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COLUMN SLAMMING LOADS ON A TLP FROM STEEP AND BREAKING WAVES

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ABSTRACT

Previous model test campaigns of various large-volume platforms indicate that wave impact loads on vertical platform columns can become high in extreme sea states. Column slamming is a highly non-linear and complex problem and reliable estimation[1] of Ultimate Limit State (ULS) and Accidental Limit State (ALS) design loads is a challenge. Previous measurements indicate ALS pressures of about 3 MPa acting on an area of typically 50m^2 in North Sea and Norwegian Sea wave conditions. The corresponding ULS loads were in the range 1.5-2.0 MPa for the same impact area. Such high predictions for ULS and ALS impact pressures may be critical for both steel and concrete platforms, and accurate predictions of design loads is therefore crucial to establish the correct level of safety.

A model test campaign dedicated to investigate column slamming has been performed on the Heidrun platform, a large concrete Tension Leg Platform (TLP). The column diameter is 31 m. The test campaign was performed in 2013 at Marintek (now Sintef Ocean), at a model scale of 1:55. The main objective of the test campaign was to estimate the characteristic slamming loads, defined as the q-annual extreme 3-hour slamming load level of 10^{-2} for the Ultimate Limit State (ULS) and 10^{-4} for the Accidental Limit State (ALS).

To ascertain that the test campaign would result in reliable load estimates, a pre-study on column slamming was performed, involving a selected expert group with participants from several organizations. Review of previous work, identification of governing parameters for wave impact and assessment of model uncertainties and extreme value prediction of slamming loads was performed. It was concluded that two challenges were to be specifically addressed during the planning and execution of the test: 1) the localized nature and short duration of the slamming loads and 2) the large statistical variability of the slamming loads. To address the first challenge, special focus was given to the extent and quality of the instrumentation capturing the slamming loads. Comprehensive documentation of the instrumentation was also performed using hammer testing, structural analysis and drop tests. The second challenge was addressed with a carefully planned test strategy. The resulting model test campaign set a new standard for model testing of such loads, using over 80 slamming panels with a sampling frequency of 19.2 kHz, and over 300 sea state realizations.

This paper presents the planning and execution of the model test campaign, including the instrumentation and model set-up, the test matrix, main challenges, findings and results.

INTRODUCTION

A model test campaign dedicated to investigate column slamming has been performed on the Heidrun platform, a large concrete Tension Leg Platform (TLP). The mass of Heidrun is approximately 260 000Mg, and the total draught is about 78 m. The column diameter is 31 m. The water depth at the field is 350 m. The test campaign was performed in 2013 at Marintek's Ocean Basin Laboratory, at a model scale of 1:55. The main objective of the test campaign was to estimate the characteristic slamming loads, defined as the q-annual extreme 3-hour slamming load level of 10^{-2} for the Ultimate Limit State (ULS) and 10^{-4} for the Accidental Limit State (ALS).

PRE-STUDY

To ascertain that the test campaign would result in reliable load estimates a separate pre-study was performed involving experts from NTNU, Marintek, Aker Solutions, Kværner, Statoil and Reinertsen. The work packages included 1) review of previous model tests and research projects on wave impact and

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[1] MARINTEK and SINTEF Fisheries and Aquaculture have merged into SINTEF Ocean AS. The new company became operative from 1 January 2017.

sloshing, 2) identification of governing parameters for impact loads from extreme waves, 3) assessment of model test uncertainties, 4) extreme value prediction of slamming loads, and 5) planning and specification of the Heidrun model test. It was concluded that two challenges were to be specifically addressed during the planning and execution of the test: 1) the localized nature and short duration of the slamming loads and 2) the large statistical variability of the slamming loads. To address the first challenge, special focus was given to the extent and quality of the instrumentation capturing the slamming loads. Comprehensive documentation of the instrumentation was also performed using hammer testing, structural analysis and drop tests. The second challenge was addressed with a carefully planned test strategy. Both issues are further discussed below.

EXPERIMENTAL SET-UP AND INSTRUMENTATION

The hull model was built from steel plating as a welded structure with correct local hull geometry. A simplified model of the topside was used. Figure 1 shows a photo of the model in the basin. The Heidrun TLP has 16 tethers, 4 in each corner. In the model tests, the four tethers at each corner were modeled by a single equivalent tether, designed to obtain correct axial stiffness and approximately correct bending stiffness and weight in water and approximately correct drag area when accounting for scale effect on the drag force. Since no wind and current was included during tests, the platform offset was modeled with a cord and spring to obtain a target mean offset and, more important for the tests, mean set-down.

Figure 1 Heidrun model in basin (Photo: Marintek)

One wave heading was tested, selected to be 337.5 degrees compared to geographical North on the Heidrun field. Only long-crested waves were tested. Arrays of wave probes were mounted in front of the instrumented columns. The coordinate systems and an overview of the main instrumentation is shown in Figure 2.

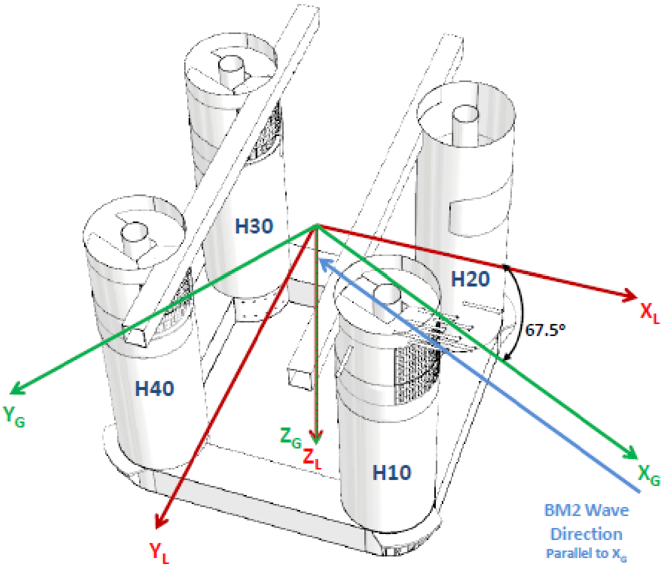

Figure 2 Coordinate system and overview of main instrumentation: force panel arrays on H10, H30 and H40. Wave heading is 67.5 degrees relative to the local coordinate system used for the platform.

An acquisition system manufactured by HBM GmbH was used for all the measurements. The model was instrumented with wave probes, accelerometers, force transducers on the tethers, position measurements and force panels. The system consisted of two separate acquisition configurations to be able to sample the wave impact data at a higher sampling rate than the relative wave and position measurements. The force panel and local accelerometer channels (mounted on one slamming frame and behind one force panel) were sampled at 19200 Hz (and then filtered at 2000 Hz), while the other channels were sampled at 400 Hz (and then filtered 40 Hz).

A total of 80 slamming panels were mounted on three of the four columns, 40 on the front column and 20 on each of the aft columns, see Figure 3. The aim was to capture the temporal and spatial distribution of the slamming loads as accurately as possible. The force panels covered a sector of 78 degrees of the up-wave column from the still water line to a vertical position of 24 m full scale. All panels were 3x3 m full scale, numbered by row 1-8 and column 1-7 as shown in Figure 3.

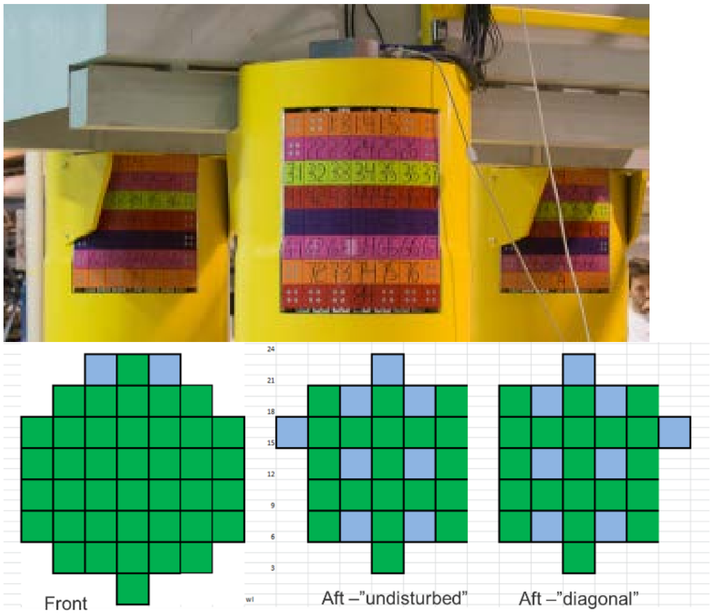

Figure 3 Top: Photo showing all 3 columns with panels. Bottom: Configuration of panels on the three columns. Green panels are active. Some changes on which panels were active were done during testing. (Photo: Marintek)

In the pre-study it was concluded that special attention was to be given to the extent and quality of the instrumentation capturing the slamming loads. Previous experience has shown that using force panels to measure slamming loads is challenging because loads with such short rise times tend to trigger structural eigen modes in the sensors and the foundations they are fitted to. This leads to dynamics that may contaminate the force measurements. For the present project with so many slamming panels, individual, manual treatment of impact load time series should be avoided. Thus, extra effort was put into the design of the force measurement system. The force panels were made of a light and stiff plastic material. The panels were produced by a 3D printer, allowing for curved geometry. They were mounted on new, stiffer sensors (barrel transducers) than previous used by Marintek. The foundation was also designed to minimize structural vibrations in the relevant frequency range. Figure 4 shows a photo of the force panel section during assembly. A more comprehensive description of the up-wave force panel section is given in [1].

WAVE CONDITIONS AND TEST PROGRAM

The focus of the model test campaign was wave impact of steep or breaking waves on the platform columns. The slamming load is highly dependent on the fluid particle velocity and the local impact angle between column and wave, and small changes in the details of the incoming flow causes large differences in the resulting load. Thus, very large statistical scatter is expected – and observed – in wave impact experiments.

Figure 4 The transducers and force panel assembly were mounted on a stiff steel sector. (Photo: Marintek)

This extreme variability represents a challenge when estimating design loads. Design loads from model tests are often obtained using the metocean contour line approach [2]. In the case of column slamming, the method is not necessarily appropriate. For the contour line approach to be applicable, the severity of the response should increase with increasing severity of the sea state. Morover, the coefficient of variance COV should not be too large (range for typical responses is 0.1-0.3). If the contour line approach is not applicable, a long term analysis should rather be performed to obtain q-probability loads. Experience from a previous model test [3] indicated that the contour line approach might be unsuitable for columns slamming. However, these tests were performed on a shallow-water GBS, where the geometry turned out to be very important.

The test program was divided into two phases. The first phase would determine the validity of the contour line including an approximate long term analysis to determine the appropriate percentile level. The second phase would either consist of a test program using the contour line approach, or a test program catering for a full long term analysis. This would require a prolonged test period.

In the first phase, one sea state on each contour line (1, 10, 100 and 10,000 years) was tested. As an estimate for the governing sea state at each contour line, the sea state with a maximum wave parameter as suggested by Stansberg [5]: $c_{TS} = [H_S^2/(1.56\,T_P^2\,)\,]^2$ along the contours was selected. Each sea state was tested with 20 realizations. This was considered sufficient to be able to indicate an increasing trend with increasing return period of the sea state. It was concluded that the slamming intensity and frequency increased with increasing return period. Further, a sufficient amount of sea states to perform an approximate long term analysis were then tested. This included both more sea states along the contour lines, and some sea states in between the contour lines.

The long term analysis performed during the model test campaign was presented in [4], concluding that if the contour line approach is to be utilized, a very high percentile would have to be used. It was nevertheless decided to proceed with the contour line approach. The second phase of the test program therefore consisted in testing more realizations of the sea states that were assumed to be governing. Full scale duration was 3 hours for all tests. All calibrated and tested sea states are shown in Figure 5. More sea states were calibrated than eventually were tested, for reasons explained above. The final test program is given in Table 1.

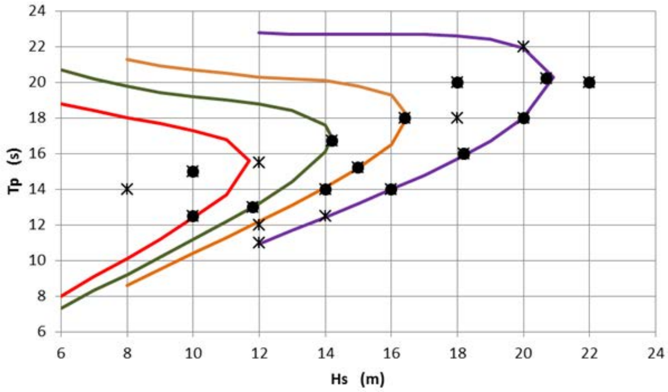

Figure 5 Contour lines, calibrated sea states (asterisks) and tested sea states (black dots).

Table 1 Overview of all irregular sea tests. Full scale duration was 3 hours for all tests.

Test Series	Return period	Hs [m]	Tp [s]	No. of realizations
20	1 yr	10.0	12.5	20
21	-	10.0	15.0	10
30	10.000 yr	18.2	16.0	19
31	10 yr	11.8	13.0	20
32	10 yr	14.2	16.7	10
40	100 yr	14.0	14.0	20
41	100 yr	15.0	15.2	40
42	100 yr	16.4	18.0	20
50	-	18.0	20.0	10
60	10.000 yr	20.0	18.0	10
61	10.000 yr	18.2	16.0	90
62	10.000 yr	16.0	14.0	10
63	10.000 yr	20.7	20.2	20
64	-	22.0	20.0	5
65^{**}	10.000 yr	18.2	16.0	5
66^{**}	10.000 yr	18.2	16.0	10

** Test series 65 and 66 are repeatability tests. The same realization was repeated, as opposed to the other tests where different realizations of the spectrum were run for each test.

DOCUMENTATION TESTS

As described above, the force panel sections were designed to give as little structural contamination as possible. Extensive hammer testing was performed prior to the basin tests to document the performance of the sections when mounted in the model. Different hammer tips were used to vary the rise time and duration of the impulse. Each panel was hit at the center, and at all four corners of the panel. All transducers were active while the hammer test were performed, and all measurements were checked for any cross talk between panels. The results showed that it was unlikely that sensor dynamics or foundation dynamics would contaminate the measurements. However, it was duly noted that the results from the hammer tests represent results in air. When the panels are exposed to a wave slam the dynamic mass will be increased and this may affect the dynamic behavior to such an extent that some corrections may be necessary. The deviation observed between the measured panel response and the hammer impact was small, typically less than 3%, and is being considered to be well within the error tolerances when it comes to the correction regime necessary for deriving the actual impact load.

Prior to the basin tests, it was thus assumed that the measurements could be used directly. During the first irregular sea tests, large oscillations in the force measurements were nevertheless registered for some force panels. The frequency of the oscillations varied, and could generally not be identified as a structural response. Examples of time series for is shown in Figure 6.

Several additional quality control tests were therefore performed with the model in the basin, such as hammer tests on submerged panels, hammer test on the model hull, accelerometers mounted on the panel back sides, irregular wave tests without wave probes in front of force panels and with panel segment covered with plastic foil. These tests confirmed the hammer test program, indicating that the observed oscillations in the force measurements were not, in general, caused by structural vibrations. It was assumed that these oscillations were caused by oscillating air bubbles trapped on the column surface. Similar behavior is found and analyzed in sloshing experiments, see [6]. To study the observed oscillations in more detail and to further document the force panel instrumentation set-up, drop tests of the H10 slamming panel section was performed after the model test campaign. In the drop tests, air bubbles were trapped by using panels with different cut-outs, see examples in Figure 7. Force measurements with oscillations corresponding to the estimated oscillations of the trapped air bubble were observed, see Figure 8. These tests are further described in [1].

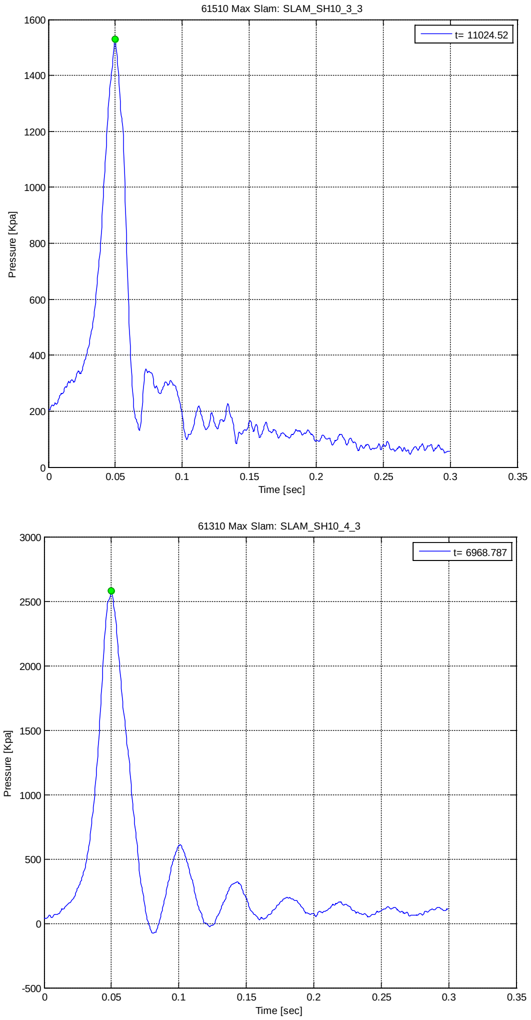

Figure 6 Examples of measured pressure time series with (bottom) and without (top) oscillations.

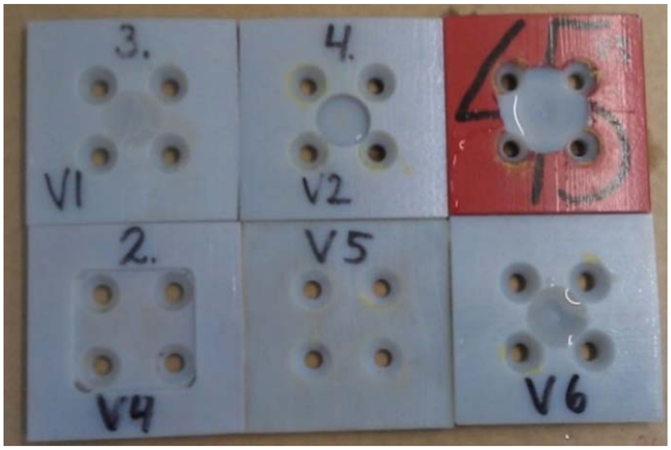

Figure 7 Drop tests with panels trapping air bubbles of different volumes as shown above were performed.

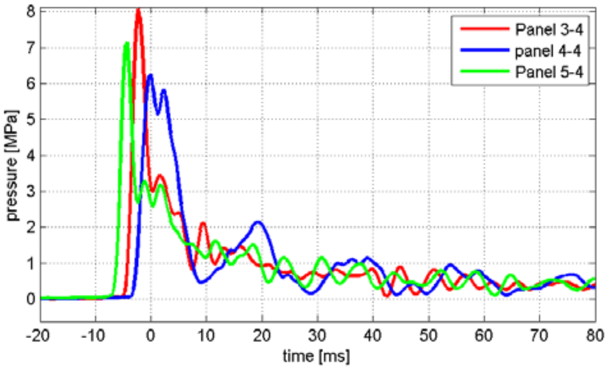

Figure 8 Measured pressures on 3 adjacent force panels. Middle panel (panel 4-4) cut-out corresponds to red panel in Figure 7, all other panels are smooth.

The findings and observations from the drop tests can be summarized as follows:

- The measuring system captures the expected slamming forces quite accurately in the applied scale.
- Entrapped air in the waves leads to oscillations in the force measurements. The peak force can be increased or reduced (typically +/- 20%) depending on the size of the air bubble. The rise time and duration of the peak force increases somewhat when a bubble is present.
- Compared to the measured forces when no air bubble is present, the presence of an air bubble does not significantly alter the measured force. It is also quite likely that entrapped air will occur in full scale slamming events also. However, the size and behavior may not scale, and this is a remaining uncertainty.
- It is difficult to adjust the slamming events measured during the Heidrun tests to take the effects due to air bubbles. However, the effect does not significantly alter the main results. The variability of the slamming events is increased due to these effects, but compared to the inherent variability of the wave slamming phenomenon, the contributions are assumed to be small. It is however recommended to investigate these findings in further work.

OBSERVATIONS AND MODEL TEST RESULTS

Large amounts of data and video were obtained during the test campaign. The main observations and results are summarized in this section. Before the tests, the pressures on the two down-wave columns (H30 and H40 in Figure 2) were of most concern because the structural capacity of the inside of the columns is less than in front of the up-wave columns. During the tests, it became clear that the pressures on the down-wave columns were significantly smaller than the pressures measured on the up-wave column (H10 in Figure 2), and well below the structural capacity. In the present paper, emphasis will be given to the impact loads measured on the up-wave column (H10). A threshold of 300 kPa peak pressure over the panel area of 9 m^2 was chosen for further analysis of the data.

Figure 9 shows the number and severity of registered slamming events per row on column H10 for a 1-, 10-, 100-, and 10,000-year sea state, respectively. The peak pressure is presented. As discussed above, it was decided to proceed with the contour line approach, and the test program was completed accordingly. However, large variation of the loads made it difficult to determine the worst sea state along a given contour line. The 41- and 61-series were determined to be the worst sea state along the 100-, and 10,000-year contour, respectively. 40 realizations were tested for the 41-series and 90 realizations were tested for the 61-series.

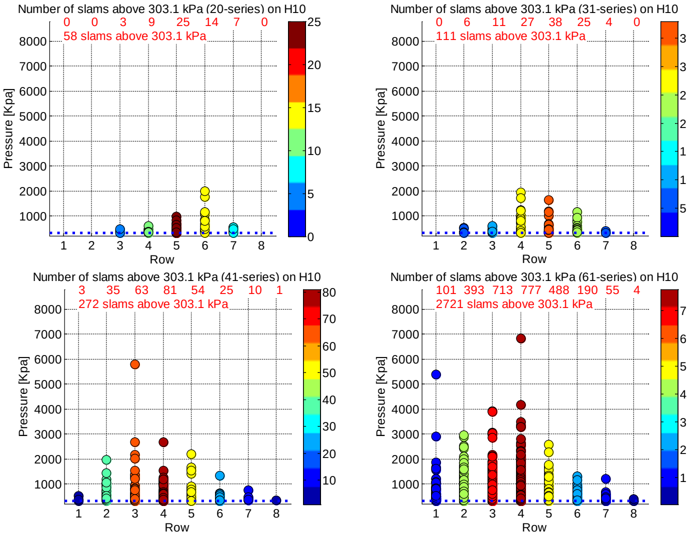

Figure 9 Number and severity of registered slamming events on Column H10. Top left: 21-series, top right 31-series, bottom left 41-series, bottom right 61-series, see Table 1.

The large variability of the slamming loads was demonstrated by repeating the same sea state realization 10 times. In Figure 10 the top plot shows the resulting maximum single panel peak pressure for the 10 repeats together with the original test (red marker). The bottom plot shows that the variability in the repeat tests is in the same order as the variability of tests with different realizations. It should be noted that in addition to the inherent variability of slamming loads previously discussed, the fact that the model is a TLP with slowly varying horizontal motion will increase the variability.

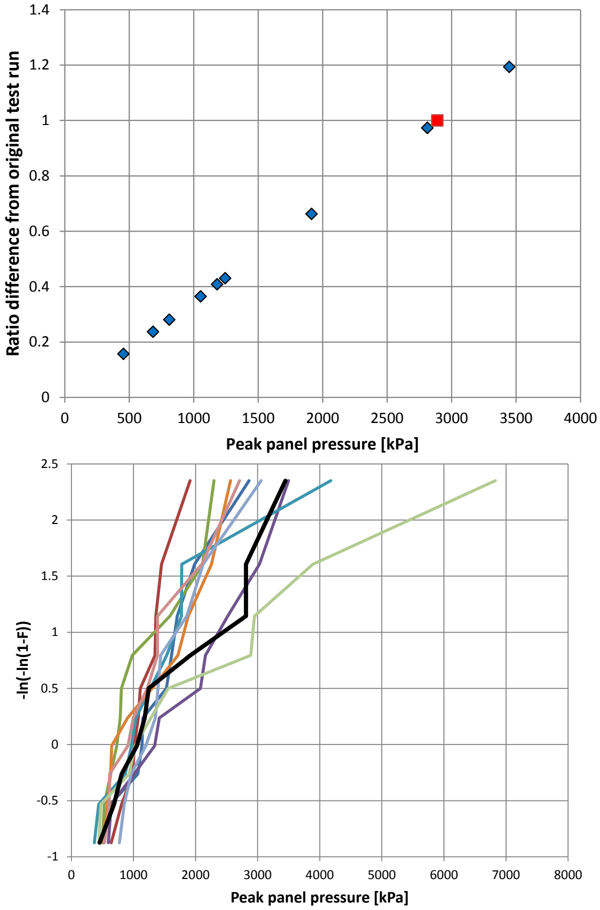

Figure 10 Tests demonstrating the low repeatability of the slamming loads. Top: 10 repetitions of one of the tests shows maximum peak pressures varying from less than 500 kPa to 3500 kPa on 9m^2. Red marker denotes original test, blue markers are repeat tests. Bottom: Gumbel plot of 3-hour maximum peak pressures using 10 realizations (coloured lines) and 10 repetitions (black line).

The rise times of the largest slamming events are shorter than was assumed in the pre-study. Based on previous model test results, rise times of 50 ms were assumed for forces distributed over 50 m^2. In the Heidrun tests, rise times of 5 ms are observed for one panel of 9 m^2. The durations are also small, typically 20-60 ms. Figure 11 shows the force time series on single panels for a large slamming event. If the measured forces over several panels are integrated in time however, the rise time and duration increase. For the largest events, the total force over all panels typically have rise times of 30-70 ms and durations of 250-350 ms. It should be noted that for the structural response of these loads on the concrete column wall, the local rise time and duration seems to be most important, together with the speed and spatial expansion of the pressure pulse moving outwards from the initial hit. This is further discussed in [7].

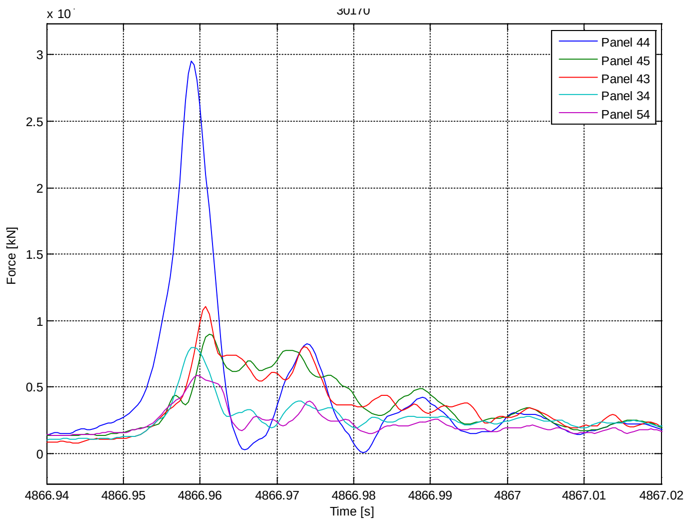

Figure 11: Force time series for selected 9 m² panels measured during a large slamming event.

For the H10 column, the height at which the majority of the slams occur does not increase much with increasing sea state severity. Row 4-5 (10-14 m above MSL) received the largest amounts of slamming events in most sea states. However, the rate of large slamming events higher up on the column increased for the higher sea states. Figure 12 and Figure 13 show the occurrence and intensity of measured slamming events for all force panels on the H10 column for the 41- and 61-series. For the 41-series, the highest mean pressure occurred at row 3. For the 61-series, where 90 realizations were run, rows 1-4 all experienced high slamming loads. For all series, the middle panel columns (column 3-5, directly facing the incoming waves) have the largest slamming rates and the highest mean pressures, as could be expected.

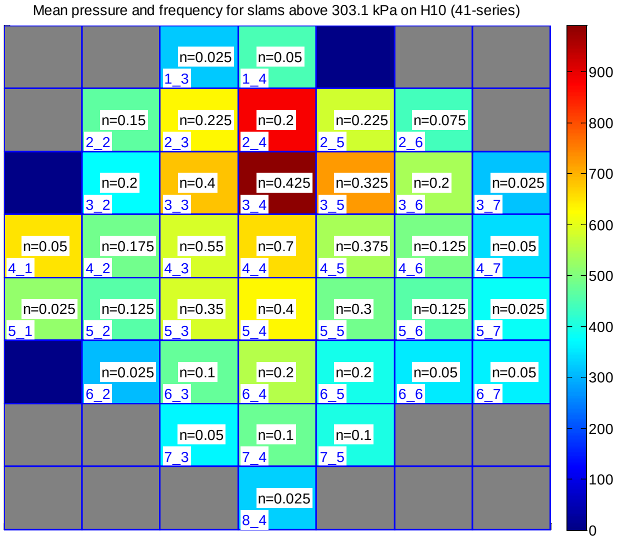

Figure 12 Spatial distribution of slams on H10 for the 41-series. The number *n* denotes the rate of slams while the color of the panel shows the averaged pressure in kPa.

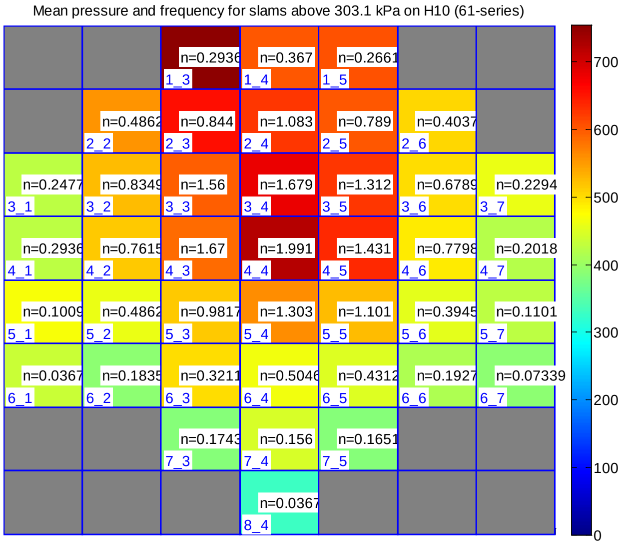

Figure 13 Spatial distribution of slams on H10 for the 61-series.

In the following, the panel receiving the highest force during a slamming event is denoted as the center panel. The number of panels activated in a slam generally increases with the maximum peak pressure on the center panel, see Figure 14. This means that the total force on the platform column also generally increases with increasing center panel peak pressure. The correlation between single panel peak pressure and total force measured on the H10 column is shown in Figure 15.

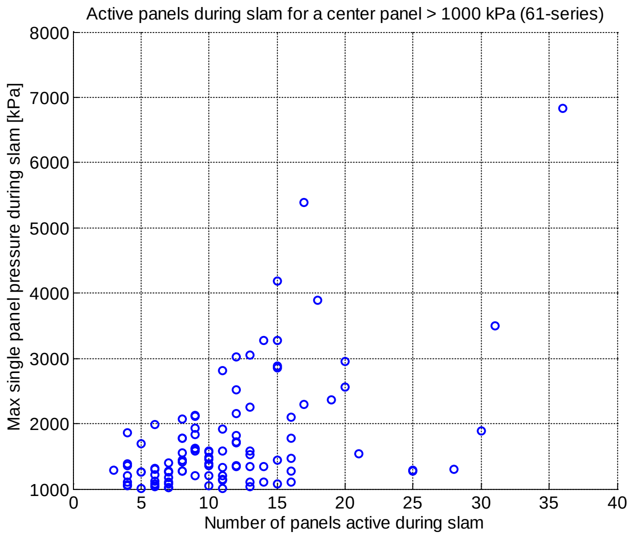

Figure 14 Number of active panels for slams with maximum peak panel pressure > 1000 kPa. Results are plotted for the 61-series.

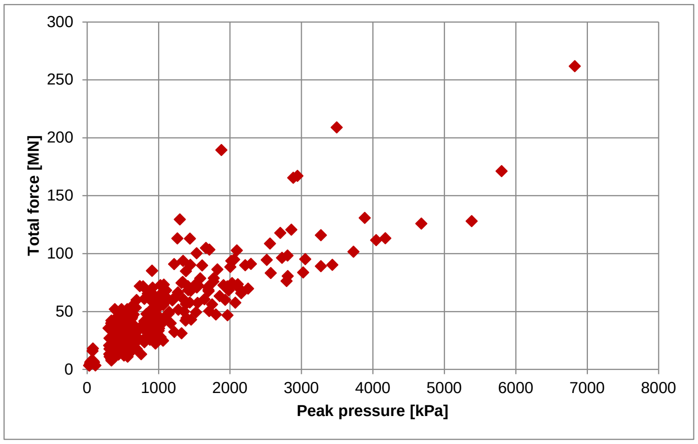

Figure 15 Correlation between measured peak pressure on one panel (9m^2) and total maximum measured force on all panels.

The reduction in the peak pressure between neighboring panels and the speed of the pressure pulse moving outwards from the first water contact are important effects for the resulting structural response. These effects were studied in some detail for the 61-series. No significant trend was found in the pressure reduction from center panel to neighboring panels in vertical or horizontal direction, see Figure 16 and Figure 17.This made it difficult to decide on design loads on larger areas based on the peak panel pressure. It was decided to use the actual measured pulses in the structural analysis. This could be done due to the amount of pulses measured during the tests.

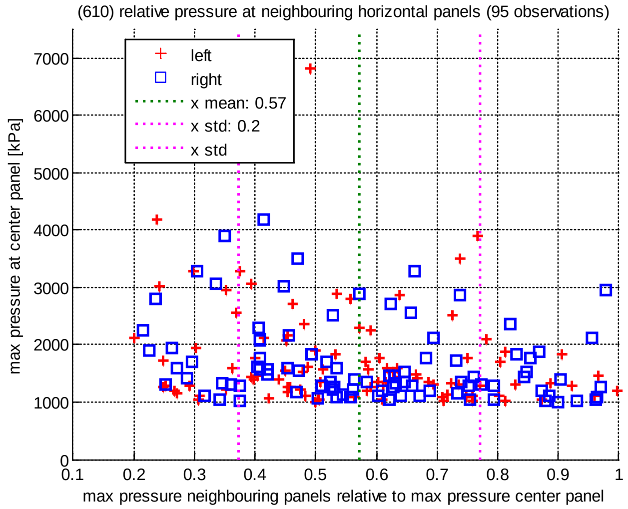

Figure 16 Correlation between peak pressure at center panel and peak pressure at neighboring panels to the left and right.

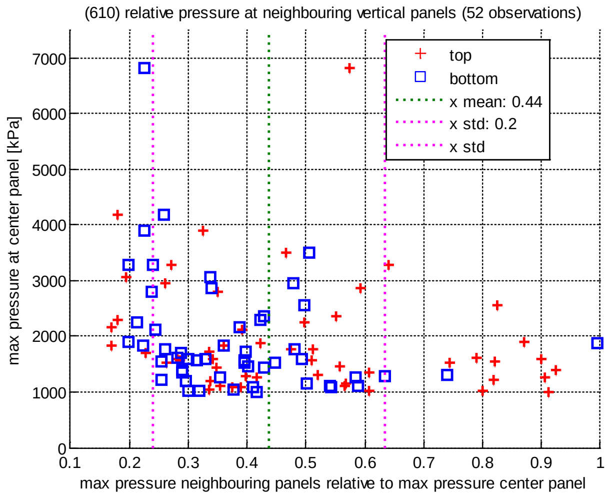

Figure 17 Correlation between peak pressure at center panel and peak pressure at neighboring panels above and beneath.

LONG-TERM ANALYSIS, RESULTING DESIGN LOADS AND STRUCTURAL ANALYSIS

As mentioned above, an approximate long-term analysis was performed to estimate the correct percentile needed to obtain design loads when using short-term analysis. The long-term analysis is approximate because fewer sea states and fewer realizations of each sea state are used than what is usually considered sufficient. The analysis is considered sufficiently accurate to give an estimate of the correct percentile needed for using the contour line approach, but not accurate enough to estimate the design values directly. Short-term analysis is used to estimate design pressures. It should be noted that the obtained percentiles are so high, and the variability of the slamming events so large, that using the contour line approach is questionable. This is a remaining uncertainty that needs further work, as discussed in the last section of this paper.

As presented in [4], the resulting percentiles were found to be 0.96-0.98 for ULS and 0.994-0.998 ALS values. Values are given for single panels, with emphasis on row 4. The high percentiles for the slamming forces are caused by the large variability in the model test results. It also means that the slamming loads are not as dependent on the sea state as other typical platform responses. With such high percentiles, large amounts of data are needed to obtain statistically robust estimates for the design values. It is fair to say that the use of the contour method is stretched to its limits. Performing a full long-term analysis using model test data, would however require even more tests.

The short-term design values in ULS are taken from the 41-series, and the corresponding ALS values are taken from the 61-series. Because of the relatively large amount of data in row 4, the design pressures on columns H10 are taken from the statistical analyses focusing on row 4 The design pressure on 9 m^2 is approximately 2.5 MPa in ULS, and 7 MPa in ALS. The corresponding values for an area of 45 m^2 are 1.5 MPa in ULS and 3 MPa in ALS. These pressures are applicable on any up-wave position of the column for vertical positions of 10-24 m over the mean water level.

In the structural analysis performed after the model test campaign, the original strategy was to derive design loads using an averaged pressure over a larger area (typically 45 m^2), and the corresponding rise time and duration of the integrated force. Structural analysis on the Heidrun column shows however that there is a large difference in response using this approach compared to using the local panel pressures and taking into account the spatial and temporal distribution of the load. Since the measured forces are believed to give a more realistic loading, the latter approach is chosen when analyzing the structural response due to the slamming events. Measured events with a maximum panel peak pressure corresponding to the design peak pressure are chosen and analyzed. More details regarding the structural analysis is given in [7].

CONCLUSION

From the Heidrun model tests the ULS and ALS impact pressures on the upwave columns, averaged over 45 m^2, are found to be 1.5 MPa and 3.0 MPa, respectively. This is in line with previous model test results. However, the rise time, duration and spatial distribution of the load were found to be very important for the structural response resulting from the slamming pressures. Such detailed load history has not been available previously, but in the Heidrun tests, a sufficient number of slamming panels with sufficient sampling frequency were used to obtain the load history in time and space.

In the Heidrun model test, a grid of slamming panels covering the complete affected area for the given wave heading was used. Each slamming panel had an area of 9 m^2. The set-up gives a good picture of the pressure distribution in time and space during an impact event. The instrumentation was verified with hammer testing and drop tests. The actual measured pressure distributions on the slamming panel grid was used for analyzing the structural response.

The design impact pressures are obtained using a contour line method. To obtain exceedance probabilities of 10^{-2} and 10^{-4} for the impact pressures, the corresponding fractiles were estimated using an approximated long-term analysis. Due to the large variability of the impact pressures, the fractiles are very high compared to commonly recommended values.

On the upwave columns, the ULS and ALS impact pressures averaged over 9 m^2 are 2.5 MPa and 7.0 MPa, respectively. For the down-wave columns, the impact pressures were significantly lower. The ULS and ALS impact pressures averaged over 9 m^2 are 1.5 MPa and 2.5 MPa, respectively.

FURTHER WORK

Multi-scale experiments, e.g. performed during the Sloshel JIP [8] and Wave Impact JIP [9] suggest that slamming measurements may be prone to scale effects. Considering the large statistical scatter involved, the conclusions are uncertain. But the trend is that the smaller scale tends to overestimate the loads. This is an uncertainty when using experiments to obtain design loads due to column slamming, and should be investigated. Preferably a larger scale should be included in such a study.

One possible scale effect may be the occurrence of entrapped air pockets when the wave hits the column. If geometric similarity can be assumed, Bagnold-type scaling laws for slamming with gas pocket [10] can be used. However, although entrapped air is likely also in full scale, it is not obvious that the size and shape will be equal as in small-scale experiments.

Another scale effect may be that in violent waves the water may be mixed with air, altering both the density and the sound of speed in the fluid. This effect may be studied using e.g. CFD simulations, see e.g. [11]. The scale effects due to air entrainment may lead to lower full-scale loads, and is thus important to quantify.

In the present model test, long crested waves are used. Traditionally, using long-crested waves are considered a robust and in many cases slightly conservative assumption for obtaining design responses in ULS and ALS. Moreover, it is assumed that the waves in severe weather condition will have crests of significant length compared to the characteristic lengths of the offshore installation. However, ocean waves are short-crested, and the wave kinematics and non-linear behavior is different than for uni-directional waves. It is assumed that this will affect the columns slamming loads. Model tests in both long-crested and short-crested waves should be performed to assess this affect.

Since the load from wave impacts are caused by water in motion, it is obvious that this load may change if the structure it hits is flexible. The impact pressures used in the present work is based on measurements on a stiff model. Further work on wave impact should include fluid-structure interaction effects. This is assumed to be especially important for steel structures.

The stochastic analysis performed to obtain design impact pressures is kept within the contour line approach in this paper. As discussed earlier in the report, this may not be the optimal stochastic analysis for this type of highly non-linear response, see also [12] and [13]. In the further work with this topic, investigation of other stochastic methods should be included. The Heidrun data set is very well suited for such investigations.

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