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# DYNAMIC RESPONSE OF MARINE COMPOSITES TO SLAMMING LOADS

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**SUMMARY:** Marine vessels are often subjected to significant dynamic loads through impact with the water surface, commonly known as slamming. Failures are common, and the understanding of the dynamic loads and response is poor. This paper describes a dynamic finite element analysis based study of slamming impacts on marine composite panel structures. It is shown that the response is highly dependent on the impact velocity, deadrise angle, natural frequency of the panel and the frequency content of the loading. The most significant factor determining the magnitude of the dynamic response is the correlation between the first natural frequency of the panel and the frequency content of the loading.

**KEYWORDS:** dynamic, impact, marine, slamming, sandwich panel, finite element

## INTRODUCTION

Fibre reinforced composite sandwich structures have been used for marine applications for several decades, particularly on smaller vessels. The high specific stiffness and strength and good fatigue life of modern composite materials make these an attractive alternative to aluminium and steel. Such materials are increasingly being used in larger, higher performance vessels, such as racing sailing yachts, luxury craft, and high speed passenger ferries. The tendency towards designing and building faster vessels increases the importance of properly considering slamming events in the structural design process.

Slamming can be defined as “A hydrodynamic pressure phenomena that occurs when a ship’s hull in rough seas re-enters water at a sufficiently high relative vertical velocity.” [1]. Many studies have been conducted to determine the hydrodynamic characteristics of a slamming impact, such as the shape and magnitude of resulting pressure distributions [2]. However the amount of published research on the response of the hull structure to slamming loads is comparatively limited. Finite element analysis methods are replacing the traditional semi-empirical design codes provided by scantling authorities, particularly for design of advanced composite marine vessels. However these analysis methods are usually only based on linear elastic, static behaviour. The loading rates associated with slamming events are such that the inertia of the structure and the entrained water mass can have significant effects on the structural response.

The aim of the work described in this paper is to use dynamic finite element analysis (FEA) modelling to determine the effect that parameters such as entry velocity, deadrise angle, added mass, panel stiffness, natural frequency and aspect ratio have on the response of sandwich composite marine panels subjected to slamming loads.

This project is part of a research programme that includes measurement of motions and loads on full-scale vessels (Fig. 1 and 2), and laboratory based panel testing. The slam testing system shown in Fig. 3 and 4 is capable of performing servo-hydraulic controlled water slamming impacts, enabling events measured on real vessels to be reproduced on instrumented panel specimens. This system can achieve velocities of up to 10m/s, and unlike previous drop test based approaches, controls specimen motion throughout the slamming event. Parameters measured include displacement, acceleration, pressure on the panel, panel deformation, and skin and core strains.

Fig. 1 Motion measurement on 12m rigid hull inflatable police craft

Fig. 2 Motion measurement on 6m rigid hull inflatable craft

Fig. 3 Servo-hydraulic Slam Testing System

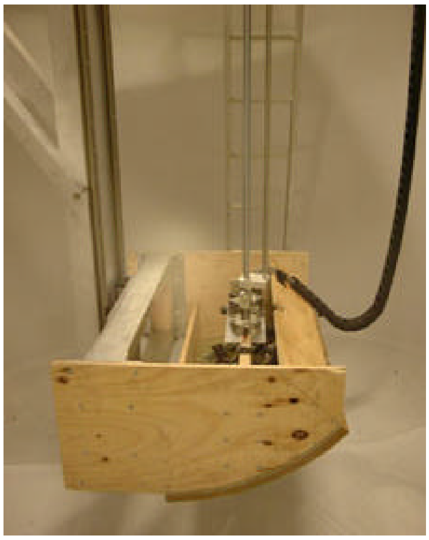

Fig. 4 Curved panel slam test specimen

## PROBLEM DEFINITION

Geometry and materials of the sandwich panel are representative of a bottom hull panel in the forward region of a 130 feet power yacht. The panel had a length of 1900 mm and width of 950 mm. The sandwich laminate consisted of a total of nine layers as shown in Table 1, giving a total thickness of 48.24 mm.

Table 1 Laminate sequence

| **Layer** | **Material** | |
|---|---|---|
| 1 | 615g/m$^2$ E-glass bi-axial cloth | Outer skin (4.19mm) |
| 2 | 890g/m$^2$ Aramid cloth | |
| 3 | 890g/m$^2$ Aramid cloth | |
| 4 | 815g/m$^2$ E-glass double-bias cloth | |
| 5 | R63.140 PVC Foam | Core (40mm) |
| 6 | 815g/m$^2$ E-glass double-bias cloth | Inner skin (4.05) |
| 7 | 890g/m$^2$ Aramid cloth | |
| 8 | 890g/m$^2$ Aramid cloth | |
| 9 | 890g/m$^2$ Aramid cloth | |

## ANALYSIS APPROACH

The finite element analyses were performed with the commercial FE software package EMRC NISA version 9.0, using 8 node sandwich shell elements (NISA NKTP33). A typical mesh is shown in Fig. 5. Clamped boundary conditions were used on all panel edges. Modal transient dynamic analysis was used for most of the study. Linear direct transient analyses were also performed, giving identical results to the modal transient approach. However the linear direct transient technique required greater effort to obtain a numerically stable solution, and provided less post-processing capability for the composite elements.

The modal transient method initially performs an eigenvalue analysis to determine the undamped vibration response of the structure. From the eigenvalue analysis it is possible to select which modes to include in the subsequent modal transient dynamic analysis. In the transient analysis a transformation of the nodal displacements into modes found in the eigenvalue analysis is performed. The dynamic response of the original system is then obtained by superimposing the response from the various modes in the transformed system.



Fig. 5  Typical finite element mesh for panel models

The main challenge in performing analyses of slamming events is to realistically simulate the load application. Many studies have been performed to determine the pressure distribution and magnitude for slamming impacts [2], the general consensus being that a typical slamming event results in a pressure pulse propagating from the keel towards the chine of the hull. The magnitude of the pulse declines as the pressure front propagates across the panel.

Several authors have suggested formulas for calculating the pressure, beginning with von Karman (1929). Milchert et al. summarises some of the approaches used in [1]. Payne [3] suggested some improvements to von Karman's original work and proposed eq. 1 to predict mean slamming pressures ($p_{mean}$) away from the keel. It should be noted that neither the hull flexibility nor the forward velocity is considered.

$$p_{mean} = \frac{1}{2} * r_{water} * V_{entry}^{2} * \left( \frac{p * \left(1 - \frac{b}{p}\right)}{\tan b} \right) \qquad \text{eq. 1}$$

$v_{entry}$ is the velocity with which the hull penetrates the surface, $\beta$ is the deadrise angle for a v-wedge shaped hull and $\rho_{water}$ is the density of the water.

Based on theoretical studies and full-scale tests Stavovy and Chuang [5] proposed eq. 2 to predict the peak pressure for deadrise angles above 20°. This approach produces pressures that are higher than Payne's other formula for the peak pressure, which may be regarded as the lower limit, and lower than Wagner's, which seems to overestimate measured pressures.

$$p_{peak} = \frac{1}{2} * \rho_{water} * V_{entry}^2 * 0.769 * \left(1 + \frac{0.25 * \pi^2}{\tan^2(\beta)}\right), \beta > 20° \quad \text{eq. 2}$$

According to both eq. 1 and 2 pressure rises with a reduction in deadrise angle and with the square of increasing entry velocity. This is consistent with drop tests and full-scale measurements, such as those by Hayman et al [4,6] on GRP hull sections, Rosen et al. [7] on a small high-speed naval craft, and Wraith [8] who performed a comprehensive set of drop tests on different hull shapes.

Several approaches have been used to numerically model a characteristic slamming impact. Riber [9] used a time dependent pressure pulse applied simultaneously over the whole panel. Milchert et al. [1] used a similar type of pressure distribution, moving across the panel. Both approaches used a peak pressure twice the mean pressure. Applying the load as a prescribed pressure is a significant simplification of reality, and ignores any effect that deformations of the panel may have on the pressure distribution. Modelling the actual water impact at the air/water interface is a very challenging task, however explicit FEA solvers such LS-Dyna claim to have this capability [10].

In this study slamming loads were approximated by applying a time-varying pressure consisting of a peak pressure pulse followed by a uniformly distributed pressure, as shown in Fig. 6. This is similar to the approach taken by Milchert et al [1]. At a vertical velocity of 7.5 m/s and a deadrise angle of 20°, the peak pressure will traverse the panel in approximately 55 ms. Rise and fall times of 5 and 10 milliseconds respectively are representative of values that have been observed in full-scale measurement [7] and drop tests [4, 8]. For typical velocities of 5 to 10m/s and deadrise angles of 20 to 40°, eq. 1 and 2 predict peak pressures from 100 to 800 kPa, and mean pressures of 50 to 200 kPa.

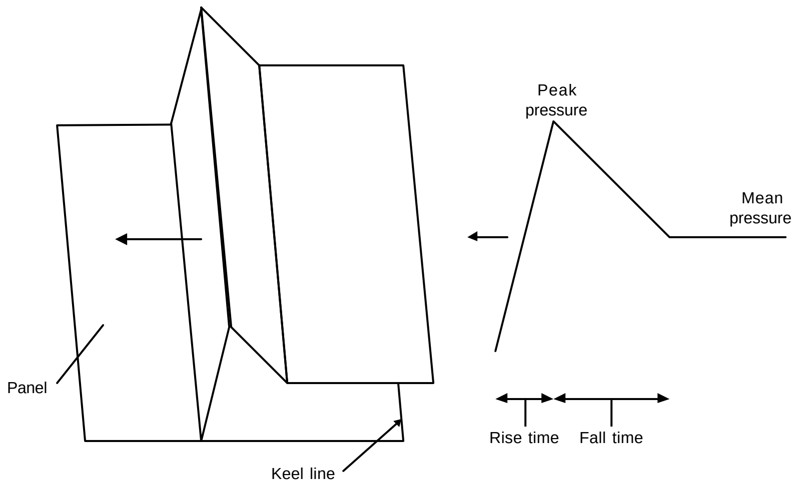


Fig. 6 Characteristics of slamming load

## RESULTS

### Typical panel response

Fig. 8 shows the out of plane deflection at various panel locations (Fig. 7) as a function of time for a slamming event with a deadrise angle of 20° and an entry velocity of 7.5 m/s (mean and peak pressures of 215.8 kPa and 424.5 kPa, respectively). The pressure propagates in the Y-direction entering at the edge where A is located. The maximum deflection for positions B, C and D, respectively occurs at different times, due to the movement of the pulse across the panel. The maximum deflection at position D is greater than at B because a larger area of the panel is subjected to the transverse pressure. There is symmetry in the loading about the A-E centreline of the panel hence the out of plane deflections for locations G and H are identical.

The skin tensile stresses (Fig. 9) for the innermost surface of the panel at positions A and E are twice the midpoint stress at position C once the peak pressure has passed (> 55 ms), as expected for a panel with clamped boundaries. Core transverse shear stresses (Fig. 10) at positions on the centreline of the panel (G, C and H), change sign as the pressure traverses the panel, with no shear stress being present after the pressure pulse has left the panel, as expected for a uniformly loaded panel. Both maximum skin tensile stress and core shear stress occur at position E, corresponding to the time of the maximum total load on the panel. After the peak pressure has passed the stresses are almost the same as when the panel is subjected to the mean pressure acting statically. The slight difference, which is less than 5 %, is believed to be due to how many modes are used in the modal transient analysis. The magnitude of the core shear stresses is very high, in excess of the strength of the core material.

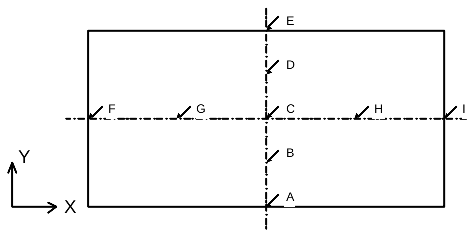


Fig. 7 Measurement positions on panel

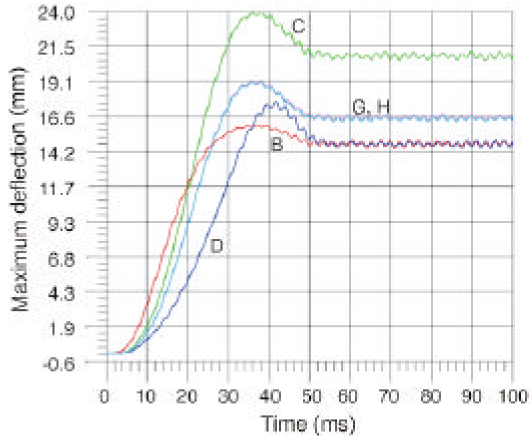


Fig. 8 Out of plane deflection versus time[1]

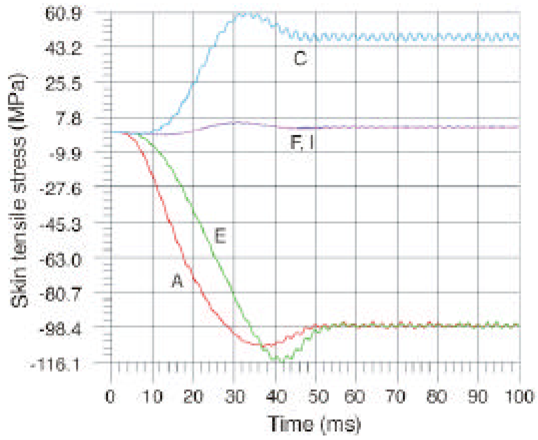


Fig. 9 Skin tensile stress versus time.

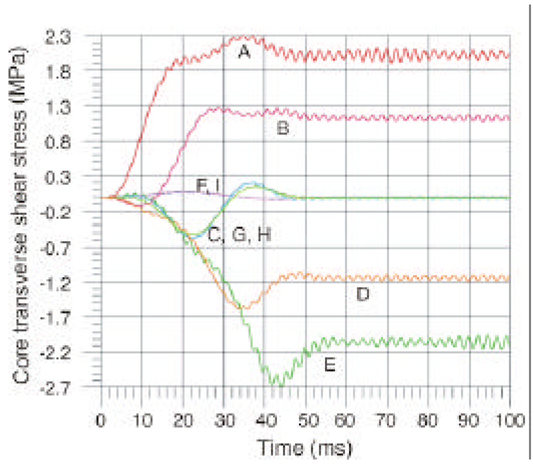


Fig. 10 Core transverse shear stress versus time.

[1] (Entry velocity 7.5m/s, deadrise 20° for Fig. 8, 9 and 10)

### Entry velocity and deadrise angle

The primary factors that characterise a slamming event are the entry velocity and deadrise angle. Fig. 11 shows the slamming pressures predicted by eq. 1 and 2 for entry velocities of 5, 7.5 and 10 m/s, and deadrise angles of 10, 30 and 40°. These pressures are much higher than those typically used in design codes.

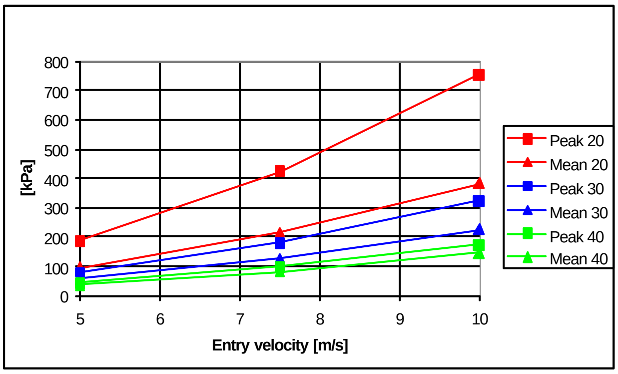


Fig. 11 Peak and mean pressures for different deadrise angles

As shown in Fig. 12 there is a significant increase in deflection with reduction in deadrise angle and increase in entry velocity. Hentinen et al. [11] claim that geometrical non-linear behaviour has to be accounted for when deflection exceeds twice the thickness of one skin, approximately 8 mm in this case. Fig. 12 reveals that deflections are of that magnitude for most cases, suggesting that geometrical non-linearity may have to be included when analysing a slamming event.

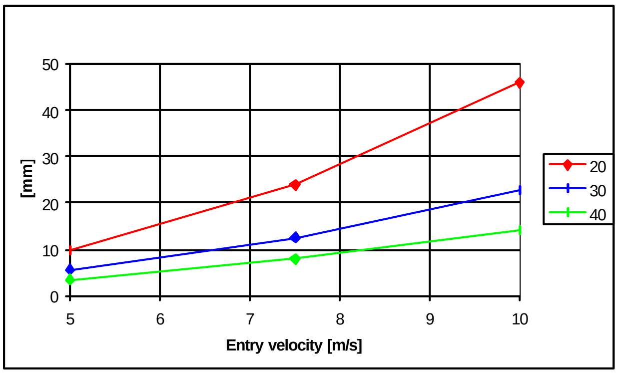


Fig. 12 Maximum deflection for different deadrise angles

The effect of dynamic loads can be quantified by the use of an amplification factor, which is defined as the maximum response value divided by the steady-state value, thus normalising the response relative to the mean value of the applied pressure. As shown in Fig. 13, amplification increases gradually with higher entry velocity, but rises very quickly when the deadrise angle is less than 30°.

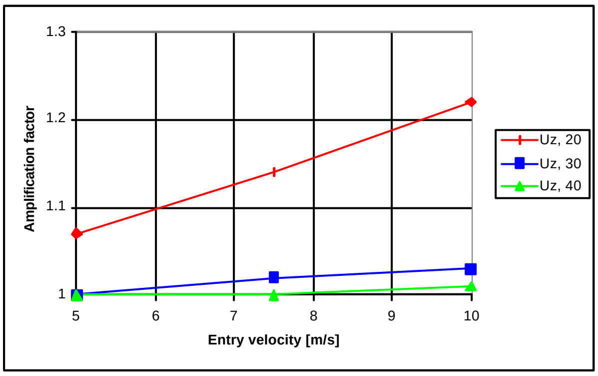


Fig. 13  Amplification in maximum deflection relative to steady-state response

**Propagation velocity across panel**

The velocity with which the pressure pulse propagates across the panel depends on the deadrise angle and the entry velocity. To evaluate the effect on the panel an analysis was performed where the mean and the peak pressure were kept constant at 100 and 200 kPa respectively. The deadrise angle was also kept constant at a value of 10 degrees. The propagating velocity was consequently solely determined by the entry velocity, which was set to 2, 4, 6, 8 and 12 m/s.

Fig. 14 shows that the maximum deflection increases significantly with entry velocity, with an amplification of approximately 60% at 12 m/s, while at low entry velocities the maximum deflection is almost the same as the steady-state response. The time where maximum response occurs correlates well with the timing of the pressure pulse traversing the panel.

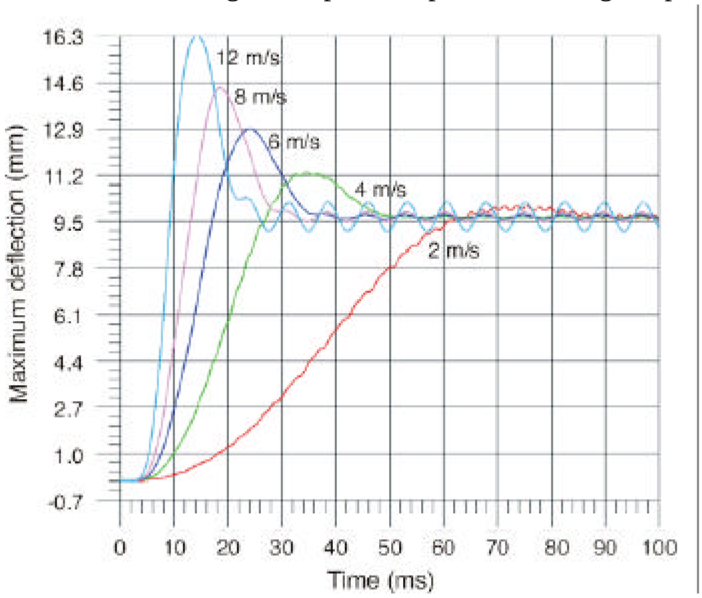


Fig. 14  Maximum deflection versus time for different water entry velocities
(Mean pressure 100 kPa, peak 200 kPa, deadrise 10°)

As the propagation velocity increases the oscillations after the peak tend to the first natural frequency of the panel, which was 137 Hz. For the lower velocities higher modes are more pronounced. Performing a Fast Fourier Transform-analysis (FFT) on the applied pressure distribution revealed that frequencies around 36 Hz have a large energy content. Although the first natural frequency of the panel is well above this frequency, which was a design criterion suggested by Milchert et al. [1], there is still a significant dynamic response.

### Natural frequency of panel

The natural frequency of the panel appears to have a large influence on the response due to the peak pressure. Panel natural frequency is primarily determined by its stiffness and mass during the slamming impact, which consists of the mass of the panel and any added mass from entrained water.

Ramachandra et al. [12] have suggested a method to predict the added mass when estimating the natural frequency of a panel in contact with water. Riber [9] also presents a simplified method for estimating the amount of added mass from the water. The approach suggested by Ramachandra gives a ratio between panels vibrating in air and in contact with water. By calculating the natural frequency of the panel in air this ratio can consequently be used for estimating the corresponding frequencies for panels in contact with water. The approach also explicitly estimates the amount of added mass from the water. For this model added mass was accounted for by increasing the density of the core. For this particular panel, 403 kg was added, reducing the first natural frequency of the panel from 136.7 Hz to 35.6 Hz.

Fig. 15 shows that for an entry velocity of 12 m/s the maximum deflection more than doubles with the added mass. However, for an entry velocity of 2 m/s the maximum deflection is almost unchanged. It is also apparent that the rate of initial response and frequency of subsequent oscillations change with the panel's mass and associated natural frequency.

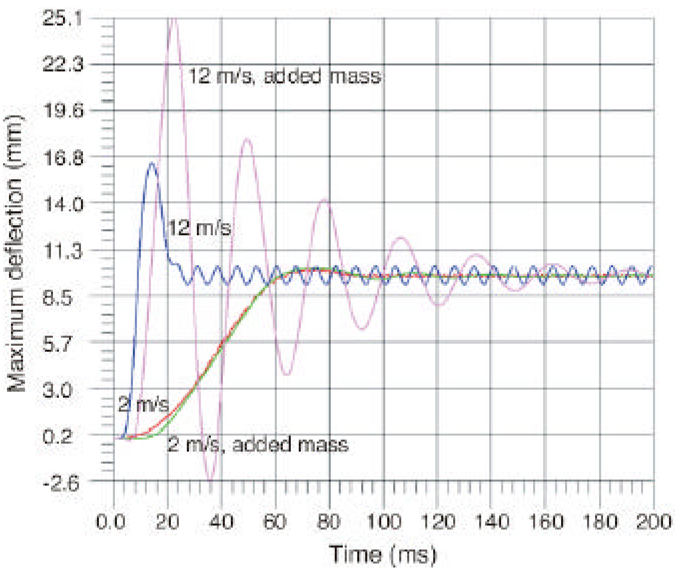


Fig. 15 Effect of added mass on maximum deflection, for entry velocities of 2 and 12 m/s (Mean pressure 100 kPa, peak 200 kPa, deadrise 10°)

The amplification in maximum deflection relative to the steady-state response is presented in Fig. 16. With the added mass from the water there is a considerable increase in maximum deformation, especially for larger entry velocities. Entry velocities larger than 8 m/s result in an amplification factor of more than two, with similar effects on the skin and core stress levels.

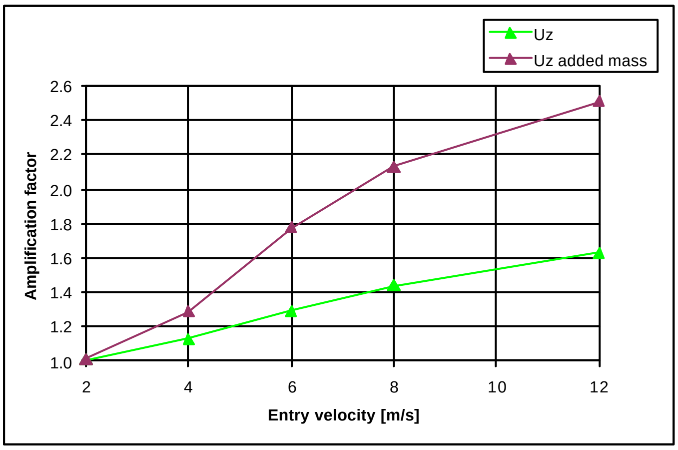


Fig. 16 Amplification in maximum deflection relative to steady-state response

With the added mass of the water the first natural frequency of the panel (36.7 Hz) is very close to the predominant 36 Hz frequency of the pressure pulse. The large dynamic effect observed for this case is consistent with the conclusion drawn by Milchert et al [1], that a dynamic analysis must be performed when the natural frequency of the panel and the loading coincide.

The approach taken to include added mass of the water is very simplistic and needs to be validated and refined. Ramachandra's [12] technique does not include the effect of transverse shear stiffness of the sandwich panel, which is likely to affect the overall behaviour significantly since this panel's deflection due to shear is of the same order as due to bending. The approach also assumes that one side of the panel is completely in contact with water. In reality this will not be true since the amount of added mass at any time will depend on how deeply immersed the panel is.

## CONCLUSIONS

The most significant factor determining the magnitude of the panel response to a slamming load is the correlation between the first natural frequency of the panel and the frequency content of the loading, which is determined by the shape and magnitude of the applied pressure distribution. In addition to geometry, boundary conditions and materials, the panel natural frequencies also depend on the added mass of the water that is moved by the panel. Analytical techniques exist to approximately predict the effect of this added mass. However, these do not enable the effect of a panel semi-immersed in the water to be accurately evaluated.

For the type of panel and the range of parameters studied in this work, without the effect of added mass, the panel's maximum deflection reached a peak value approximately 160 % of the steady-state response. If the effects of the estimated added mass are included in the analysis the natural frequency of the panel is brought much closer to the frequency content of the loading. This raises the maximum deflection to approximately 250 % of the steady-state response.

This study clearly shows that even when the natural frequencies of a panel do not coincide with the frequency content of the loading there can still be a significant dynamic response, leading to higher deflections and stresses than would be predicted by a static analysis. When the natural frequencies of a panel do coincide with the frequency content of the loading, it is even more necessary to account for dynamic behaviour.

The pressures predicted by existing slamming theories are much higher than those used in most design codes. The combination of these high pressures, and the dynamic effects simulated by this modelling, result in predicted panel stresses that are much higher than typical material limits, particularly for the core. Therefore it is highly recommended that further studies be performed, including both experimental verification and more detailed modelling that includes the fluid/structure interaction, wave profile, and vessel motion.

## ACKNOWLEDGEMENTS

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