

An alternative approach to the design of structures exposed to slamming loads.

P.F.Manganelli, M.A.Hobbs, SP Technologies, UK

Introduction

The past twenty years have seen significant progress in the performance of motor and sail yachts, which has been partly driven by the use of polymeric composite materials. The science of structural design has moved forward in parallel. Better understanding of mechanical phenomena, together with wider availability of powerful tools like finite element analysis have contributed to this development. At present, there is wide agreement on the fact that the main issue for structural designers is not so much "how to design and build a structure to resist a given load", but rather "what loads should the structure be designed for?"

In particular, one of the challenges currently faced by designers is the prediction of the dynamic loads acting on and within yacht structures. In this respect, the phenomenon of slamming and its effects on the structure present one of the areas of greatest interest.

A general definition of "slamming" may be given as "the violent impact of the hull of a vessel with the water surface". Slamming generally produces extremely high local pressures on the hull bottom, and these often drive the structural design of the hull shell and of the internal support structure.

A little bit of history

The first theoretical studies of water impact problems date back to the early twentieth century, with the classical works of Von Karman [19] and Wagner [20], which provide the background for later studies. These works were mainly concerned with the hydrodynamic forces and pressures acting during water entry of two-dimensional V-shaped sections, typical of planing hulls. By the second half of the twentieth century, several more studies had been published, extending the original works of Von Karman

and Wagner to a wider variety of 2D and 3D shapes [16].

While these early works were breaking grounds in terms of understanding and predicting the loads exerted upon an object falling into the water, none of them produced a practical prediction method that could be used by designers of high-speed crafts to determine impact pressures. As a result, in the early 1950s, Heller and Jasper set out to devise a semi-empirical procedure for calculating pressure loads on structural components of the hull bottom of high-speed crafts [9].

Since Heller and Jasper's work originated from empirical tests on a single vessel (the YP-110 75-ft motor torpedo boat), in the 1960s Allen and Jones worked to validate and extend their results for a larger number of boats with different configurations (e.g. surface effect ships, swaths, etc.). This gave rise to a new design method, published in 1978, which became the reference for most following design-oriented studies [1].

Different authors worked during the 1970s and the 80s to further improve the work of Allen and Jones, but none managed to produce a design method that would be as widely accepted as the former.

The problem of slamming loads in the field of sailing yacht design began to be addressed with the spread of offshore sailing and the development of lighter displacement hulls toward the end of the 1970s. Until then, sailing yachts had been relatively unaffected by slamming, due to the shape of their sections, their relatively heavy displacement and high pitching inertia. Some of the first recorded cases of slamming-induced damage were observed on yachts that entered long offshore regattas like the British Steel Challenge or the Sydney-Hobart Race in the 1970's. Joubert, in a paper published in 1982, quoted several examples of failures of hull bottom panels of different yachts, all of

which had been sailing upwind in steep seas [11].

After the disastrous 1979 Fastnet race, at the request of the International Technical Committee (ITC) of the Offshore Racing Council (ORC), the American Bureau of Shipping devised a new structural standard aiming to provide greater safety in the races under the ORC jurisdiction. This was published for the first time in 1981 as the "Guide for Building and Classing Offshore Sailing Yachts" [2]. Compliance with the guide became a condition for yachts to be rated under the Offshore Rule and the International Measurement System (IMS) rule. Also, for the 1989/90 and subsequent Whitbread Races, the Whitbread Committee made compliance with the guide a condition for race entry. This was generally achieved by a review of submitted drawings.

Around 1995 ABS decided to discontinue classification of motor and sailing vessels under 24 metres in length, and also stopped their plan approval process except as part of full classification. However the guide is still published and regularly used as a reference by many yacht designers and structural engineers for engineering hull and deck shells and their supporting structures. The rules for both the TP52' class and the new ORC Level Rating Classes, for instance, require the designers to certify that the plans of their yachts meet the criteria of the ABS guide.

Whether the requirements of ABS rules (or any other classification society rules) are adequate in terms of design of the structure of modern yachts in the slamming area has been the subject of debate for quite some time. On the basis of different experimental evidence, Brown and Joubert [11] and Hentinen and Holm [10] observed that hull bottom pressures predicted by ABS could be exceeded.

Hentinen and Holm also commented that the reason why comparatively little failures have been observed in yachts designed to ABS rules was that these actually underestimate the strength of structures by neglecting nonlinear deformation effects.

Empirical rules can give incorrect indications when they are used to analyse cases that fall outside the range from which they originate. With the increased performance of

modern offshore racing yachts, a general tendency to apply additional safety margins on top of those already present in the ABS guide or carry out additional checks of the slamming regions has developed in the recent years. SP developed an empirical design tool using data from past boats to provide an additional check on core strength in the slamming region following industry wide concern over core shear failures such as experienced in the first generation of the Whitbread 60's.

These methods have been used successfully, but at present there is no commonly accepted method for calculating slamming design loads of fast offshore sailing yachts, and so it is difficult to determine the margin of safety in modern hull structures

A little bit of physics.

Before proceeding to consider a new alternative method for designing structural components exposed to slamming loads, it is worth making a few considerations on aspects of the existing methods.

The importance of acceleration

Most methods following from the works of Heller and Jasper and Allen and Jones, take the vessel acceleration at the centre of gravity as a starting point to the definition of slamming loads. The basic assumption here is that the vessel vertical acceleration is proportional to the total hydrodynamic force exerted during an impact, and that the pressure distribution on the hull bottom is of a standard known type. Hence, by considering the maximum acceleration a vessel is likely to experience, one can derive the worst pressure loading on a given part of the hull surface.

Heller and Jasper have pointed out that maximum acceleration and maximum pressure on a panel do not generally happen simultaneously. The reason for this is that, while the maximum slamming pressures tend to appear at the very first stage of impact (when the impact velocity is normally the highest and the relative deadrise the lowest), the maximum upward force results from hydrodynamic pressure acting on a larger portion of the hull underside, at a later stage of the slam.

While it seems justified to assume that there is a unique correspondence between acceleration and overall hydrodynamic force, the same force can result from different pressure distributions on the hull. A more peaked distribution, giving rise to higher local loads, will not necessarily result in the largest overall force. Slamming can occur over a wide range of conditions for sailing yachts (i.e. different heel angle, ballast condition, heading relative to the waves, velocity, etc.), so a 'local pressure-acceleration' relation can be more difficult to establish than for power crafts.

Part of the historical success of the Allen and Jones type acceleration-based approach can be attributed to the fact that LCG vertical acceleration is something that is clearly perceived by the crew and is relatively straightforward to measure. In reality, it has been shown that since boats are flexible structures, a sensor placed at the longitudinal centre of gravity will not always provide a reliable indication of the actual rigid-body acceleration. This means that the relation between pressures and accelerations may be masked by effects related to the dynamic response of the boat structure [13]. Combined with the difficulty of obtaining reliable and comparable measurements of hull bottom pressures, this may explain why general agreement on the subject has never really been achieved.

The role of dynamics

Slamming loads are of a transient nature, their typical duration being different depending on the scale of structural element that is considered. A hull panel subject to water impact will typically see a pressure peak of several atmospheres travelling over its surface as it progressively penetrates the water [6]. The overall hydrodynamic force on the panel will rise to a maximum in the time it takes for the panel to become fully wet and then slowly decay to the hydrostatic level. Since modelling the dynamic response of the panel to such a load is not a simple task, the most common approach used for designing hull panels is to consider an equivalent static uniform pressure. This would be either the maximum value of the average pressure found on the panel at any stage of the impact, or, more often, the pressure that would produce the same

strains or stresses that result from the actual load.

The value of latter type of equivalent pressure really depends on the mechanical properties of the structure being examined. To illustrate this concept, we may consider two hypothetical panels subject to the same water impact. We shall assume that all conditions are identical (i.e. geometry, impact velocity, etc.) except the mechanical properties of the panels: one panel should be taken to be extremely light and stiff, while the other would be very heavy and relatively "soft". The first natural frequency of the first may be so high that the panel could react to the transient slamming load in a quasi-static way, showing maximum amplitude of deflection equivalent to the one that would be found if the maximum load had been applied statically. On the other hand, the "soft heavy" panel, would hardly respond to the same impulse, showing a maximum amplitude of deflection considerably lower than what would be found under quasi-static loading of the same amplitude. The equivalent pressure found in both cases would not have the same value, being lower in the second instance.

The role of "hydroelasticity"

From the previous example, one may conclude that, two panels with different mechanical properties, while subject to the same external hydrodynamic load, will not "see" the same equivalent static load. By looking at things in even more detail, it turns out that actually the same two panels, subject to the same water impact, would not even experience the same hydrodynamic pressures. This is explained by the fact that instantaneous hydrodynamic loads on a hull panel are determined by its velocity relative to the water, which, in turn, results from the sum of the vessel rigid body velocity and of the local panel velocity associated with its deflection. Rather intuitively, if a panel deflects upward (i.e. away from water) while being loaded by hydrodynamic pressure, its velocity relative to the water diminishes, leading to lower loads. The interaction between hydrodynamic loads and structural deformations commonly goes under the name of "hydroelastic" effects and is a phenomenon predicted by theory, and also observed in experiments [3,6,14].

The influence of both dynamics and hydroelastic effects is illustrated by figure 1. Here the maximum amplitude of the dynamic response of a panel (q) is compared to the response that would correspond to the peak slamming load being applied statically (q_{qs}). Results are presented as a function of the ratio between the panel wetting time (t_i), which is a measure of the slamming impulse duration, and the panel first natural period (T_n). It can be seen how, as the impulse gets shorter in comparison to the panel natural period, the dynamic response becomes smaller and vice-versa. Equally, the influence of hydroelastic effects is shown by the vertical spread of points at constant 'impulse duration-natural period' ratios. The lower envelope of the points corresponds to the relatively 'softer' panels which, in absolute terms, present higher amplitudes of response and, hence, larger hydrodynamic load attenuation.

Panel size

There are several further remarks that could be made about figure 1. Firstly, the points in the graph have been calculated for a square panel with a side length of 0.56 metres. Larger panel sizes would result in higher wetting times (i.e. impulse durations), but equally longer natural periods. With all other variables kept constant, panel natural periods are approximately proportional to the square of the side length, while impulse durations may be assumed to increase linearly with panel dimensions. Hence, as one moves to larger size panels, the ' t_i/T_n ' ratio of figure 1 is expected to drop, which indicates lower dynamic response. Things may not be so clear cut in reality as variables like panel size, stiffness, weight, and geometry are not mutually independent, however it may still be argued that generally larger panels experience lower dynamic response to slamming loads.

Figure 2 shows a comparison of the equivalent uniform static pressure (EUSP) obtained from the Allen and Jones method and from an analytical model accounting for dynamic and hydroelastic effects. Pressures have been calculated for a panel of fixed length (0.9m) and variable width (from 0.2 to 1.1m), and normalised in order to obtain the same value for a standard reference size (i.e. 0.9 x 1m). The two curves are qualitatively very similar. In fact, they may

be even closer if, in the analytical model calculations, one was to account for the fact that narrower panels tend to have lower flexural stiffness as the result of design strength considerations.

Allen and Jones deduced their formulas from empirical data (in particular, from measured values of strain in the panels [1]). While they did not consider the effect of different panel dynamic response, attributing the reduction in pressure with increasing panel size only to the averaging out of peak pressure, figure 2 suggests that their prediction was indeed qualitatively correct.

When considering the evolution of materials employed in boat construction, it is interesting to note that in going from metallic materials to polymeric composites, and then, in particular, from lower modulus fibre glass to stiffer carbon reinforcements, there has been a considerable increase in the structures specific stiffness (i.e. a decrease in natural periods), which suggests that modern structures show comparatively much higher dynamic response to slamming loads than the older ones.

The role of curvature

Panels with curvature will deflect less under out of plane loading than flat panels (providing that the loads do not exceed the snap through load of the panel). As discussed previously, the stiffness of a panel has an effect on behaviour under slamming loads, and the increased stiffness of a curved panel would tend to increase the dynamic response of the panel.

However, when considering the dynamic hydroelastic response of the panel curvature will have a double effect:

- 1) It contributes to reducing hydrodynamic loads in a significant manner as shown in figure 3.
- 2) It raises the (initial) stiffness of the panel and brings in non-linear behaviour at smaller deflections than for a flat panel.

Although the panel is stiffer and responds more, the lowering of the hydrodynamic loads is predominant and overall curved panels will see a smaller response to slamming loads.

A new analytical method

In order to account properly for the different physical parameters involved with the behaviour of hull panels subject to slamming, a new analytical method has been developed by the authors.

The method allows the response of a panel undergoing slamming onto a flat free surface to be simulated. The influence of both dynamic and hydroelastic effects can be observed as the instantaneous deformation of the panel and its influence on the hydrodynamic loads are calculated at a number of time steps following impact.

The actual method is outlined in figure 4. First, the velocity of the panel relative to the free surface is derived from the rigid-body motion of the hull. The initial time for the calculation corresponds to the instant when any part of the panel first touches the water.

The hydrodynamic load on the panel is calculated by dividing the panel into several strips. The flow over each strip and the corresponding pressure distribution is derived by a Wagner-type approach as described in [13]. The actual response of the panel is calculated by a modal approach. The generalised hydrodynamic forces are derived by integrating the pressure over each strip. The response and, in particular, the instantaneous velocities on each point of panel surface, are then obtained and summed to the overall rigid-body velocity to calculate the panel immersion and the hydrodynamic loads for the following time step. With a constant or decaying impact velocity, the maximum amplitude of response is attained during the first cycle of oscillation of the panel; hence the iteration is normally stopped after the first response peak is observed.

The method has been validated by comparing its predictions against published experimental data and against output from other analytical models [13]. Figure 5, in particular, shows a comparison of the overall slamming force measured in a towing tank for a hull bottom panel of a 7th scale model [14], and the corresponding predictions from the present method. The agreement appears to be extremely good, particularly when considering the typical scatter that normally affects experimental measurements of slamming pressures.

Figure 5 shows that the analytical method can reproduce accurately a typical feature of equivalent slamming loads, which is that the relation between the panel response and the impact velocity is close to parabolic for lower impact velocities and tends to become linear as the later increase. This is explained by the fact that, at lower impact velocities, the dynamic amplification factor is almost constant and the hydrodynamic loads increase with to the square of the impact velocity. Conversely, for the higher impact velocities, the hydrodynamic loads are still proportional to the relative velocity squared, but the dynamic amplification factor decreases (as shown in figure 1), since impulse durations decrease with increasing velocity. Hence, overall, the amplitude of response tends to increase only linearly at the higher relative impact velocities.

The limitations

The validity of this approach relies on two main assumptions being verified. First of all, over the simulation time the flow on each strip of the panel is close to two-dimensional and independent of the conditions on the adjacent strips. This has been shown to be an acceptable approximation for bodies with relatively constant sections impacting the water with low trim angles [4]. When considering actual yacht hulls, this assumption may be expected to be verified for panels of limited longitudinal extent and when the local panel trim angle relative to water surface is approximately lower than 5 degrees.

Secondly, in order for the modal approach to be justified, it is required that the behaviour of the structure is linear. While this may be the case under most loading conditions, it is believed that, in some instances, slamming loads can produce structural deformations which are beyond the linear domain. In this case, neglecting non-linear effects would equate to underestimating the stiffness of the structure and overestimating its deflections.

The limitations brought by this later assumption are currently being addressed by incorporating a finite difference method for the solution of the panel dynamic response. This will allow both in-plane and shear deformations to be more accurately modelled.

Extending the capability of the model to account for three-dimensional flow effects over hull shapes with variable sections is expected to require considerably more effort. While some promising results have been published for methods modelling the flow around three-dimensional ellipsoids undergoing water impact, the complexity of the associated numerical models is believed to be incompatible with the requirement for a method that could be used as a design tool.

Finally, it should be noted that, like most models of water entry, the present analytical method neglects the influence of the following parameters:

- water aeration, i.e. the presence of air bubbles near the free surface, typically observed at sea under wave breaking conditions;
- hull wetting prior to impact, i.e. the presence of a layer of water adhering to the hull surface before the actual slam takes place;
- small scale irregularities of the free surface such as those associated with capillarity waves and other extremely short length waves;
- air entrapment, i.e. the presence of air pockets becoming trapped between the hull and the free surface in the instants preceding the impact.

Experimental data published by Campbell et al. [4] suggest that the first three phenomena in the list affect the variation in time of the overall hydrodynamic force on a panel more than its maximum magnitude. The structural dynamic response may change as a result, but differences are expected to be minor under most circumstances.

The consequences of air entrapment have been discussed in detail by [8,12,18]. This phenomenon is generally assumed to lower the overall hydrodynamic impact loads as it contributes to reducing the relative impact velocity and the average density of the fluid in the vicinity of the hull. Neglecting its influence should result in conservative estimates of panel response. Since air entrapment effects are believed to be significant only during the instants immediately before and after the time of first contact between the hull and water, their consequences (and the error resulting from neglecting them) should be more important for configurations where extremely short

impulse durations are expected (e.g. panels of extremely small size, very high impact velocities, very small deadrise angles, etc.).

Towards a new design tool.

The analytical method described in the previous paragraphs can be used as the basis of a design tool for assessing the ability of different structural solutions to withstand slamming loads.

To use the method as a design tool requires definition of the design impact conditions for different parts of the hull. This could be done either on the basis of empirical data measured on similar vessels or seakeeping calculations.

This process would be similar in principle to the way in which common classification society rules devise design loads for different elements of the structure.

However whilst current design methods define a load that is independent of the characteristics of the structure, our approach would allow the influence of the dynamic response of the structure to be taken into account.

In particular, as the relative effects of different structural design parameters like stiffness, weight and geometry are accurately modelled, these parameters can be properly accounted for in the analysis.

The more realistic analysis of the response enables the true influence of structural arrangement and panel construction to be realised. For example, addition of internal structure to reduce panel size will modify the dynamic response of the panel. Without considering the effect of this on the slamming event, it would be difficult to understand the complete impact of the change in panel size on the strength of the structure.

Conclusion

Current methods of designing hull structure derive design pressures based on empirical calculations. These methods do not take full account of the dynamic response of the structure during slamming.

The dynamic response of the structure can have a significant effect on the loads experienced by the panel. In order to account for this, an alternative analysis method has been developed which considers the dynamic response of the structure and the influence of this on the hydrodynamic loads on the hull.

The analysis method is being developed to form a design tool that will enable the influence of the structural characteristics of the hull shell on the slamming response of the hull to be modelled for modern high performance craft. This will enable comparisons between different design solutions to be made.

References

- [1] Allen, R. & Jones, R., "A Simplified Method for Determining Structural Design-limit Pressures on High Performance Marine Vehicles", AIAA/SNAME Advanced Marine Vehicle Conference, 1978
- [2] American Bureau of Shipping, "Guide for Building and Classing Offshore Racing Yachts", 1994
- [3] Bereznitski, A., "Slamming: the role of hydroelasticity", International Shipbuilding Progress, Vol. 48, pp. 333-351, 2001
- [4] Campbell, I. and Weynberg, P., "Measurement of Parameters Affecting Slamming", Technical report, WUMTIA, UK, 1980
- [5] Fabula A.G., "Ellipse fitting approximation of two dimensional normal symmetric impact of rigid bodies on water." Proceedings of the fifth midwestern conference on fluid mechanics. University of Michigan, USA, 1957. p. 299-315.
- [6] Faltinsen, O., "Sea Loads on Ships and Offshore Structures", Cambridge University Press, 1990
- [7] Faltinsen, O., Kvålsvold, J. and Aarsnes, J., "Wave impact on a horizontal elastic plate", Journal of Marine Science and Technology, Vol. 5, pp. 87-100, 1997
- [8] Haugen, E.M., "Hydroelastic analysis of slamming on stiffened plates with application to catamaran wetdecks", PhD thesis, NTNU Trondheim, Norway, 1999
- [9] Heller, S. and Jasper, N., "On the Structural Design of Planing Craft", Transactions of the Royal Institution of Naval Architects, Vol. 103, pp. 49-65, 1961
- [10] Hentinen, M. and Holm, G., "Load measurement on the 9.4m sailing yacht 'Sail Lab'", Thirteenth International Symposium on Yacht Design and Yacht Construction, Amsterdam, 1994
- [11] Joubert P.N., "Strength of bottom plating of yachts", Journal of Ship Research, Vol.26, No 1, Society of Naval Architects and Marine Engineers, p.45-49, March 1982,
- [12] Koehler, B. and Kettleborough, C., "Hydrodynamic impact of a falling body upon a viscous incompressible fluid", Journal of Ship Research, Vol. 21, 1977, SNAME, pp. 165-181,
- [13] Manganelli P. "Experimental investigation of dynamic loads on offshore sailing yachts", PhD thesis, University of Southampton, UK, 2006
- [14] Manganelli, P., Wagemakers, B. and Wilson, P.A., "Investigation of slamming loads using slam patches on a scale model of an Open60' class yacht", 17th International Symposium on 'Yacht Design and Yacht Construction', Amsterdam, 2002
- [15] Schnitzer E., "Estimation of hydrodynamic impact loads and pressure distribution on bodies approximating elliptical cylinders with special reference to water landings of helicopters." NACA TN 2889, National Advisory Committee for Aeronautics, Washington, USA, April 1953.
- [16] Seddon C.M. and Moatamedi M., "Review of water entry with applications to aerospace structures," International Journal of Impact Engineering, Volume 32, Issue 7, July 2006, Pages 1045-1067.
- [17] Shiffman M, Spencer DC. "The force of impact on a sphere striking a water surface (approximation by the flow about a lens)". AMP Report 42.1R AMG-NYU no.15, Applied Mathematics Panel, February 1945
- [18] Takagi K.; Dobashi J., "Influence of Trapped Air on the Slamming of a Ship", Journal of Ship Research, Volume 47, Number 3, September 2003, SNAME, pp. 187-193
- [19] Von Karman T., "The impact of seaplane floats during landing". NACA TN321, National Advisory Committee for Aeronautics, Washington, USA, October 1929
- [20] Wagner H., "Über stoß- und gleitvorgänge an der oberfläche von flüssigkeiten" (Phenomena associated with impacts and sliding on liquid surfaces). Zeitschrift für Angewandte, Mathematik und Mechanik, Vol.12, p.193-215, 1932.

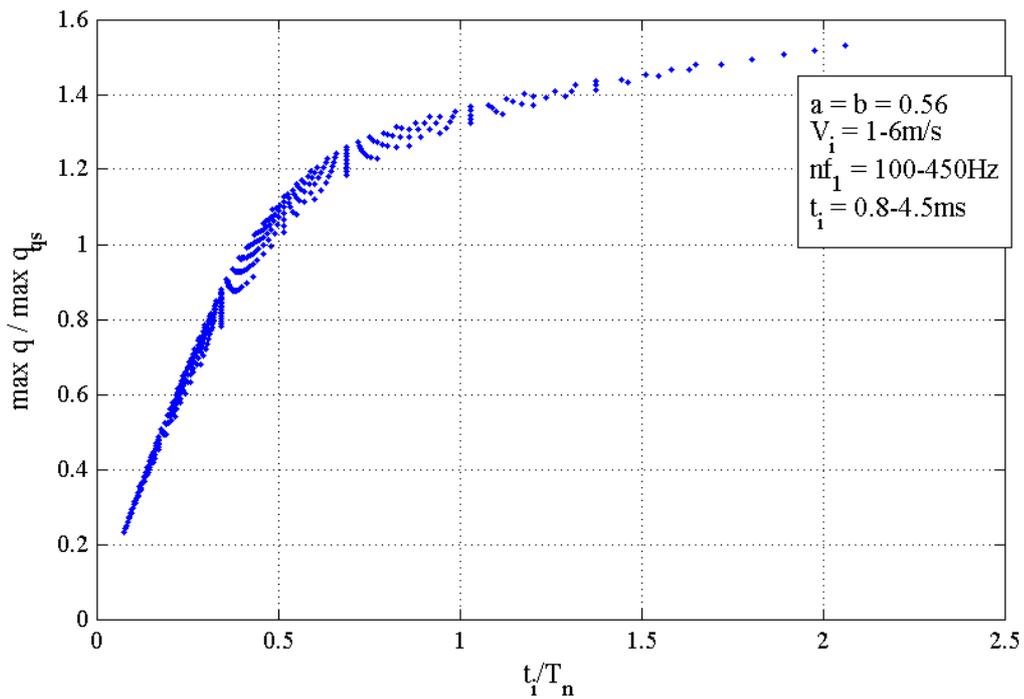


Figure 1 - Dynamic response of a hull panel to slamming load

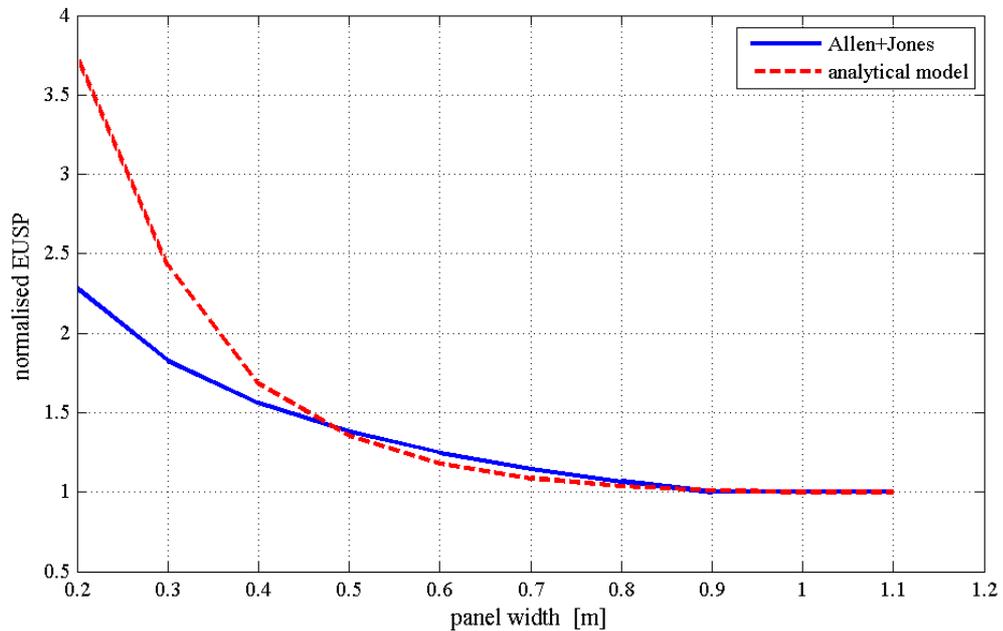


Figure 2 - Comparison of EUSP Vs panel width from Allen and Jones method and from analytical model accounting for dynamic and hydroelastic effects. EUSP from the analytical model are calculated on the basis of same maximum panel deflection and with constant panel mechanical properties.

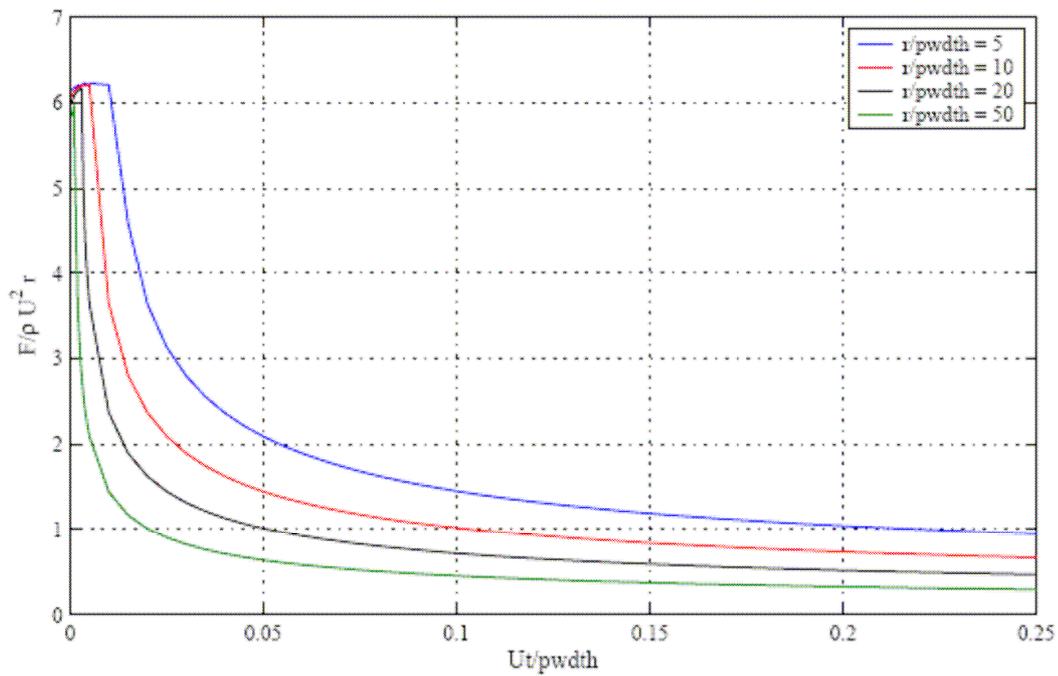


Figure 3 – Comparison of overall hydrodynamic forces on a hull panel with different curvature radii and constant width. Forces are normalised by the impact velocity squared and by the curvature radius.

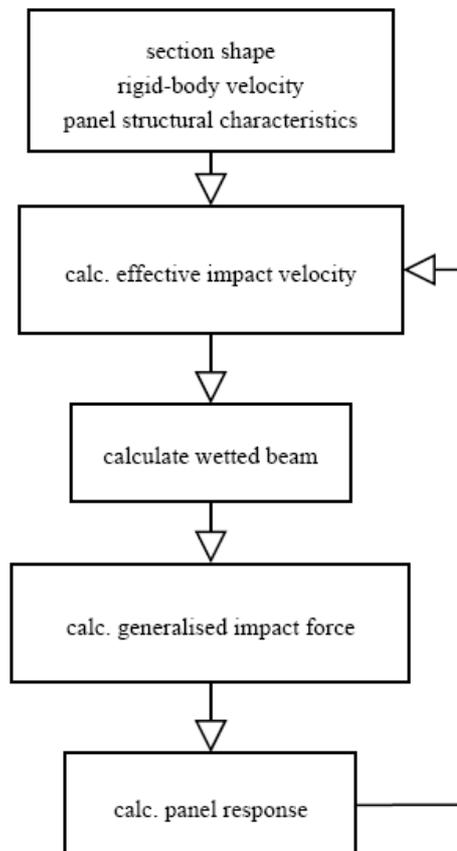


Figure 4 – Outline of the analytical method for the prediction of hull panel response to slamming loads

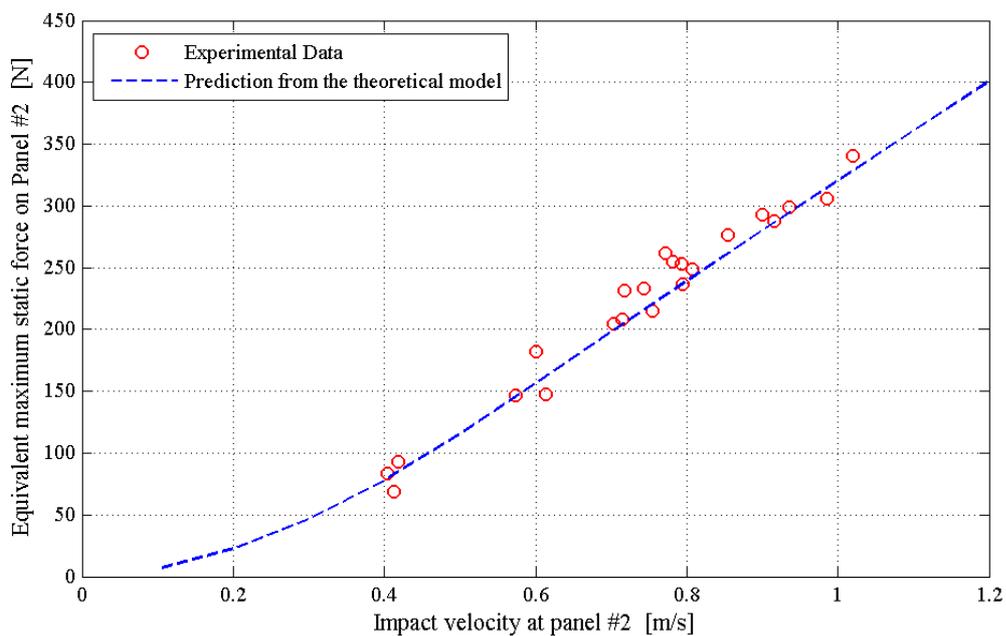


Figure 5 - Comparison of predictions from the analytical model with experimental data from towing tank tests on a model equipped with slam patches.