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Slam occurrences and loads of a high-speed wave piercer catamaran in irregular seas

Benjamin J French[1], Giles A Thomas[1] and Michael R Davis[2]

Abstract

In order to optimise the structural design of large lightweight high-speed catamarans, a thorough understanding of the structural loads is required. Not only is slam severity an important factor in the structural design, but also the occurrence rates of such events in realistic sea conditions is vital for long-term load estimations. The slamming behaviour of a 2.5-m hydroelastic segmented model representative of an Incat wave piercer catamaran was investigated over a range of realistic irregular sea conditions. The model was instrumented with strain gauges to record centrebow slam loads, pressure transducers, wave probes and linear variable displacement transducers. More than 2000 slam events were identified over 22 test conditions, providing an extensive database of slam events. Slam events were identified from the pressure transducer measurements and two important slam parameters investigated: occurrence rates and slam severity. The slam magnitudes were found to be scattered; numerous outliers were detected with magnitudes up to 4 times the median observed in every tested condition. Slam occurrence rates and severity are generally greater in conditions where motions are large. A slam occurrence threshold was identified by extrapolating the experimentally measured occurrence rates. For a 112-m vessel with speeds between 20 and 38 knots and with a modal wave period of 8.5 s, slams are shown not to occur at significant wave heights less than 1.5 m. The slam loads and occurrence data obtained through scale model testing can be used by high-speed catamaran ferry designers to assist the development of structural load cases and operation limits for future designs.

Keywords

Load response: marine craft, naval architecture, ship hydrodynamics, dynamics: maritime systems, structural (solid/fluid) interactions (maritime)

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Introduction

Large high-speed catamarans are currently used to transport payloads of over 400 vehicles and 1200 passengers at speeds of up to 40 knots. In order to optimise performance at such high speeds, it is essential to minimise structural weight while maintaining structural integrity. Therefore, knowledge of the wave loads caused by hydrodynamic forces, including slamming, in a range of operating conditions is essential for efficient structural design.

Classification societies provide rules that specify design loads and loading conditions (such as the rules provided by the classification society Det Norske Veritas (DNV), including still water and hollow landing conditions[1]). The design rules provided by the classification societies are the amalgamation of many years of operating experience of similar vessels and simplified structural analyses. This method is effective when designing conventional vessels where the amount of previously gathered empirical data provides high confidence in the design rules. However, for novel ship designs on the fringe of the conventional design space, confidence in the rules may not be as high. For instance, it has been found that a slam event measured during full-scale trials of an Incat Tasmania 96-m

[1]National Centre for Maritime Engineering and Hydrodynamics, Australian Maritime College, University of Tasmania, Launceston, TAS, Australia
[2]School of Engineering, University of Tasmania, Hobart, TAS, Australia

Corresponding author:
Benjamin J French, National Centre for Maritime Engineering and Hydrodynamics, Australian Maritime College, University of Tasmania, Launceston, TAS 7248, Australia.
Email: b.french@amc.edu.au

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Wave Piercer Catamaran exceeded the maximum sagging vertical bending moment class rule defined by DNV by 16%.[2] It is of course not known whether even larger slam forces could occur.

Currently, there is a lack of data on the influences of occurrence rates and loads with respect to sea conditions and speeds in a systematic investigation. Full-scale measurements on similar existing vessels can be used to gather sea loading data; however, this is expensive financially and in terms of the time required to obtain a substantial loading history, particularly for slamming investigations. Full-scale testing has additional challenges such as complete control of the environment is impossible and measurement of the required variables, such as sea condition, is not easy. Scale model testing, however, can replicate the full-scale behaviour of the vessel much more cheaply and with much greater control over the test environment.[3] Therefore, in this work, scale model towing tank testing was chosen to investigate the slamming behaviour of large high-speed catamarans.

The systematic investigation presented here focuses on the slamming occurrences and severity of high-speed wave piercer catamarans in irregular seas. These observations will provide designers with valuable information on slam occurrence and severity under irregular sea conditions and provide a basis for considering possible mitigation strategies.

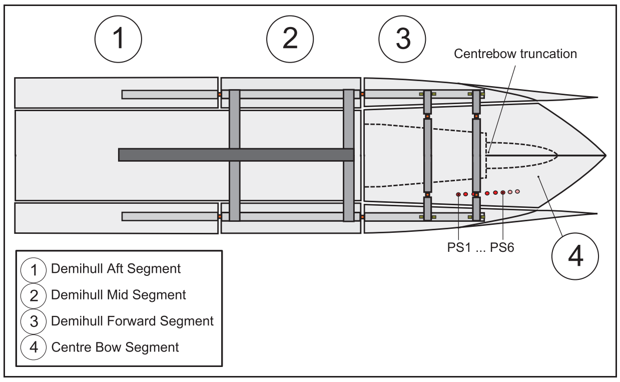

Figure 1. Diagram showing the model layout and locations of the pressure transducers during experimentation. The two aft pressure transducers (PS1 and PS2) were moved to the forward positions, shown by the faded circles, during the larger sea states. The demihull segments and centrebow segment are also labelled and shown.

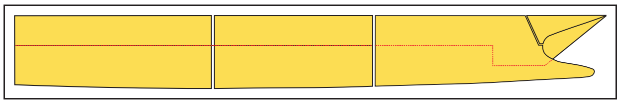

Figure 2. Profile view of the segmented model, showing the centre line profile and the centrebow truncation.

Design of the hydroelastic test model

In order to accurately simulate the full-scale slamming and whipping response, the model needs to be hydroelastic, allowing simultaneous interaction between the fluid flow and the structural response.[4] This is particularly important when the period of whipping is comparable with the duration of a slam impulse, both being about 0.4 s for a 2500-tonne aluminium catamaran.[5] Different approaches are possible when designing a hydroelastic model: the model may be continuous[6] or segmented.[7,8] Segmented models may contain a continuous rigid girder with the segments attached to the girder via load cells or other force/moment transducers. Dessi and Mariani[7] used a six-segment model with a continuous backbone beam of varying cross section to give the desired vertical bending behaviour. The segments were attached to the backbone beam with load cells measuring vertical force and strain gauges mounted on the backbone beam measured bending moments. Another approach is to use a segmented rigid backbone beam, joined together by elastic links at the hull segments.[8] In the case of wetdeck slamming on catamarans, the wetdeck may be segmented in the same manner as a monohull.[9]

For the present investigation, a 2.5-m hydroelastic segmented model of the segmented backbone type was employed.[10] The hydroelastic segmented catamaran demihulls consist of three segments, making possible the measurement of bending moments at the two segment join locations. Short aluminium relatively elastic links connect the segments and have strain gauges on top and bottom surfaces connected in a single bridge circuit to facilitate direct measurement of bending moment under unsteady conditions. The link dimensions were selected to tune the model to simulate the required full-scale whipping frequency. The centrebow was isolated as a separate segment from the rest of the model to allow the measurement of slam loads. Figure 1 shows a schematic representation of the model layout, and Figure 2 shows the model profile, highlighting the centrebow shape at the centre line. The centrebow segment contains 84 pressure tappings over the starboard arch (8 of which were used in this study). Figure 3 shows a perspective photograph of the model in the towing tank, the transverse beams isolating the centrebow from the demihulls. The starboard demihull backbone beam can also be seen in the aft and mid segments. The two segment cuts and centrebow section are highlighted by the yellow waterproof tape. The segment gaps were covered by flexible latex strips to maintain a smooth flow around the hull and to prevent water entering the gaps.

The hydroelastic segmented model was designed to have a whipping frequency correctly scaled to the full-scale vessel. However, since the full-scale vessel was not built at the model design stage, the target resonant frequency of the model was based on the predicted finite element modal analysis results of an Incat Tasmania 112-m Wave Piercer Catamaran Hull 064.[12] This

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yielded a whipping frequency of 2.4 Hz at full scale and 13.8 Hz at model scale. Table 1 summarises the scale model parameters compared with the full-scale equivalents where possible.

Test facility and model instrumentation

The model was tested in the Australian Maritime College towing tank, which is 100 m long and 3.55 m wide with a maximum water depth of 1.5 m. A wave maker, capable of producing irregular wave spectra, is located at the southern end of the tank. A large beach is installed at the northern end of the tank to reduce reflections from the wave maker. A towing carriage is mounted on rails and is free to traverse the entire length of the tank. The velocity of the carriage can be varied up to a maximum of 4.6 m/s. The carriage carries its own on-board data acquisition system (DAQ) and signal conditioning systems with the capacity to record up to 16 channels.

The wave maker, controlled by the software developed by HR Wallingford, creates random waves by using digitally filtered white noise (such as the method described by Fryer et al.[13]). In this method, a 65-bit shift register is used to generate a Gaussian-distributed pseudorandom white noise. Each bit position is weighted according to the transfer function of the paddle and the parameters of the idealised spectrum that is to be produced. Therefore, as each bit passes through the shift register, it produces a signal that when fed to the paddle will generate irregular waves with an energy distribution of the desired wave spectrum. Unwanted high-frequency repeat spectra are removed by a low-pass filter. The desired wave spectrum is defined by 16 spectral ordinates. The filtered white noise method, being a digital system, has the advantage of being able to reproduce identical wave trains by initiating the same binary sequence in the shift register. During the tests presented here, the initial sequence was altered for each run, guaranteeing different encountered waves for each run.

The model was attached to the towing tank carriage by two tow posts, the forward post was connected to the model via a ball joint, while the aft post was connected through a ball joint and a slider, permitting the model to move in heave, pitch and roll only. Vertical motions were measured at each of the tow posts using linear variable differential transducers (LVDTs), allowing the calculation of heave and pitch motions as well as vertical acceleration.

A foil-mounted resistance wave probe, to measure encountered wave elevations, was fixed to the carriage floor in plane with the centrebow truncation. Pressure transducers were used to record surface pressures at different locations along the top of the starboard archway of the model. Six piezoresistive pressure transducers (Endevco model 8510C-50) were installed on the model, along the top of the archway fore and aft of the centrebow truncation, as shown in Figure 1. Technical details of the Endevco model 8510C-50 are shown in Table 2; this model was chosen because it is ideal for measuring dynamic pressures due to its high sensitivity and resonance. During testing, the largest pressures were measured further forward on the archway in larger wave heights. Therefore, the two furthest aft transducers (PS1 and PS2 in Figure 1) were moved to the forward positions as shown when testing in the larger sea states.

Figure 3. A 2.5-m hydroelastic segmented model representing Incat Hull 064.
Source: from Matsubara.[11]

Table 1. Main particulars of the 2.5-m hydroelastic segmented catamaran.

	Model scale	Full scale
Scale	1:44.8	1:1
Configuration	Pressure bow; transverse centrebow segment beam	
Displacement	30 kg	2 764 tonnes
Trim	Level	
Radius of gyration in pitch	640 mm (25.6%L)	
Trim tab angle	7°	
Centrebow truncation from transom	1902 mm	85.2 m
LCG from transom	954 mm	42.7 m
Centrebow truncation to LCG	948 mm	42.5 m
Maximum arch height from undisturbed calm water line (CWL)	76.4 mm	3.4 m

LCG: longitudinal centre of gravity.

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Table 2. Endevco piezoresistive pressure transducer technical details.

Specification		Units
Range	0–50/0–344.74	lbf/in^2/kPa
Positive sensitivity	4.5 (2.8)	mV/lbf/in^2 (typical, minimum)
Resonance frequency	320,000	Hz
Electrical configuration	Active four-arm piezoresistive bridge	
Noise	5 rms (typical)–50 rms (maximum)	μV
Weight	2.3 (cable weight = 9 g/m)	g
Sensing diameter	3.86	mm

rms: root mean square.

Two DAQ systems were used to record data during the experiments. The carriage-mounted DAQ was used to record the carriage speed, LVDTs and wave elevations, and a portable National Instruments (NI) Compact Reconfigurable Input/Output (cRIO) DAQ was used primarily to record strains via strain gauges fixed on the aluminium links on the model. The controller is the NI cRIO-9004 model; it contains a 200-MHz Pentium processor and a field-programmable gate array (FPGA) programmed by the NI LabVIEW software. The chassis (cRIO-9101) has four slots in which four modules are inserted. Two 4-channel, 16-bit, $\pm$10 V analog input modules (NI-9215) and two 4-channel, 24-bit simultaneous bridge modules (NI-9237) are available. The simultaneous bridge modules are used exclusively to record strains. The other channels are for general purpose. A common signal, provided by a simple push button trigger device supplied by a 9-V battery, was recorded on both systems. The DAQs could then be easily synchronised (even though they acquired data at different sample frequencies) by matching this signal in the initial phases of analysis.

Test conditions

A series of idealised Joint North Sea Wave Project (JONSWAP) spectra was chosen for the testing. These represent typical sea conditions encountered by this design when in military operation when significant levels of slamming take place (commercial operators would generally avoid slamming for reasons of passenger comfort). Three modal periods (7, 8.5 and 10 s at full scale), three vessel speeds (20, 28 and 38 knots, Froude numbers 0.32, 0.45 and 0.60) and two significant wave heights (3.5 and 4.0 m) were selected giving a total of 18 test conditions. In order to investigate the influence of wave height on slam occurrence rate, two additional sea conditions were included in the test programme: 3.0 and 2.5 m significant wave heights (both with a model period of 8.5 s, full scale). These conditions were tested at a vessel speed of 20 and 38 knots, adding an additional four conditions to the original test matrix. Table 3 summarises the test parameters for the results to be presented in this work.

Under random sea conditions, a statistical investigation into slam loading requires a large amount of experimental data to build sufficient distributions of typical slam events. Not only is a statistically sufficient amount of experimental data required, but it is required over a range of conditions to gain a complete picture of the vessel behaviour. Lloyd[3] recommends that at least 100 pairs of peaks and troughs should be encountered to obtain reasonable estimates of root-mean-square motions. Therefore, the minimum run time, T_H (in minutes), is given by

Table 3. Test parameters.

	Modal period (s)	Significant wave height	Ship speed
Model scale	1	55.8 mm	1.53 m/s
	1.3	67.0 mm	2.15 m/s
	1.5	78.1 mm	2.92 m/s
		89.3 mm	
Full scale	7	2.5 m	20 knots
	8.5	3.0 m	28 knots
	10	3.5 m	38 knots
		4.0 m	

$$T_H = \frac{100\overline{T_P}}{60} \tag{1}$$

where $\overline{T_P}$ is the mean period of the peaks for the chosen motion. This value is the absolute minimum, Lloyd suggests adding an additional 10 min as a contingency.[3]

Lloyd's approach was taken when considering the number of runs required in order to obtain an accurate response amplitude operator (RAO) in the towing tank. This equates to roughly eight towing tank runs at each test condition (i.e. at each speed, modal period and wave height). While this is appropriate for spectral analysis of global wave response, for slamming investigations, a large number of slam events need to be collected to gain a statistical distribution of slam loads. Slams were counted during each test run so that at least 80 slams were recorded for analysis at each test condition. Table 4 shows the number of identified slams observed at each test condition.

Wave spectra measurements were also conducted to ensure that the spectra generated by the towing tank wave maker accurately simulated the desired and idealised full-scale spectra. The spectral energy contained in

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Table 4. Test conditions, the corresponding dimensionless encounter frequency, ω_e^*, and the number of slams per condition.

Model scale		Full scale		ω_e^*	Number of slams identified ($H_{1/3}$)	
T_0 (s)	U (m/s)	T_0 (s)	U (knots)		3.5 m	4.0 m
1.5	1.54	10	20	3.50	83	82
1.5	2.15	10	28	4.06	110	100
1.3	1.54	8.5	20	4.28	131	171
1.5	2.92	10	38	4.72	90	66
1.3	2.15	8.5	28	5.02	132	137
1.3	2.92	8.5	38	5.91	98	86
1.0	1.54	7.0	20	6.28	97	83
1.0	2.15	7.0	28	7.54	101	106
1.0	2.92	7.0	38	9.04	83	58

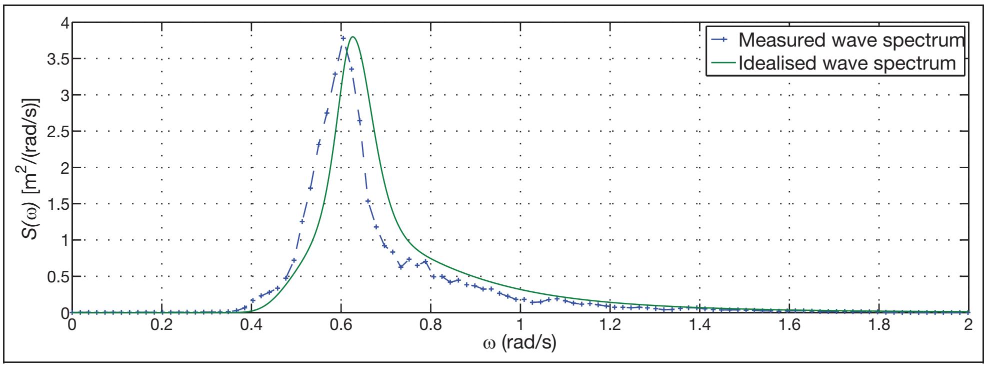

Figure 4. Comparison of measured and idealised wave spectra (scaled to full-scale JONSWAP spectrum T_0 = 10 s, $H_{1/3}$ = 3.5 mm).

each irregular sea condition was determined by conducting a Fourier analysis on the measured wave elevation trace recorded by the foil-mounted wave probe. Spectral leakage was minimised by ensemble averaging each run in each condition. The measured wave spectrum for one of the conditions in the test region of the towing tank is compared with the corresponding idealised wave spectrum in Figure 4. Good correlation between the two spectra can be seen with regard to the wave energy magnitude; however, the spectrum is shifted slightly to the left, resulting in more energy density in the lower frequencies. The idealised spectrum in Figure 4 has a modal period of 10 s, whereas the measured wave spectrum is more suited to a spectrum with a modal period of 10.47 s (full scale). This frequency shift means that the modal period of the generated spectrum is slightly higher than the desired period (as shown in Tables 3 and 4), resulting in a slightly reduced encountered wave frequency. This frequency shift can potentially affect the motions of the vessel when testing around its resonance frequency and thus the slamming occurrence. For the purpose of this article, the slight mismatch in wave energy density is neglected.

Analysis of recorded slams

Sample rate

In order to adequately capture the peak centrebow surface pressure during a slam event, the ideal sample frequency of the DAQ system was investigated. Initially, several calm water runs were conducted, and the pressure signals were examined for any abnormalities such as unexpected spikes that could be misidentified as slam events. Then, the model was subjected to regular waves where the ship motion response was known to be large. This condition was repeated, and the sample rate of the carriage DAQ was systematically altered from 500 Hz to 5 kHz for each run. Figure 5 shows the minimum, maximum and average pressures measured during runs at different sampling frequencies. Even though these tests were in regular waves, a significant variation in peak pressures was observed. Repetitions of runs showed variations in maximum and minimum recorded pressure peaks. Therefore, it was decided to sample at 5 kHz, the highest frequency practically possible in order to capture the peak pressures. This sampling rate was found to give good resolution of pressure traces without producing unwieldy data files; the data file from a 40-s run was approximately 30.5 MB.

Slam identification

In previous experiments, slams have been identified by defining two slam event criteria, namely, a threshold centrebow load and rate of change of load (N/s during model tests or MPa/s in the case of full-scale trials[14]). In the investigation by Thomas et al.,[15] a slam was said to have occurred if the peak load was greater than 10 N (model scale) and the rate of change of load exceeded the threshold criterion of 5000 N/s (model scale).

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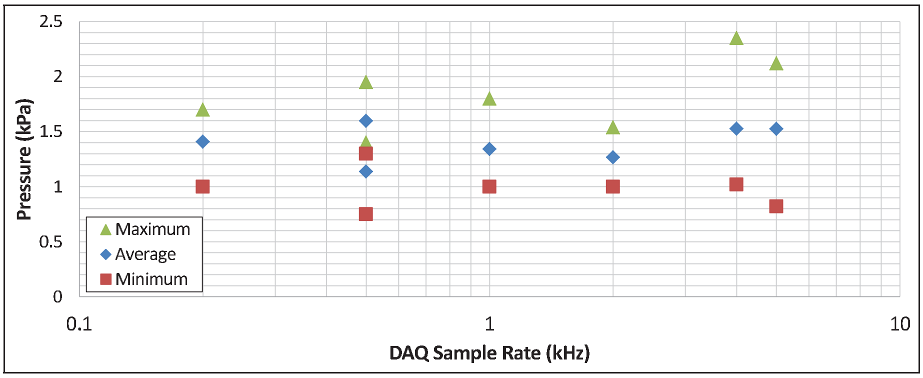

Figure 5. Measured minimum, maximum and average pressure peaks against DAQ sample rate (regular wave, vessel speed = 1.54 m/s, wave frequency = 0.7 Hz, wave height = 60 mm).
DAQ: data acquisition system.

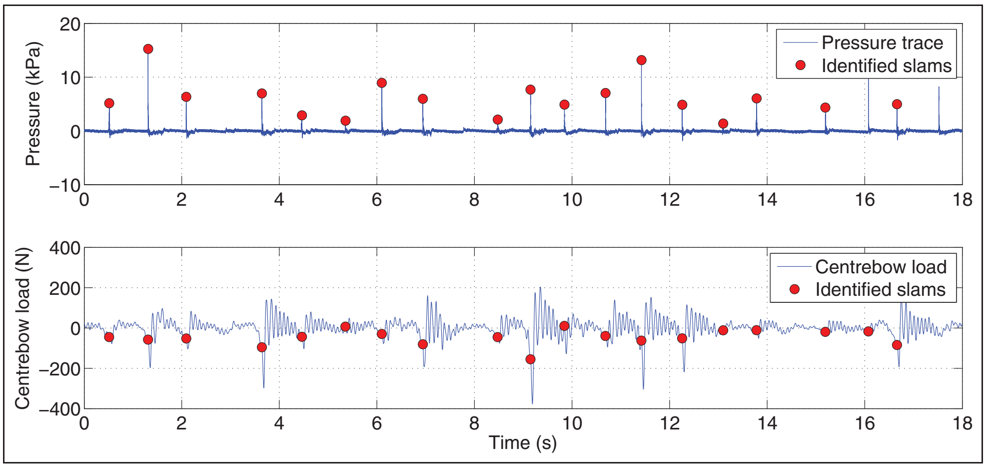

Figure 6. Pressure and centrebow load traces with identified slams highlighted with circles (negative load is on the centrebow). Note that the pressure peak at 17.5 s is not identified (T_0 = 1.5 s, $H_{1/3}$ = 78.1 mm, U = 2.15 m/s).

Another method of slam identification, implemented by Amin,[16] involved conducting wavelet analysis on the time-domain strain gauge data. In this study, a more convenient technique to identify slam events was found by using the centrebow surface pressure transducer data. These pressure data clearly showed the presence of a sharp peak value when the water surface impacted the underside of the hull in the archway.

The pressure transducer closest to the centrebow truncation was used as the reference location. Use of this approach therefore means that an arbitrary slam criterion is not necessary, and due to the large spike measured by the pressure transducer in the event of water impact on the centrebow compared to the noise of the system, only a peak detection method with a very low threshold was required to identify peak pressures and thus slam events. This process was semi-automated: once the data had been scanned and the majority of events identified, the data were then manually examined to ensure that all slam events were appropriately identified and any non-slams that had been erroneously selected were removed. This ensured that all impacts of the water surface with hull were identified as slam events as no threshold limit on the magnitude of the slam load was used. A total of 2103 slam events were identified in the 22 test conditions.

Figure 6 shows time traces of the pressure and centrebow load data from a typical test run. Slams are easily identifiable from the pressure trace alone; circles are used to highlight the identified slams and they are translated from the pressure record to the centrebow load trace.

A typical surface pressure time record during a slam event can be seen in Figure 7. This figure is a magnified view of the run shown in Figure 6 from 3.6 to 3.7 s. The slam is seen to commence just after 3.64 s, characterised by a sharp increase in pressure followed by a slower decay and a brief plateau for about 0.004 s before finally reducing back to 0. This whole process occurred within 0.01 s. The time when the maximum pressure peak was recorded is defined as the slam instant time for convenience; this is shown by the circles in Figures 6 and 7. The maximum slam load measured by the centrebow strain gauges occur 0.05 s after the maximum pressure peak. The circle of the lower plot shows the time when the maximum pressure was

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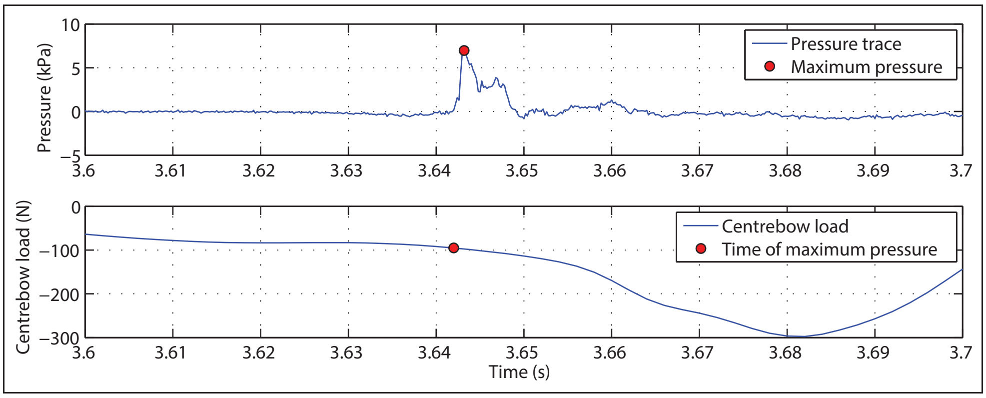

Figure 7. Typical surface pressure record of one slam event compared with the centrebow slam load (negative load is on the centrebow).

Table 5. Number of encountered waves, full-scale sea time and waves encountered per hour for 3.5 m significant wave height conditions.

ω_e^*	Full scale		Number of waves encountered	Number of slam events	Sea time (full scale) (min)	Slam events per 100 waves	Slam events per hour
	T_0 (s)	U (knots)					
3.5	10	20	432	83	23.2	19.21	215
4.06	10	28	316	110	16.1	34.81	411
4.28	8.5	20	490	131	23.2	26.73	339
4.72	10	38	269	90	10.7	33.46	504
5.02	8.5	28	355	132	16.1	37.18	493
5.91	8.5	38	294	98	10.7	33.33	549
6.28	7.0	20	570	97	26.1	17.02	223
7.54	7.0	28	406	101	16.1	24.88	377
9.04	7.0	38	348	83	10.7	23.85	465

measured, this does not exactly match up with the pressure trace as the pressure transducers were sampled at 5 kHz and the centrebow strain gauges at 200 Hz.

Encountered wave frequency

In order to group slam characteristics depending on the sea condition and ship speed, the encountered wave frequency was estimated from the wave spectrum modal period and vessel speed. The dominant encountered wave frequency can be estimated by considering the modal period of the spectrum. The wave celerity, c, is defined by (assuming deep water)

$$c = \frac{T_0 g}{2\pi} \tag{2}$$

where T_0 is the period of the wave (modal period in this case). By knowing the speed of the model, U, the average encountered wave frequency can be estimated by applying a Doppler shift

$$f_e = \frac{U + c}{cT_0} \tag{3}$$

The encountered wave frequency was then non-dimensionalised by putting

$$\omega_e^* = 2\pi f_e \sqrt{\frac{L}{g}} \tag{4}$$

here, L is the length of the vessel and g is the acceleration due to gravity. Table 4 summarises the test conditions and the corresponding calculated dimensionless encountered wave frequencies for convenience. The number of recorded slam events in each condition is also shown in Table 4; the sample size of each group varies from condition to condition but generally contains more than 80 slam events. The number of wave encounters for each test condition was also measured by applying a peak detection method to the wave elevation trace recorded by the moving wave probe and also the amount of (full scale) time spent in each condition. These data, summarised in Tables 5 and 6, for 3.5 and 4.0 m significant wave height, respectively, are useful for investigating slam occurrence behaviour of the vessel.

Results and discussion

Slam occurrence rates

Slam occurrence rates for different operating conditions are essential for defining safe environmental conditions

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Table 6. Number of encountered waves, full-scale sea time and waves encountered per hour for 4.0 m significant wave height conditions.

ω_e^*	Full scale		Number of waves encountered	Number of slam events	Sea time (full scale) (min)	Slam events per 100 waves	Slam events per hour
	T_0 (s)	U (knots)					
3.5	10	20	338	82	17.4	24.26	283
4.06	10	28	287	100	14.1	34.84	427
4.28	8.5	20	492	171	23.2	34.76	442
4.72	10	38	231	66	9.4	28.57	423
5.02	8.5	28	407	137	16.1	33.66	512
5.91	8.5	38	272	86	9.4	31.62	551
6.28	7.0	20	436	83	20.3	19.04	245
7.54	7.0	28	347	106	14.1	30.55	452
9.04	7.0	38	244	58	8.0	23.77	433

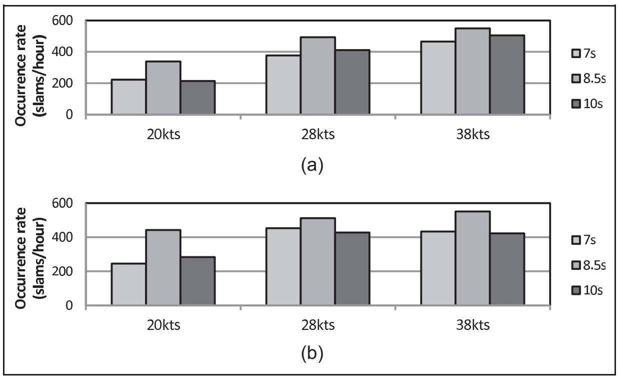

Figure 8. Slam occurrence rates for (a) 3.5 and (b) 4.0 m significant wave heights and various speeds and modal periods.

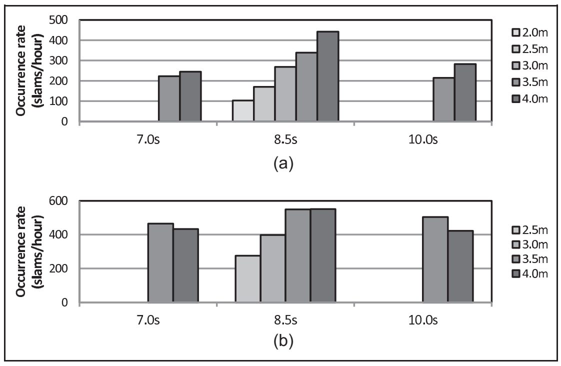

Figure 9. Slam occurrence rates for vessel speed of (a) 20 and (b) 38 knots.
Data are grouped by significant wave height and modal period.

for ship operators and in providing long-term estimates of structural load statistics. Figures 8 and 9 show slam occurrence rates for the conditions tested and have been constructed by dividing the number of slams encountered by the total amount of sea time tested (scaled to full-scale time).

Figure 8 compares slam occurrence rates for different speeds and modal periods. Figure 8(a) shows the occurrence rates for a significant wave height of 3.5 m, whereas Figure 8(b) shows the occurrence rates for the 4.0 m significant wave height conditions. Occurrence rates are found to increase with forward speed; this is due to a combination of increased vessel motions as speed increases and the greater number of waves encountered within any given time. For this particular model configuration, the 8.5 s modal period conditions tended to give the greatest heave and pitch motions and slam rates. The most severe slamming condition for both tested significant wave heights is at 8.5 s modal period and a vessel speed of 38 knots, with more than 500 slam events occurring per hour (approximately one slam every 6.5 s). This may seem excessive; however, it is unlikely that a ship operator would be sailing at 38 knots in these conditions. Also, it is important to note that a ride control system is installed on the full-scale ship to reduce motions, whereas the 2.5 m test model did not incorporate a ride control system. Therefore, the slam occurrence rates for the full-scale vessel will be lower than those presented here.

Figure 9 shows the influence of wave height on slam occurrences. This figure confirms that the occurrence rate generally increases regularly with significant wave height; this is particularly evident in Figure 9(a) for the 8.5 s modal period conditions. There is expected to be a minimum threshold wave height (dependent on encountered wave frequency) below which vessel motions are insufficient to induce slamming. The maximum occurrence rate of course would equal the number of waves encountered per hour, if a slam occurred on every wave. In smaller seas with a shorter modal period, the slam rate did not increase with wave height as much as in the longer seas, and Figure 9(b) shows a small decrease in slam occurrence rate for the 38 knots conditions at 4.0 m significant wave height compared with the 3.5 m conditions. This small effect could be due to non-linearity of the vessel motions with respect to wave height, and the RAOs tending to reduce in larger seas.[17]

Slam occurrences as a function of encountered waves were also investigated. The number of measured slam events was divided by the number of encountered waves, taken from Tables 5 and 6, for each condition and are shown in Figures 10(a) and 10(b). The most

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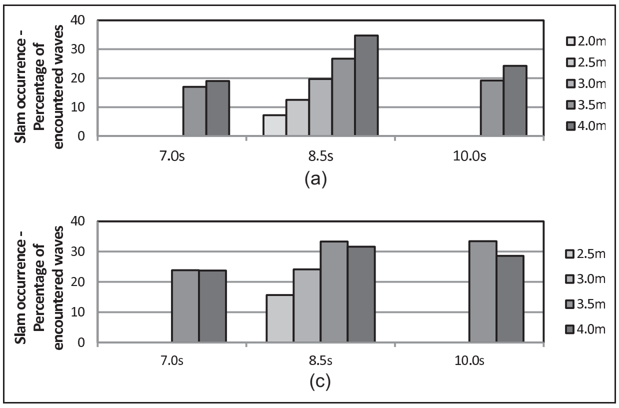

Figure 10. Slam occurrences as a percentage of encountered waves for vessel speed of (a) 20 and (b) 38 knots.
Data are grouped by significant wave height and modal period.

severe condition with regard to slam occurrence was found to be in the 4.0 m significant wave height condition, at the relatively slow speed of 20 knots (8.5 s modal period, see Figure 10(a)). Here, the vessel slammed on one in every three encountered waves. Slam events were observed to occur in packets, the vessel may slam on three consecutive waves, with the first slam in the packet often being the most severe, and then encounter the next 9 or 10 waves with no slamming. This observation was reported by Fu et al.[18] during sea trials of the experimental vessel *Sea Fighter*. They found that an initial large wave in a train would cause a large deviation in pitch angle, then as this wave passed, the ship would 'fall' into the next approaching wave, resulting in a slam. Successive slam events were caused by the encountering waves more quickly than the vessel could react. They concluded that the phase difference between the waves and the ship's pitch response has an effect on the slam severity.[18]

The observed increase in slam occurrence rate with significant wave height was examined in detail for the 8.5 s modal period cases shown in Figures 9(a) and 9(b). Figure 11 plots the occurrence rates for these conditions, linear least squares trends are extrapolated down to the x-intercept representing a slam occurrence rate of 0. The maximum significant wave height when no slams occur is defined as the threshold significant wave height. From Figure 11, the threshold wave height for both 20and 38 knots vessel speeds in 8.5 s modal period sea conditions is in the vicinity of 1.5 m (the slam occurrence threshold for 20 knots was found to be 1.43 m, and for 38 knots, it was 1.51 m). This slam threshold is further supported by a series of towing tank tests with the same model, conducted in relatively mild irregular seas (1.12 m, 8 s modal period JONSWAP spectrum, full scale) with the purpose of investigating ship motions in the absence of slamming.[19] No slam events were recorded during these tests.

Slam loads

Centrebow slam load traces were passed through a high-pass Butterworth filter in order to isolate the high-frequency wave impact load and remove the lower frequency global loads resulting from the centrebow entering and leaving the water at a frequency that coincides with the encountered wave frequency. It was found that a cut-off frequency of twice the encountered wave frequency successfully isolated the high-frequency wave impact load and subsequent whipping without excessive attenuation. The model was tuned such that the structural response of the model can be correctly scaled to full scale. When considering slam loads, only the maximum first cycle load was considered, the subsequent whipping was not analysed in this work.

Not all the slam events measured were significant; it can be argued, in fact, that due to the slam identification method outlined in section 'Slam identification', any contact between the wetdeck at the centrebow truncation and water surface can be potentially classified as a slam, no matter how minor. This section examines the severity of each of the 2103 identified slam events.

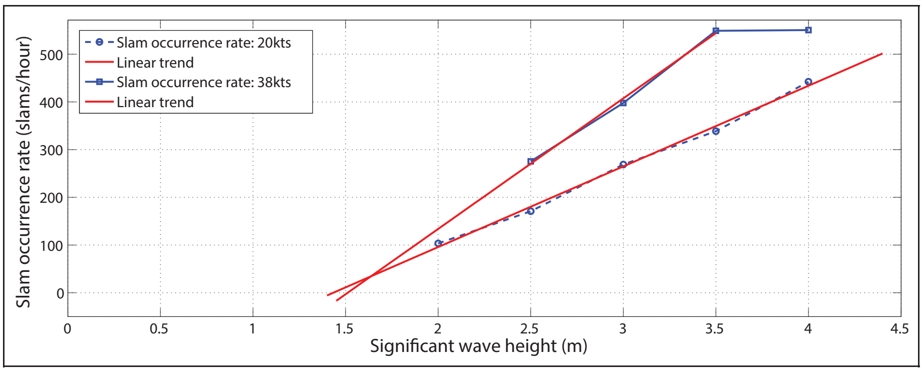

Figure 11. Significant wave height against slam occurrence rates for the $T_0 = 8.5$ s conditions, linear trend lines are extrapolated down to the x-intercept to show an estimated slam occurrence threshold of 1.43 m when the vessel speed is 20 knots and 1.51 m for the 38 knots conditions.

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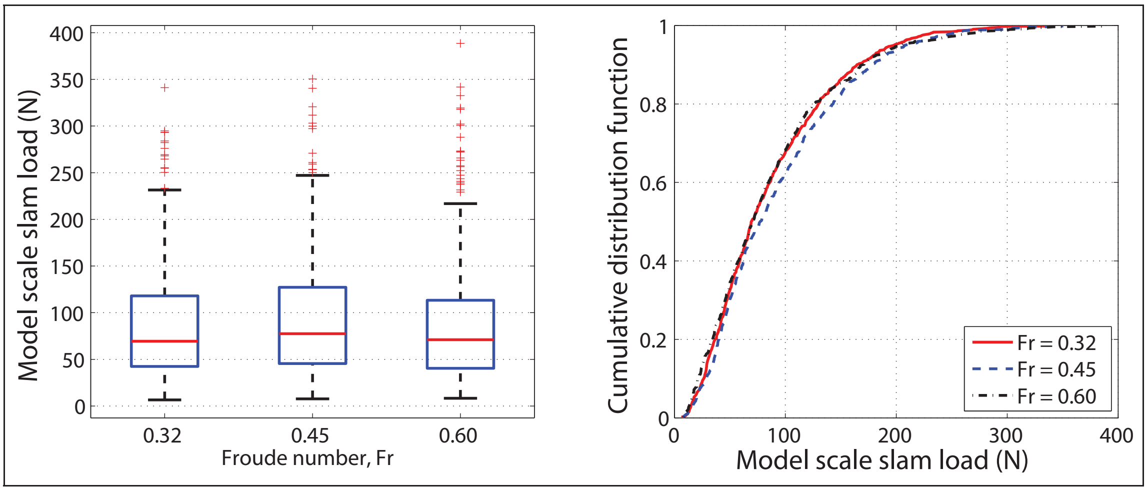

Figure 12. Distributions of slam load magnitude for differing Froude number.

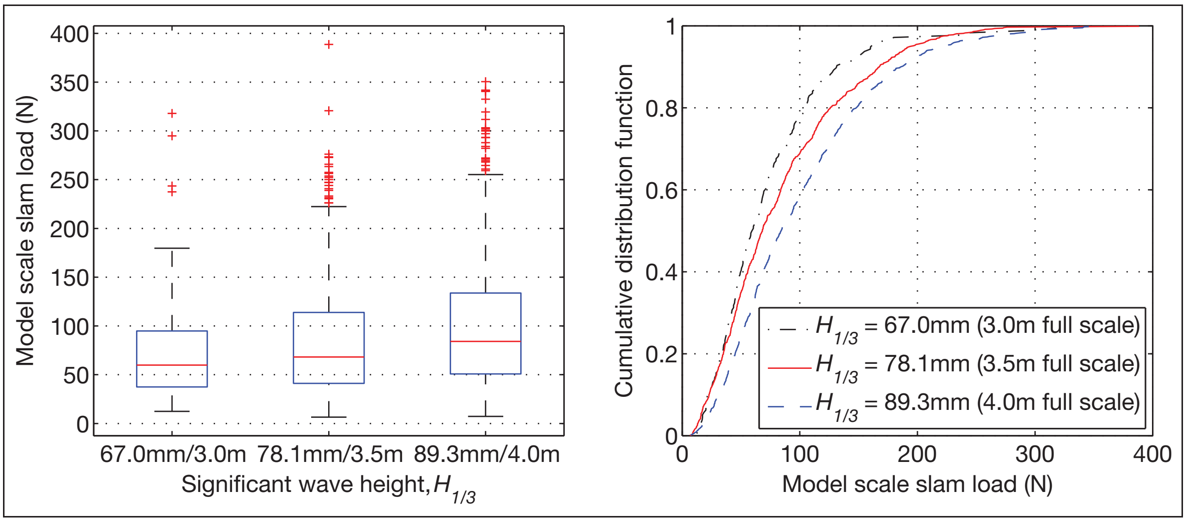

Figure 13. Distributions of slam load magnitude for differing significant wave heights.

The largest slam in the measured data was found to be 388.6 N (model scale), equivalent to 132% of the displacement of the model. The largest slam reported in the previous model scale tests in irregular seas was 70% of the model displacement.[15] The relatively small investigation consisted of two conditions and 284 identified slam events. Of the 2103 slam events identified in the present investigation, 14 (0.67%) had a magnitude exceeding the total displacement of the model. Severe slam magnitudes of the order of the total vessel displacement are not surprising; full-scale strain measurements of an Incat 96-m catamaran used in conjunction with a finite element model estimated a severe slam to be 93% of the vessel displacement.[20] These important results demonstrate the severe magnitude of slam loads, which clearly represent extreme structural load cases and should be the basis for future designs where vessels are expected to be operated in more severe wave conditions.

Figures 12–14 show the distribution of slam loads when the data are grouped by Froude number, significant wave height and modal period, respectively. The left hand plots are box plots representing the probability density functions of the distributions, and the right hand plots are the corresponding cumulative distribution functions (CDFs). The model scale slam load appears to be independent of Froude number, as seen in Figure 12. The distributions for all three Froude numbers are quite spread, with numerous outliers (outliers are defined here as data that fall outside 1.5 times the interquartile range (IQR)). The CDF also show little deviation between the slam load distributions at different speeds. This result is interesting, as it suggests that reducing the vessel speed reduces the slam rate but does not necessarily reduce the slam severity. Figure 13, in contrast, shows a clear increase in slam load with significant wave height. This is not surprising as it is an effect that has been previously observed in regular wave tests.[11,12] Although exceptionally large and small slams are present, there is a general increase in the median slam magnitude when significant wave height is increased. The IQR also becomes larger with significant

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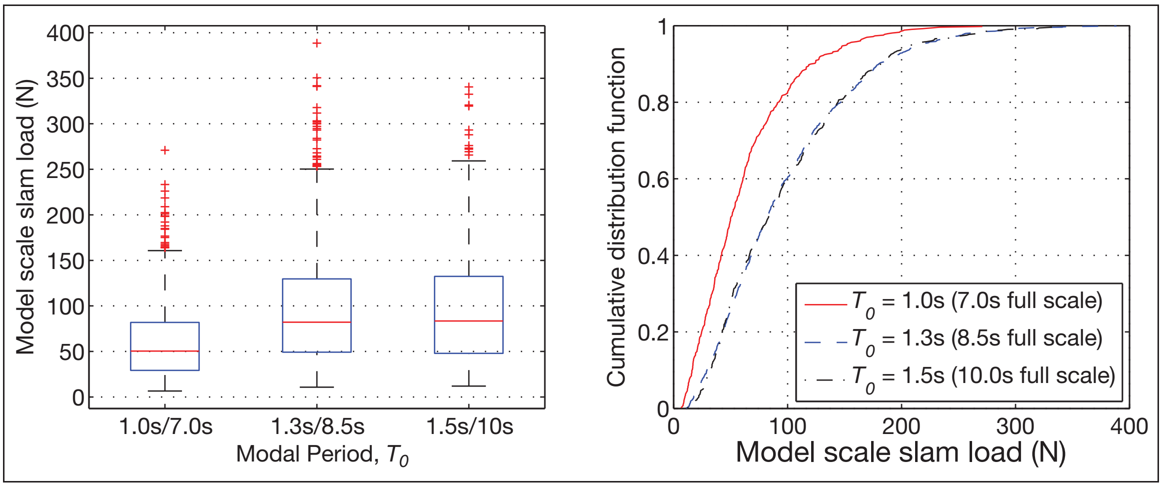

Figure 14. Distributions of slam load magnitude for differing modal periods.

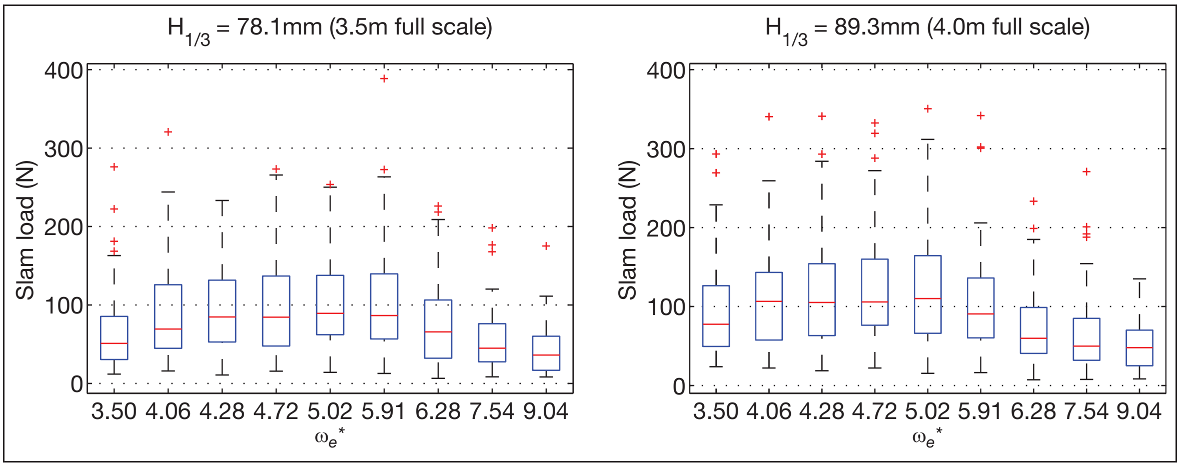

Figure 15. Box plots describing the distributions of slam load against dimensionless encounter frequency: (a) $H_{1/3}$ = 78.1 mm (3.5 m, full scale) and (b) $H_{1/3}$ = 89.3 mm (4.0 m, full scale).

wave height, suggesting that the variance of the distribution is also a function of $H_{1/3}$. The CDF distributions also clearly demonstrate the increase in slam load severity with significant wave height.

With reference to Figure 14, the conditions with a modal period of 1.0 s (model scale, 7.0 s at full scale) appear to be much less severe than the other two modal periods tested; the median slam magnitude of the 1.0 s period condition lies around the 25 percentile of the other two conditions. The 1.3 and 1.5 s modal period conditions (8.5 and 10.0 s at full scale) are quite similar in distribution except that the 1.5 s modal period condition contains a significantly larger number of outliers; this aspect can also be seen in the tail end of the corresponding CDFs.

Figure 15 illustrates the distribution of slam severity for each mean dimensionless wave encounter frequency. Figure 15(a) shows the slam magnitude distribution for 78.1 mm significant wave height (3.5 m, full scale), and Figure 15(b) shows the slam distribution for $H_{1/3}$ = 89.3 mm (4 m, full scale). It is immediately clear from these plots that the increase in median slam magnitude occurs around the frequency of maximum motion of the model (at $\omega_e^* \sim 5$[21]). Also evident is that the median slam magnitudes for the 4.0 m sea conditions are larger than the corresponding 3.5 m conditions. The IQRs are also larger in Figure 15(b), showing that the slam load magnitudes are more spread than in the smaller wave condition. Even though the slams tend to be more severe in the plot in Figure 15(b), the largest individual slam (4 times the median) was recorded in the 3.5 m condition, $\omega_e^* = 5.91$ ($T_0 = 8.5$ s, $U = 38$ knots). This observation highlights the importance of taking a statistical approach when investigating slamming, especially in irregular conditions. A *typical* slam magnitude could be defined as the median (the median statistic is a better choice opposed to the mean, as the median is robust to outliers). However, extreme events need to be also considered as extreme slams up to 4 times the median have been measured (e.g. $\omega^*_e = 7.54$ and 9.04 for both significant wave heights).

In this investigation, as well as a slam identification tool, archway surface pressures were used as an indicator of slam location. Figure 16 is a box plot showing

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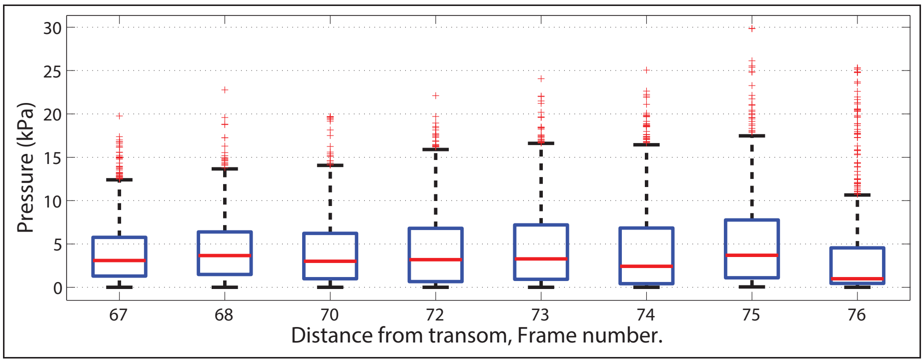

Figure 16. Box plot describing the centrebow arch pressure distribution during slamming.

the distribution of maximum surface pressures during slamming: the ship frame number is displayed on the x-axis, and pressure (model scale) is shown on the y-axis. Frames are numbered from the transom and are spaced at 1.2 m at full scale, the centrebow termination being located at frame 71 and the jaw, where the centrebow lower edge connects to the forward demihull top edge point, is located just forward of frame 79. The median slamming pressure is relatively small and consistent along the entire archway, and the general spread of pressure magnitude tends to increase towards the bow, from frame 70 to a maximum at frame 75 and then rapidly reduces at frame 76. However, large pressures, 8 to 10 times the magnitude of the median, have been recorded at each frame. This observation has important design implications: designers must need to design the centrebow and wetdeck surfaces to withstand occasional extreme impulsive pressure loading for all locations along the arched wetdeck structure.

In previous investigations, deterministic approaches to pressure investigations were undertaken in regular waves.[16] However, a stochastic approach to pressure investigations, even in regular wave tests, can provide useful information in the prediction of slamming pressure. In irregular waves, robust statistical methods will need to be applied due to the relatively large number of outliers.

Conclusion

A 2.5-m hydroelastic segmented catamaran model of the Incat Tasmania 112 m class Wave Piercer design has been tested to investigate the occurrence of bow wetdeck slam events in irregular waves. The test series consisted of 22 conditions (three speeds, four significant wave heights and three modal periods). The model was extensively instrumented with LVDTs, strain gauges were located on the demihull and centrebow segments to measure vertical bending moments and centrebow slam loads, respectively, and pressure sensors were located on the centrebow segment archway.

Slam occurrence rates are a function of encountered wave modal period, vessel speed and significant wave height. If the encountered wave frequency falls in the vicinity of the frequency of the maximum vessel motions, then the slam occurrence rate will increase. In this situation, the operator would alter the encountered wave frequency most likely by slowing down or changing heading to reduce motions and slamming. A slam occurrence threshold was identified by extrapolating experimentally measured slam occurrence rates for a range of significant wave heights and two vessel speeds. Slams were determined not to occur at significant wave heights less than 1.5 m for 20–38 knots vessel speed and for a modal period of 8.5 s.

A total of 2103 slam events were identified over the 22 conditions, each condition containing a minimum of 8-min full-scale equivalent sea time. Centrebow slam loads were determined by analysing strain gauge signals mounted on the centrebow transverse beams. Of the slams measured, 0.67% had a magnitude exceeding the displacement of the vessel; the largest slam recorded was equivalent to 132% of the vessel displacement. This is an important result for design load cases. The encountered wave frequency is an important parameter with regard to centrebow slamming; slam loads, although scattered, tend to follow motion RAO trends, where large slams are more common in conditions where vessel motions are greatest. The distribution of slam magnitudes showed that the median slam load is a function of significant wave height and encountered wave frequency. However, many outliers were detected, and extreme slam events (of the order of 4 times the median) were recorded for most conditions. Statistical investigations of slamming phenomena in irregular seas are important as they give an indication of not only the mean, or typical observations, but also their distributions and the likelihood of extreme events.

Slowing down in adverse conditions reduces wave encounter rates and thus slam occurrence rates. However, reducing slam occurrence rates does not necessarily reduce the magnitude of structural loads as severe slam events were observed at all encounter frequencies. Furthermore, reducing speed results in an increased wave exposure time; therefore, the total exposure time should be considered for a particular route when selecting the appropriate speed (and wave encounter frequency) in waves. The slam occurrences

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and magnitudes obtained through scale model testing and presented in this article can be used by high-speed catamaran ferry designers to assist in developing structural load cases for future designs. Slam occurrence rates for differing wave heights and the resulting structural load and surface pressure distributions could be of particular value for operational planning.

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Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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