-up on the Large Wave Flume FZK, global and local coordinate systems (Arntsen et al., 2013)

Fig. 2 Instrumented truss structure in the Large Wave Flume FZK and the local coordinate system. Figure used with permission from the WaveSlam project group.

The wave flume is 300 m long, 5 m wide and 7 m deep. The waves were generated by a wave paddle, acting in the horizontal direction and the strokes were superimposed by an upper flap movement in order to simulate the water wave kinematics most accurately. The truss structure was located approximately 200 m from the wave generator, on a 10% slope. The structure was suspended from a girder fixed across the frame. The legs of the truss structure were hanging freely with a bottom clearance of 4cm. There were eight wave gauges distributed along the wave flume, additionally one was located at the front leg of the structure and another one in the middle and at the back of the structure.

The truss structure was equipped with four total force transducers (Model/Type: HBM/S9M) installed at the top (two transducers: FTTF02 and FTTF04) and the bottom (two transducers: FTTF01 and FTTF03) of the structure (see Fig. 3). There were ten local force transducers (FTLF01–FTLF10) placed on the vertical front legs and twelve dual axis force transducers (FTBF01–FTBF12) on the bracings, which measure the response of the structure to the impact forces.

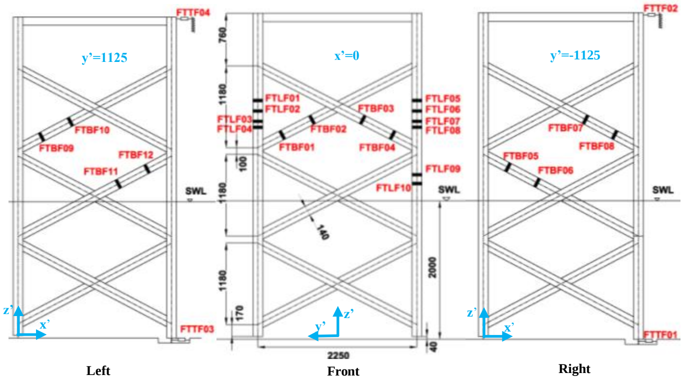

Fig. 3 Locations of the force transducers (FTLF01–FTLF10, FTTF01 –FTTF04 and FTBF01–FTBF12) and the dimensions of the truss structure (all dimensions in mm).

The majority of the measurements were carried out for regular waves (H=0.75–1.9m and T=3–5.55s) with specific frequencies and wave heights (Arntsen et al., 2013) as well as for the random waves based on JONSWAP spectrum. Readings from all instruments were logged using the GWK data acquisition system, with a true time recording. In addition, one high-speed and two normal-speed cameras were used to capture the slamming events on the structure.

METHODOLOGY

Frequency Response Function Method

In the FRF method, for calculating the wave slamming force on the structure, proper transfer functions have to be obtained for the whole structure and for the local members. A frequency response function/transfer function is the quantitative measurement of the response of the structure when it is subjected to any input. In other words, it is defined as the response of the structure for unit force, in our case it is the unit impulse force. In the experimental set up, impulse hammer tests were performed on the structure for calculating the transfer functions. The impulse hammer is a hammer look like device which has several interchangeable impact tips. The impulse hammer excites the test structure with a constant force over the frequency range of interest. The force sensor mounted on the head of the impulse hammer, transforms the force impulse into electrical signals, which completely describe the forcing function. The measured response from the total and local force transducers, which includes the response of the structure, is also recorded.

Määtänen (1979) used the Frequency response function method (FRF method) to resolve ice forces from the measured forces when the structure was subjected to moving ice. The same procedure can be applicable for calculating the wave slamming loads on the truss structure, Tørum (2013). Preliminary analysis of the WaveSlam data by Navaratnam et al. (2013) showed how effective the FRF method is in calculating the wave slamming loads on the structure. Fig.4 shows the slamming force separation procedure using FRF method.

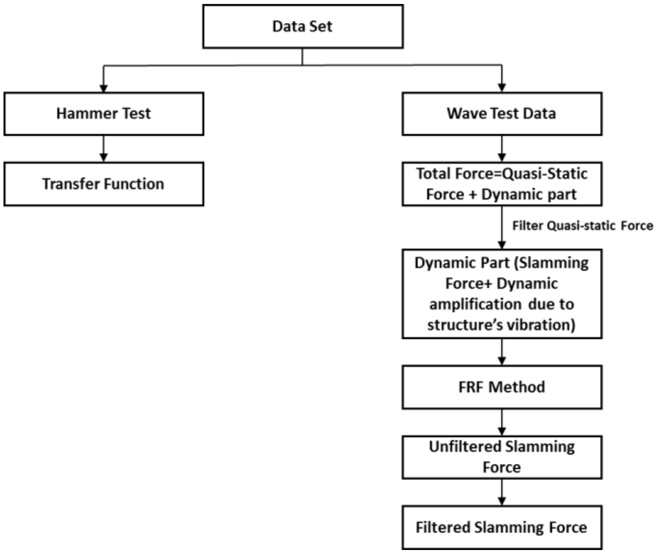

Fig. 4 Slamming force separation using FRF method

In the case of forced excitation, the response of the structure $f(t)$ can be expressed in Fourier integral form as

$$f(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}H(\omega)Y_F(\omega)e^{i\omega t}d\omega \tag{3}$$

where, $H(\omega)$ is the Frequency response function or transfer function and $Y_F(\omega)$ is the linear spectrum of the forcing function $F(t)$.

The Fourier transform of Eq. 3 gives,

$$H(\omega)Y_F(\omega)=\int_{-\infty}^{\infty}f(t)e^{-i\omega t}d\omega=Y_f(\omega) \tag{4}$$

$$Y_F(\omega)=\frac{Y_f(\omega)}{H(\omega)} \tag{5}$$

$Y_f(\omega)$ is the linear spectrum of the response function $f(t)$.The forcing function $F(t)$ can be obtained by taking the Inverse Fourier transform of the above equation.

$$F(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{Y_f(\omega)}{H(\omega)}e^{i\omega t}d\omega \tag{6}$$

The above equation implies that, if the transfer function and the response spectrum are known, the forcing function can be calculated. The transfer function $H(\omega)$, is the calibration function for finding the forcing function.

The hammer tests for estimating the transfer function were performed on various impact points on the structure. The structure was hit with the impulse hammer on various impact points. The impulse hammer recorded the impulse force acting on the structure. The force transducers on the structure recorded the response of the structure for the hammer impacts. The ratio of the linear spectrum of the response force to the spectrum of the impulse force will give the transfer function, $H(\omega)$:

$$H(\omega)=\frac{Y_{Hammer\,Response}(\omega)}{Y_{Impulse}(\omega)} \tag{7}$$

The hammer tests were performed to calibrate the response of the whole structure and the local members. The hammer response obtained for the whole structure was found to have some inconsistencies in terms of the measured response forces by the top total force transducers. It was expected that the top transducers (FTTF02 and FTTF04) would record higher responses than the bottom transducers but this was not the case. The force response recorded by the top transducers also appeared noisier compared to bottom transducers (Jose et al., 2015). The impulse loadings applied by the hammer were relatively low and as a result the top two force transducers showed signs of 'clinging' (Fig.5). This limitation was considered to be caused by installation of the measuring equipment. It is assumed, there was a certain threshold which has to be exceeded to receive proper recordings and this was not achieved during the calibration tests. This limitation in the measured response would result in an overestimation of the slamming load when using the FRF method. As a result the FRF method was not used for calculating the total slamming force on the structure. The limitation in the top total force transducers was not observed in any of the wave tests. However, the results from the hammer tests can be used to calculate the natural frequency of the structure, shown in Table 1.

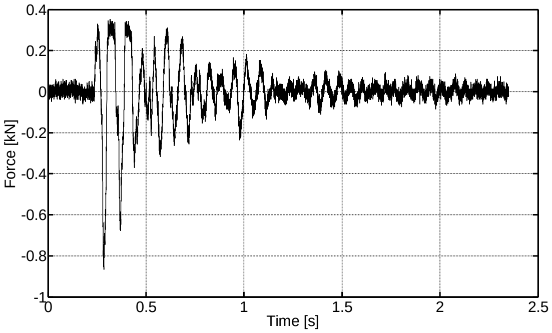

Fig. 5 Hammer response force recorded by the top total force transducer FTTF04.

Table 1. Summary of natural frequency of the jacket structure from hammer tests.

Hammer Test ID	Impact Location	Natural Frequency (Hz)
2406201324	FTBF01	25.33
2406201326	FTBF02	25.33
2406201327	FTBF03	25.66
2406201329	FTBF04	25.66

Empirical Mode Decomposition Method

The EMD method was developed by Huang et al. (1999), to decompose the given signal in the time domain. The EMD method decomposes the signal into a number of intrinsic mode functions (IMFs) and a residue. In the present study, the EMD will decompose the measured total response force into an IMF, which will represent the amplified force component due to the structure's vibration and a residue, which is the net breaking wave force. The net breaking wave force is the combination of quasi-static force and the slamming force. Choi et al. (2015) used EMD along with a low pass filter to analyse the slamming load acting on a mono-pile structure and verified the analysis method by comparing the results with values obtained from the numerical simulations. The use of a low pass filter can increase the efficiency of EMD in decomposing the measured signal. Fig. 6 shows the force separation procedure using EMD method.

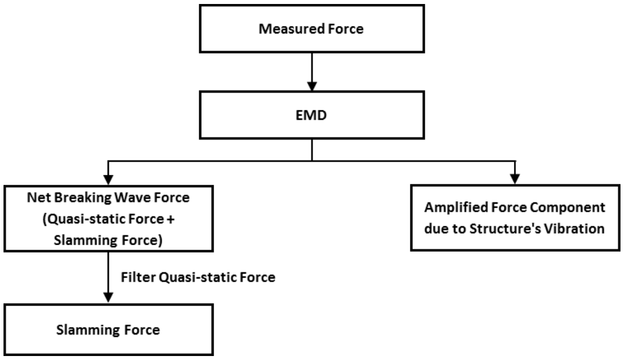

Fig. 6 Slamming force separation using EMD method

The various steps in EMD algorithm are:

1) Obtain the local extremes of the measured signal.
2) The extracted local extremes are connected to obtain the upper and lower envelope.
3) The mean of the upper envelope and the lower envelope is obtained, which is the residue and is subtracted from the measured signal to obtain the IMF.
4) The residue represents the net breaking wave force and the IMF represents the amplified component of the force due to the structure's vibration.

WAVE TEST

The details of the wave test case chosen for the present analysis are shown in Table 2. The total and local forces on the truss structure corresponding to the wave case are read from the data set. In each regular wave test, there were 20 wave samples. The response of the structure corresponding to the 14th wave sample (Fig. 7) is chosen for the present analysis as an example. The maximum wave force has been observed for this wave condition.

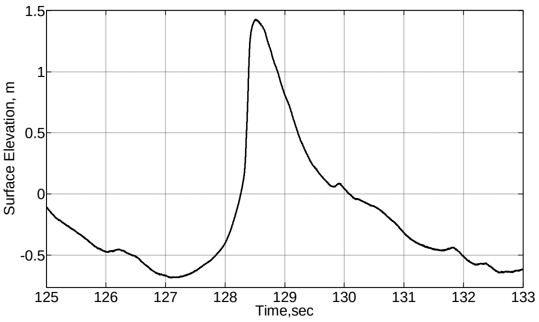

Fig. 7 Wave surface elevation time series of 14th wave measured by wave gauge at the front column of the structure.

Table 2. Wave test details

Description	Values
Test ID	2013061424
Wave Height (m)	1.7
Water Depth (m)	4.3
Wave Period (s)	5.55
Wave Type	Regular

For the current analysis, the forces registered by the four total force transducers (FTTF01–FTTF04) and one bracing transducer (FTBF01) on the front cross bracings are considered (see Figs. 8~9). The total response force of the structure presented in Fig. 8 is calculated by adding the force response recorded by the four total force transducers.

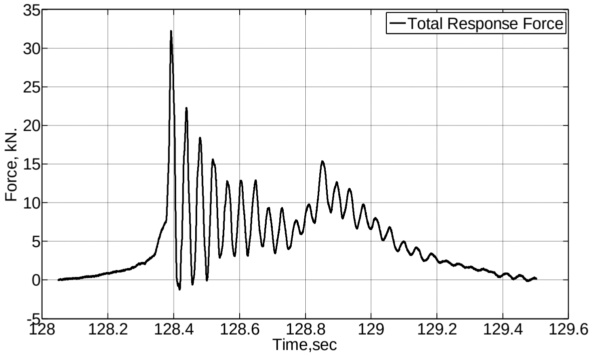

Fig. 8 Total response force of the structure for the Wave Test 2013061424 (14th wave sample).

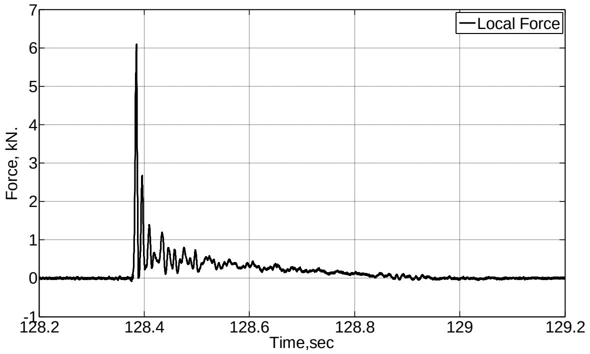

Fig. 9 Local force on the bracing measured by the bracing transducer FTBF01 for the Wave Test 2013061424 (14th wave sample).

RESULTS

Total Force Analysis

The EMD method is a time series decomposition method as mentioned previously. A Butterworth low pass filter combined with the EMD developed by Huang et al. (1999) has been used to remove the effect of dynamic amplification due to the structure's vibration (Choi et al., 2015). The cut-off frequency of the low pass filter should be chosen in such a way that it will not affect the measured slamming force signal. The low pass filter removes the high frequency noise from the measured signal and results in a smoother input signal to the EMD algorithm. This helps in effectively picking the local extremes from the measured signal. In the present case, a cut-off frequency of 100Hz was used to filter out the noise from the measured signal. The measured total force time series have mainly three different frequencies; the Morison force frequency, the slamming force frequency and the natural frequency of the structure. Based on the preliminary tests carried out on the truss structure, the natural frequency of the structure is around 24 Hz.

The EMD algorithm decomposes the measured signal into a number of intrinsic mode functions (IMFs) and a residue. The IMFs represents the effect of dynamic amplification due to the structure's vibration. The residue is the net breaking wave force, which is the combination of the Morison force and the wave slamming force. The Morison force is separated from the net breaking wave force to obtain the wave slamming force on the structure.

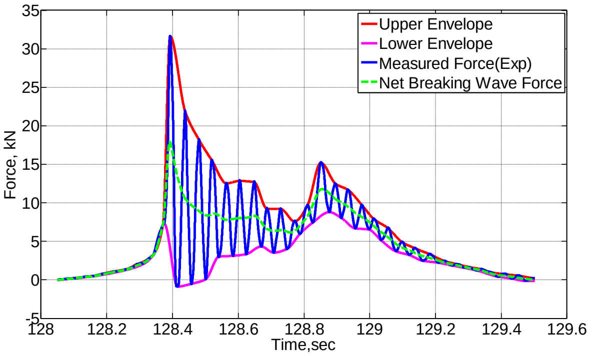

Fig. 10 Net Breaking wave force filtered out by low pass filter and EMD.

Fig. 10 shows the force separation procedure. The net breaking wave force (green dashed lines) is obtained from the total measured force by applying the EMD algorithm, as explained in the previous section.

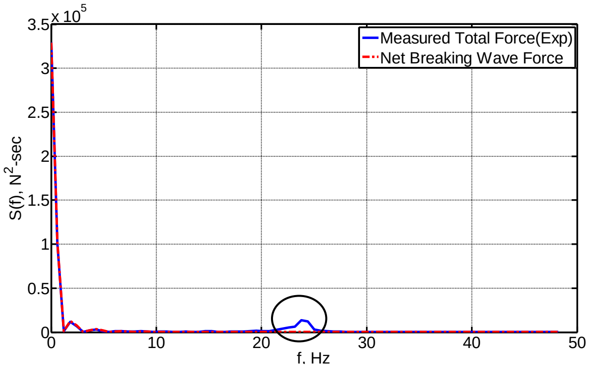

Fig. 11 Power Spectrum of the measured total force and the net Breaking Wave Force.

Fig. 11 shows the comparison of power spectrum of the measured total response force and the net breaking wave force obtained using the EMD algorithm. In the Figure, the region marked by the black circle shows the effect of dynamic amplification due to the structure's vibration. It is clear from the power spectrum that the dynamic amplification effect of the structure has been removed from the net breaking wave force. The net breaking wave force includes the Morison force and the slamming force components, however, our interest is the wave slamming force. In order to obtain the wave slamming force, the Morison force component must be removed from the net breaking wave force.

Wienke and Oumeraci (2005) carried out tests with almost breaking waves (i.e., the wave breaking at the rear side of the structure) and measured the non-breaking (or quasi-static) wave force acting on the structure. They then used this measured force as the quasi-static force, to calculate the slamming force from the total measured force when the wave breaks on the structure. Here a simpler approach is used to remove the Morison force component from the net breaking wave force. The measured response force is filtered using a low pass filter and the filtered component represents the quasi-static (Morison force) force component.

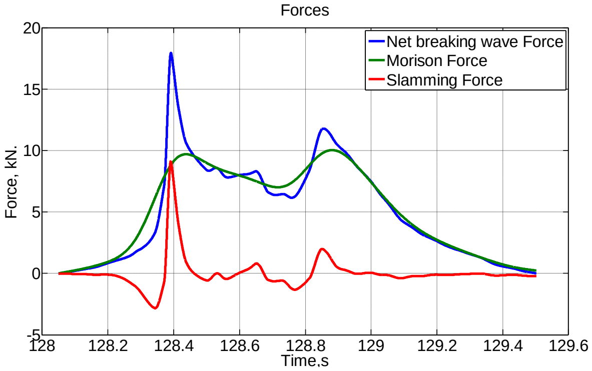

Fig. 12 Slamming force obtained after filtering the Morison force from the net breaking wave force.

Fig. 12 shows the Morison force component obtained by filtering the measured force using a low pass filter. The cut-off frequency of the low pass filter was kept near the incoming wave frequency. The wave slamming force is obtained by subtracting the Morison force from the net breaking wave force. In the slamming force time series (Fig. 12), the first peak (at 128.4s) is due to the wave slamming on the front columns and bracings of the truss structure and the second peak (at 128.85s) is due to the wave slamming on the backside of the structure. The nature of the net breaking wave force time series is similar to the one discussed by Wienke and Oumeraci (2005). The slamming force obtained from the measurements is compared with other preliminary investigations carried out on the WaveSlam data. Cieślikiewicz et al. (2014) carried out the analysis of the total force measurement data using FRF method. In the analysis, however, the limitation in the hammer test results (Jose et al., 2015) for the total force transducers were not considered. The maximum slamming force calculated was found to be slightly higher than the present values. Arntsen and Gudmestad (2014) also reported similar results from the preliminary analysis of the measurement data from the experiment. The total wave slamming force reported was in the range of 8–14kN.

Table 3 shows the comparison of the slamming force estimated by the data analysis and the existing models. The total slamming forces acting on the truss structure are calculated with existing models as a superposition of forces acting on the vertical piles and bracings within the assumed impact zone. The slamming coefficient corresponding to the measurement was obtained by comparing the measured slamming force with the theoretical formula used in the existing models, Jose et al. (2015). The values of the slamming coefficient are shown in Table 3. The maximum slamming force estimated according to the force models by Goda et al. (1966) and Wienke and Oumeraci (2005) are found to be much larger than those calculated from the measured forces.

Table 3. Comparison of slamming force and slamming coefficient

	EMD Method	Goda	Wienke
Slamming Force (kN)	9.60	26.60	61.19
Slamming Coefficient	1.10	π	2π

There are two comments we would like to make based on the comparison of the experimental values with the forces corresponding to the existing force models. Firstly, the force models according to Goda et al. (1966) and Wienke and Oumeraci (2005) were defined for monopile structures under specific experimental conditions. When these models were applied for the truss structures, the forces on the truss members in the wave impact zone were calculated and added to obtain the total slamming force. However, in reality, the wave is not acting symmetrically on the truss structure. From the video recordings and the measurements during the wave tests, the wave breaks on the front columns and the bracings of the truss structure at slightly different time in a random fashion. This reduces the total slamming force intensity on the truss structure and increases the duration of the impact. Secondly, there is an uncertainty in the values of the slamming coefficients used for calculating the wave slamming loads on the truss structure, by using the existing models. The slamming coefficient estimated based on the current experiment are found to be much lower than the literature values.

Local Force Analysis

The forces on the local members of the structure is analysed using FRF method. The hammer tests were performed on the force transducers and the response of the members for the hammer impacts were recorded. The calculation of transfer functions for each of the local force members was performed to determine the local slamming forces.

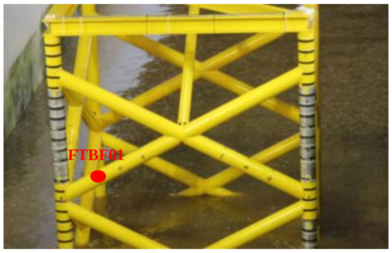

Fig. 13 The location of the bracing force transducer FTBF01 on the truss structure. The hammer test was performed on the same location.

The transfer functions were calculated for each of the force transducers based on the corresponding hammer test. The hammer test discussed in this paper is for the bracing force transducer FTBF01 (impact location: see Fig. 13) on the front cross bracing of the structure. The hammer test details are shown in Table 4.

Table 4. Hammer test details

Description	Values
Test ID	2013062424
Hammer Type	Large
Position Tested	FTBF01

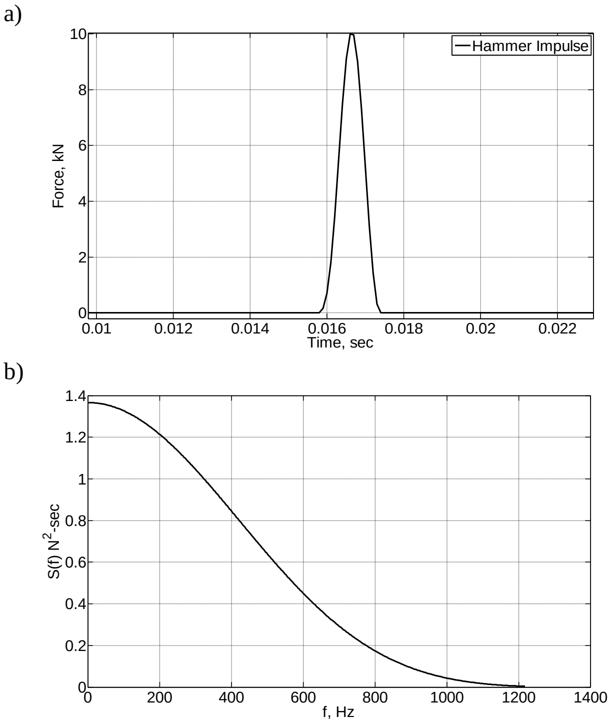

Fig. 14 a) Hammer impulse force recorded by the impulse hammer. b) Power Spectrum of the Hammer Impulse.

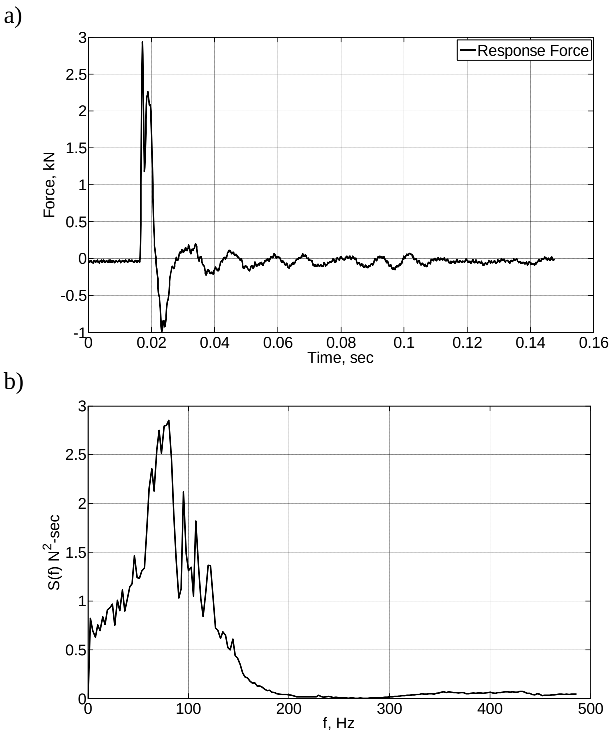

Fig. 15 a) Response force recorded by the bracing transducer FTBF01 for the hammer impulse. b) Power spectrum of the response force.

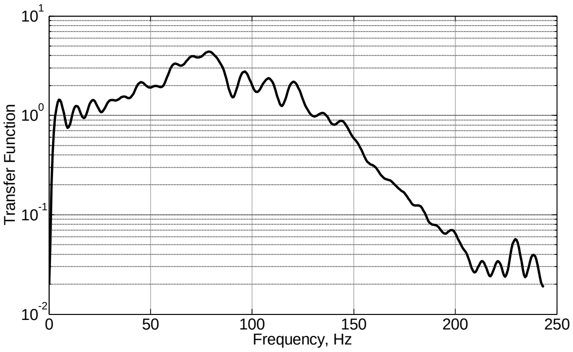

Fig. 16 Transfer function (semi log scale) calculated for bracing force transducer FTBF01.

Figs. 14~15 show the impulse hammer force and the response force of the bracing recorded by the bracing transducer FTBF01 and the respective power spectrums. The transfer function for the local force member is calculated based on Eq. 7. Fig. 16 shows the transfer function calculated for the bracing force transducer FTBF01.

The force recorded by the local force transducer (Fig. 9) is analysed using the calculated transfer function. Eqs. 3~6 show how the slamming force is calculated from the measured force using the FRF method. As mentioned, the measured force has both the quasi-static (Morison force) and the dynamic part. The Morison force component in the measured force is removed using a low pass filter. The cut-off frequency of the low pass filter is set near the wave frequency. The remaining high frequency part includes both the slamming force component and the force due to the dynamic amplification of the structure. Fig. 17 shows the result of filtering the quasi-static force from the total response force.

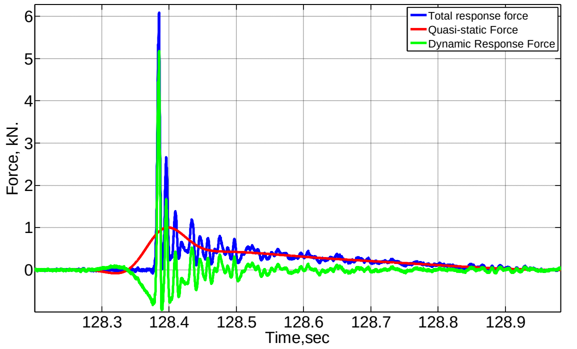

Fig. 17 Total response force recorded by the bracing force transducer FTBF01, quasi- static part and the dynamic response force.

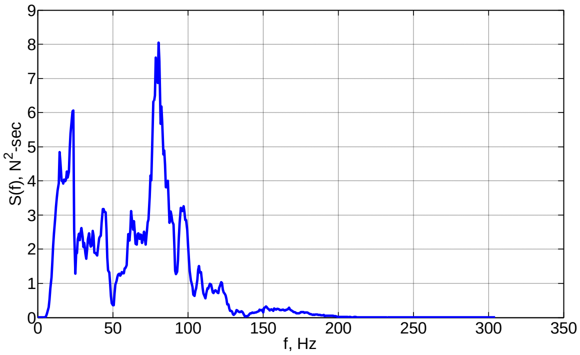

Fig. 18 Power spectrum of the dynamic response force.

The power spectrum of the dynamic response force presented in Fig. 18, shows there is no significant energy in the response force beyond a frequency of 200Hz. There are two significant peaks in the dynamic response spectrum (see Fig. 18) at around 24Hz and 80Hz. This depicts the influence of global and local dynamics of the structure on the local force response. The FRF method is applied to the dynamic part (high frequency part) of the measured force. By the virtue of this method, the effect of dynamic amplification of the structure will be removed to obtain the measured slamming force. However, in the slamming force obtained there is some spurious noise, which can be removed by applying a second low pass filter. In the dynamic response force spectrum, there is no significant energy beyond 200Hz hence, a cut-off frequency of 200Hz was chosen for the filter.

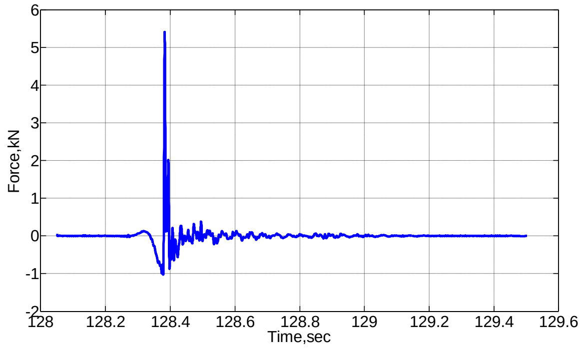

Fig. 19 Filtered slamming force (cut-off frequency 200Hz)

Fig. 19 shows the filtered slamming force. A cut-off frequency of 200Hz is reasonable enough to remove most of the spurious frequencies from the final slamming force. There is a dip in the slamming force time series just before the slamming impulse force at 128.4s, which is due to the overestimated quasi-static force just before the first peak in the response force as shown in Fig. 19. This is due to the limitation of the filter, to handle the sudden change in the force at the beginning of the impact. This limitation will not affect the final slamming force as the quasi-static force is well defined near the wave impact region.

Table 5. Comparison of slamming force and slamming coefficient.

	FRF Method	Goda	Wienke
Slamming Force (kN)	5.39	3.68	8.38
Slamming Coefficient	3.95	π	2π

Table 5 shows the comparison of the slamming force on the lower part of the bracing using the FRF Method and with the existing models for the wave case tested. The slamming coefficient obtained from the experiment was found to be lower than the one suggested by Wienke and Oumeraci (2005), 2π and slightly larger than the value suggested by Goda et al. (1966), π. Arntsen et al. (2011), in small laboratory experiments on monopile, obtained the slamming coefficients in the range of 3.5–4.3. Choi (2014), performed numerical simulations of wave slamming forces on a monopile. Based on his simulations, the slamming coefficient obtained was closer to the values obtained by Goda et al. (1966).

Due to the smaller impact duration, there will be significant slamming force energy near the natural frequency of the bracings (80Hz). If the EMD method is used to calculate the slamming force from the measured response, some part of the slamming force will be removed from the response force along with the dynamic amplification part. This may underestimate the slamming force acting on the bracings. Hence, for this reason, the EMD method is not recommended for the local force analysis.

CONCLUSIONS

Total Force Analysis

1) The EMD method is used to analyse the total force response of the structure. The EMD method is computationally less cumbersome compared to the FRF method. In addition, due to problems during the calibration hammer tests for the whole structure, the FRF method may result in an overestimation of the slamming force.
2) For the test case shown in the paper, the maximum slamming load filtered by the EMD method was found to be much lower than those calculated using the existing models by Goda et al. (1966) and Wienke and Oumeraci (2005). The force models of Goda et al. (1966) and Wienke and Oumeraci (2005) assume an impact area and a slamming coefficient. Moreover, the assumed slamming coefficient (e.g., π or 2π) is equally used for all members in the impact area and the wave is assumed to impact the total structure at the same time. Our results suggest that it is not reasonable to assume that the total slamming force can be calculated by simply adding the slamming forces due to individual members in the impact zone, which will overestimate the slamming force. There is significant uncertainty in the definition of the impact zone as well as the slamming coefficients. The slamming coefficients suggested by Goda et al. (1966) and Wienke and Oumeraci (2005) are based on experiments on monopile. These new experiments should therefore be used to define new slamming coefficients that are valid for the whole truss structures.

Local Force Analysis

1) The slamming force on the local members of the truss structure were analysed using the FRF Method. The transfer functions were calculated for each of the force transducers, using the measurements from the hammer tests performed on these transducers. The FRF Method is preferred for the local force analysis on the members of the truss structure. Due to the smaller impact duration, when the wave impacts on the local members, there will be significant slamming force energy near the natural frequency of the local members. The EMD method is suggested to remove those energies along with the structure's vibration.
2) For the test case, the slamming force calculated by the FRF method is compared with the existing force models by Goda et al. (1966) and Wienke and Oumeraci (2005). The existing models provided a reasonable estimate of the slamming force on the local members compared to the measurements. However, there is no exact agreement on the slamming coefficient to be used for the calculation. Further analysis of different wave cases is needed to comment on the final local slamming coefficient to be used.

There is a certain need to further study the slamming forces on the truss structure. The detailed analysis of the slamming force for various wave cases will be performed and the results will be included in coming papers.

LIMITATIONS

In both EMD and FRF methods, the quasi-static force component is removed from the measured force using a low pass filter. The cut-off frequency of the filter is kept high enough to eliminate the quasi-static forces and low enough to no disturb the dynamic oscillations from the impact load. The limitation of the filter restricts the removal of all the quasi-static force components from the total force response. Effect of this approximation is negligible since the quasi- static force is well defined near the slamming force region in the measured response. Further analysis of the data will be used to develop and validate a CFD model of a truss structure under breaking and non-breaking waves. This model can be used to estimate the quasi-static force on the structure and further improve our data analysis methods.

This paper is focussed on one typical wave case and further work is needed to analyse different breaking wave cases to understand the physics involved in the wave breaking on a truss structure.

The models of Goda et al. (1966) and Wienke and Oumeraci (2005) seem reasonable for the estimate of the local slamming loads on the individual members. However, there was a large difference in the total slamming load calculated by the existing models and the measurements. Further analysis is therefore needed to study the slamming loads on the local members and the whole structure for different wave cases.

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