DYNAMIC PERFORMANCE OF SANDWICH CORE MATERIALS

Mark A. Battley*, Susan E. Lake**
***Centre for Advanced Composite Materials, University of Auckland, New Zealand**
****High Modulus (NZ) Ltd**

Keywords: *Sandwich, Dynamic, Core, Foam, Marine, Slamming*

Abstract

Sandwich composite materials used for the bottom panels of high speed marine vessels can be subjected to dynamic pressure loads due to slamming with the water surface. Analysis of laboratory based slamming tests demonstrates that the transverse shear stress rates experienced by core materials in sandwich panels subjected to water slamming can be significantly higher than those prescribed by an industry standard testing method. Dynamic testing was undertaken of four point loaded sandwich beams with Aramid honeycomb, cross-linked and high elongation PVC cores at four different loading rates. The results show that the Aramid honeycomb is insensitive to the loading rate, while the cross-linked and high elongation PVC materials are stronger when loaded dynamically than at pseudo-static loading rates, but are not very sensitive to the actual dynamic loading rate.

1 Introduction

A significant contributor to improved performance of yachts and powerboats has been the use of lightweight composite materials, often as sandwich structures. As a consequence of the higher speeds achieved, such vessels can be subjected to large dynamic loads such as slamming from water impact as shown in Fig. 1.

Fig. 1. Slamming of racing yacht

Slamming events typically generate high magnitude pressure pulses of very short duration that move across the panel as the hull enters the water (Fig. 2). This results in high strain rates within the composite materials, both in the skin materials and the core.

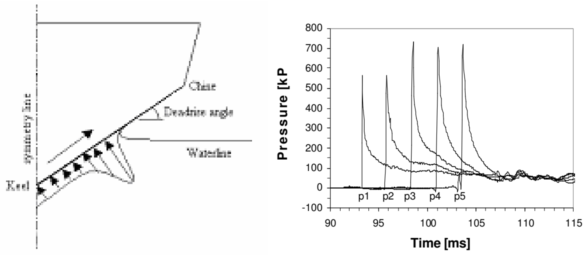

Fig. 2. Typical Slamming Event
(Experimental data for 5m/s at 10º deadrise)

The mechanical properties of some core materials, particularly cellular polymeric foams, have been shown to change significantly with loading rate, typically demonstrating increases in strength and reductions in ductility [1, 2]. However there is a lack of reliable data on the actual stress and strain rates that these materials experience during slamming events. The rapid development of new core materials also means that it is important to have reliable methods to evaluate the dynamic performance of materials.

The aims of the work described in this paper are to determine the transverse shear strain rates experienced by core materials in sandwich panels subjected to water slamming, and to characterize the rate dependency of the strength of different types of core materials at a range of typical loading rates. Materials investigated included Airex C70.130 cross-linked PVC foam, Airex R63.140 linear PVC foam and Euro-Composites NH80 Aramid honeycomb.

Laboratory based slamming tests of sandwich panels are used to determine the strain and stress rates in the skins and cores of a typical sandwich hull structure, and then high-speed four point beam testing is used to determine the rate dependency of the transverse shear strength of the core materials.

2 Strain Rates for Panel Slamming Events

2.1 Overview

The primary mechanical properties of core materials for marine sandwich panel structures are normally the transverse shear strength and stiffness. However it is difficult to directly measure the transverse shear strain within core materials. Approaches that have been used include imbedding resistance strain gauges, and mechanical systems to measure the relative displacements of the skins. Both of these techniques cause significant disruption to the internal strain fields of the core. This, combined with the difficulty of undertaking controlled slamming experiments means that there is only very limited data available on actual strain rates.

The marine scantling authority Det Norske Veritas (DNV) specifies a dynamic test for approval of core materials to be used in the slamming regions of hulls [3]. This is based on the American Society for Testing and Materials (ASTM) C393/C393M – 06 four point bending test [4], but instead of using quasi-static loading employs a high loading rate so that the core experiences a nominal shear stress rate of 65MPa/s. It is not clear however how relevant this loading rate is to actual slamming events.

Experimental measurements of slamming events have been performed on actual vessels, by using "drop tests" where a specimen is dropped from a defined height onto the water surface, and also by using scale models in towing tanks. Many drop tests have used rigid models to investigate the resulting pressure distributions, such as those by Chuang [5], who performed experiments on slamming of wedge-shaped bodies, and Wraith [6], who performed drop tests on rigid V-shaped, single and double curved specimens. Drop tests using non-rigid panels include those by Hayman et al. [7, 8], Katsaounis and Samuelides [9], and Faltinsen [10]. The main drawback of drop tests is that there is no direct control of the specimen motion once it hits the water, the retardation rate primarily being dependent on the mass and geometry of the specimen and fixtures.

In reality the velocity profile during a slamming event depends on the hydrodynamic behaviour of the vessel and the position of the panel. A panel near to the keel may have a nearly constant velocity throughout the slamming event, whereas one near the dynamic waterline of the boat will have a velocity that approaches zero at the end of the slamming event. In the case of real vessels, instrumentation is often limited to measurements of overall velocity and accelerations due to restricted access to the hull skin, and by the need to destructively modify the panels for some measurements such as pressure and core strains. It is also difficult to reproduce particular conditions in real vessel testing due to the large number of variables that contribute to a slamming event including water entry velocity, wave height and frequency and deadrise angle during the slamming event. The Servo-hydraulic Slam Testing System (SSTS) used in this work was developed in order to address these issues.

2.2 Servo-hydraulic Slam Testing System

The SSTS, shown in Figs. 3 to 6, uses a custom designed computer controlled high speed servo-hydraulic system to control the motion of a panel during water impact into a 3.5m diameter, 1.4m deep water tank. This test method is further described in references [11 and 12]. Vertical panels on the sides and behind the panel constrain the flow to 2D behaviour. The SSTS can achieve velocities of up to 10 m/s. Panels attached to the test fixture can be adjusted to have deadrise angles of 0, 10, 20, 30 and 40º.

Fig. 3. Exterior of the Servo-hydraulic Slam Testing System (SSTS)

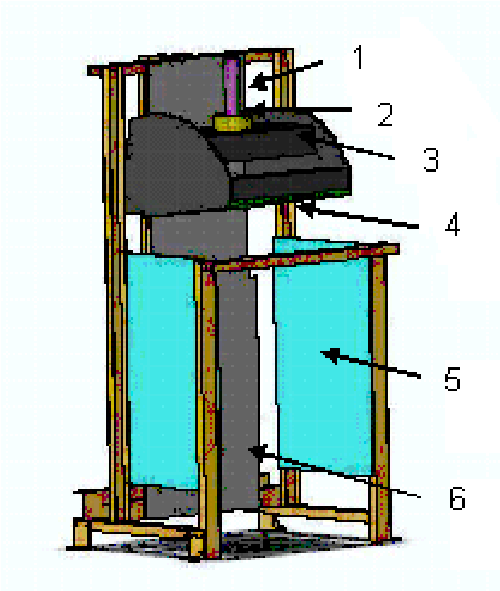

Fig. 4. Servo-hydraulic slam testing system (SSTS) Ram (1), load cell (2), sliding specimen fixture (3), panel (4), side plates (5), back plate (6)

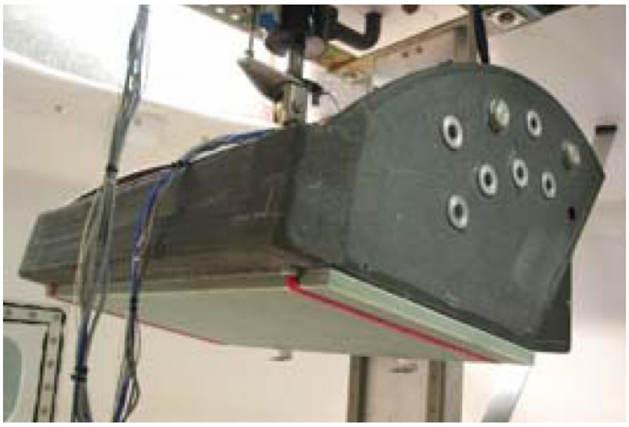

Fig. 5. Panel sample mounted in SSTS

Fig. 6. Typical slamming event in SSTS

For this study panels with simply supported edges were subjected to dynamic slam loading using the SSTS at a deadrise angle of 10º to maximize the impact force. Three resistance strain gauges (typically MM EA-13-125SAC-350) were located on the top surface of the panel as shown in Fig. 7, with their measurement axis oriented across the short span of the panel. Other instrumentation included an accelerometer (PCB 321 A02) to measure the motion of the test fixture, a 100kN load cell (PT LPC 10000) between the hydraulic ram and the test fixture, a displacement transducer for the local panel response (Schaevitz 1000 HCD) attached to the centre of the panel, and a displacement transducer for the overall motion of the text fixture (Vishay REC-139L).

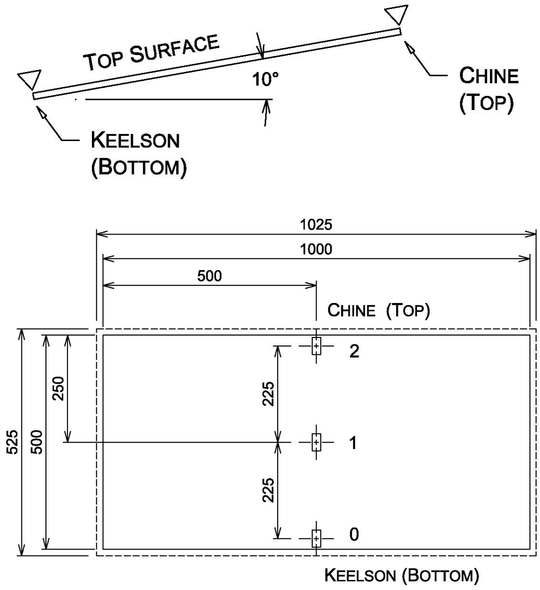

Fig. 7. Geometry and Location of Strain Gauges

The skins of the panels were 2400gsm of balanced-symmetric E-glass Quadraxial (0/+45/90/-45). The core thickness for the panels varied from 15 to 20mm. Core materials studied in the panel slamming investigation reported in [2, 11 and 12] included Airex C70.130 cross-linked PVC, Baltek SL-89 Superlite Balsa, Euro-Composites NH80 Aramid honeycomb and Airex R63.140 linear PVC foam. The focus of the first part of this paper is further analysis of the results from the C70.130 panel tests to determine loading rates for the core material.

2.3 Typical Slam Test Results

During slam testing of the sandwich panels a time history of the panel acceleration, instantaneous velocity, applied ram force, deflection at centre, and strains at the keel, centre and chine were recorded. Fig. 8 shows a typical slam test result at 4m/s for a panel with the C70.130 foam as a core. The diagram shows the load applied to the test specimen and fixture by the servo-hydraulic system, the resulting velocity profile during the slam events, the displacement of the centre of the panel relative to its edge support fixture, the average acceleration of the test fixture, and the skin strains at the two edges and centre of the panel as defined in Fig. 7. These strains are measured on the upper skin of the panel, in the short span direction. The blue vertical line represents the time at which the "keel edge" of the panel reaches the water surface, and the black line the theoretical time at which full immersion of the panel would be reached. In practice the water reaches the chine edge before this, due to the dynamic flow of water up the panel as shown in Fig. 2. Even at this relatively slow slamming velocity the total duration of the slamming event is less than 15 milliseconds.

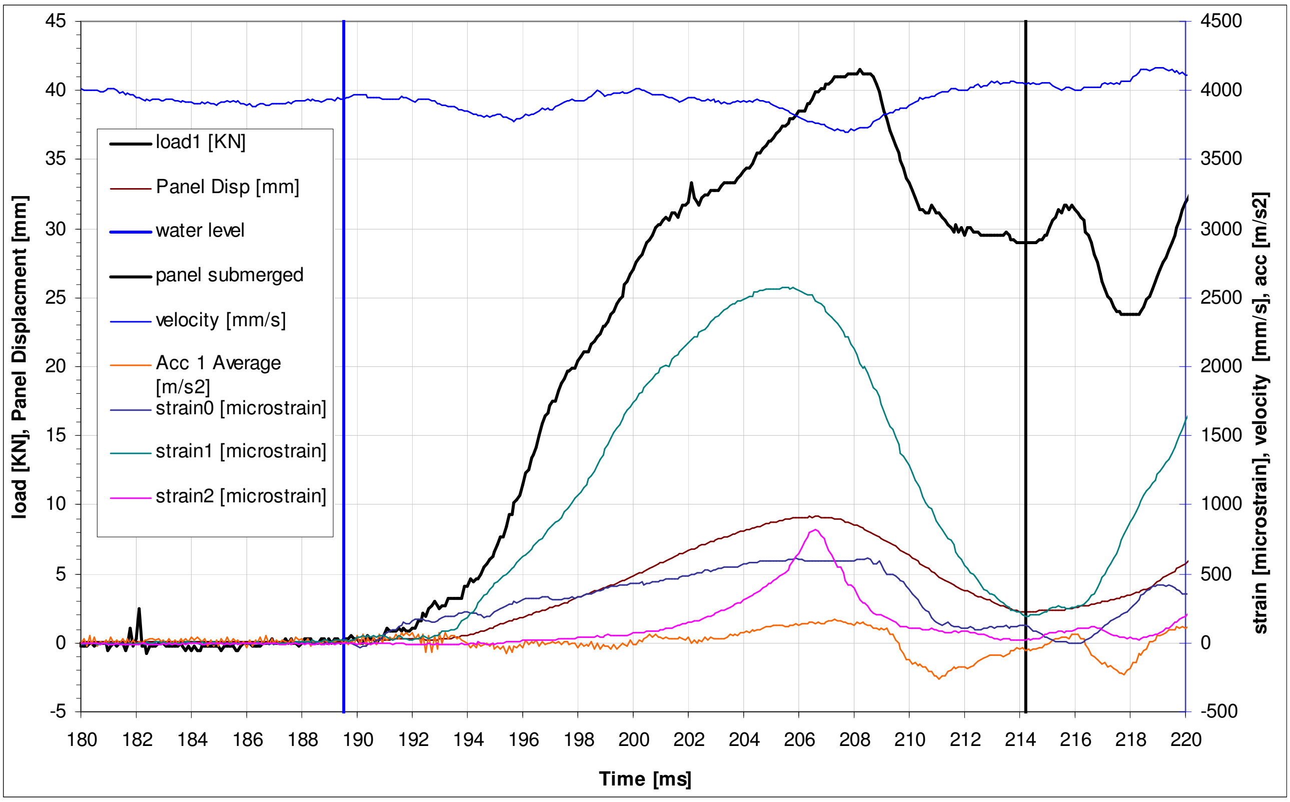

Fig. 8. Slam test results for C70.130 cored panel at 10° and 4m/s

The three panel skin strains and the centre deflection provide significant insight into the progression of the pressure pulse and resulting panel deformation during the immersion of the panel. The strain at the centre of the panel increases at a similar rate to the centre deflection, with the centre strain reaching its maximum slightly before the deflection.

The strains at the two edges are indicative of the transverse shear forces at the panel edges and thereby show the effect of the pressure pulse progressing across the panel. The keel strain increases at the start of the slamming event and then remains relatively constant, while the chine strain does not start to increase until approximately half way through the event then rises quickly, reaching its maximum when the panel is approximately 75% submerged.

The chine edge does not experience significant transverse loads until relatively late in the slamming event, but it is then subjected to larger transverse shear loads and higher local loading rates than the keel edge. This is because the chine edge of the panel is loaded both by the distributed residual pressure across the almost fully immersed panel, and also by the momentary localised peak pressure pulse as shown in Fig 2. All failures of the panels tested were by core fracture or permanent yield at the mid-point of the chine edge in the vicinity of the chine straingauge.

Fig. 9 compares the chine strain versus time for 4, 5, 6, and 7 m/s demonstrating that the magnitude and strain rate increases significantly with entry velocity. At the final test velocity of 7m/s there is residual strain, indicating that the panel has permanently deformed due to shear yielding of the core material. This was confirmed by post test inspection of the panel.

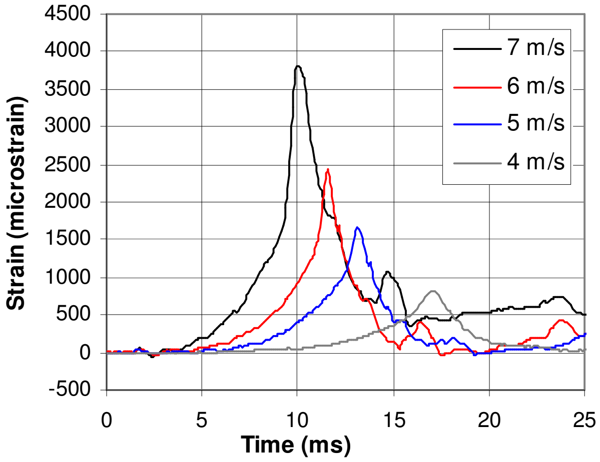

Fig. 9. Effect of loading rate on chine strain for C70.130 foam core panel

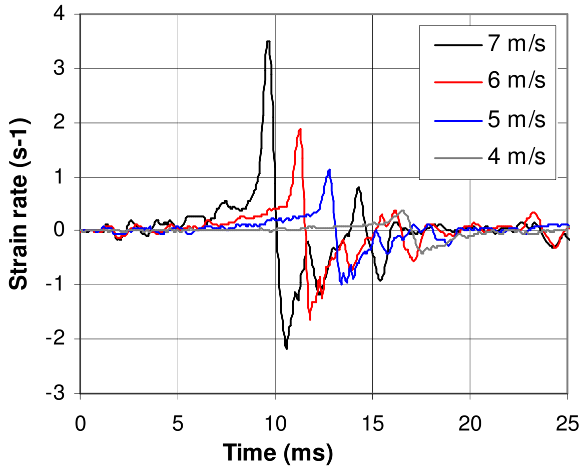

Fig. 10. Effect of loading rate on chine strain rate for C70.130 Cored panel at 10° deadrise angle

Tests of the various core materials using the SSTS were undertaken at a range of entry velocities for each material type studied. Typically the lowest velocity was 3m/s, then the test velocity was increased until core shear failure of the panel, or until a maximum of 10m/s was reached. All of the panels failed or suffered permanent deformation at the mid-point of the chine edge.

2.4 Skin Strain Rates

The results from tests on the panels constructed with cross-linked PVC cores were post-processed to determine the maximum skin strain rates for the chine strain gauges at each testing velocity. Several analysis methods were evaluated to minimize the effect of any high frequency noise in the signals, the most reliable proving to be a 5 point moving average.

Fig. 10 presents the resulting strain rates for the C70.130 foam core panel tested at 4 entry velocities from 4 to 7m/s. Comparing this to Fig. 9 shows that the maximum strain rates occur for a very short period just before the maximum strain is reached.

Fig. 11 summarises the maximum strain rates calculated for the chine strain gauge for water entry velocities from 4 to 7m/s on a typical C70.130 cored panel, showing a range from approximately 0.4 s-1 to 3.5 s-1.

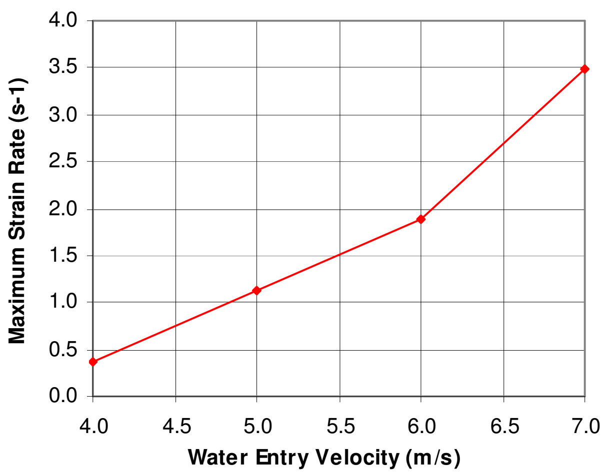

Fig. 11. Summary of maximum strain rate vs. water impact velocity (C70.130 Cored panel at 10° deadrise angle)

2.5 Conversion of Skin Strain rates to Core Transverse Shear Stress Rates

The skin strains measured at the chine edge do not directly measure the core shear strain, but do provide an indication of the local bending moment and hence transverse force and its rate of increase at this position of high transverse shear loads. Due to the complexity of the panel response it is difficult to accurately measure or predict the actual core shear stress. The following two approaches were utilized to estimate the relationship between the observed skin strain rates and the corresponding core transverse shear stress:

1. The maximum skin strain measured at the chine was compared to the measured yield strength of the core at a water entry velocity

that resulted in core yield. In the case of the C70.130 cored panels, yielding of the core was observed by residual strains and permanent panel deformation to occur at 7m/s water entry velocity. The conversion factor shown in Table 1 for this method was calculated by dividing the measured static yield strength of the C70.130 core by the maximum measured chine strain from the 7m/s test. This provides a lower bound on the core shear stress/skin strain relationship since the dynamic yield strength of the core is higher than the static and initiation of yield may have occurred before 7m/s, but not in a large enough region to be obvious in the test data.

2. The second conversion factor given in Table 1 was calculated using the predicted core transverse shear stress and maximum chine axial skin strain from modal transient Finite Element Analysis. The modeling of the slamming event was performed with a moving pressure pulse based on experimental pressure distributions. This method has previously been shown to provide reasonably accurate predictions of these slamming events. The methodology is presented in [11]. Both core shear stress and skin strain were taken at the position of the strain gauge.

The resulting conversion factors from skin strain to core shear stress were then multiplied by the observed strain rates shown in Fig. 11 to yield the estimated shear stress rates given in Table 1 and Fig. 12. The resulting stress rates cover a wide range and are all significantly higher than the 65 MPa/s defined by DNV in their HSC rule.

Table 1. Estimated core transverse shear stress rates from slamming data

Case	Conversion factor (MPa/unit strain)	Estimated core shear stress rate (MPa/s) 4 m/s	5m/s	6m/s	7m/s
Yield at 7m/s	603	217	676	1135	2101
Transient FEA	1227	442	1375	2308	4272

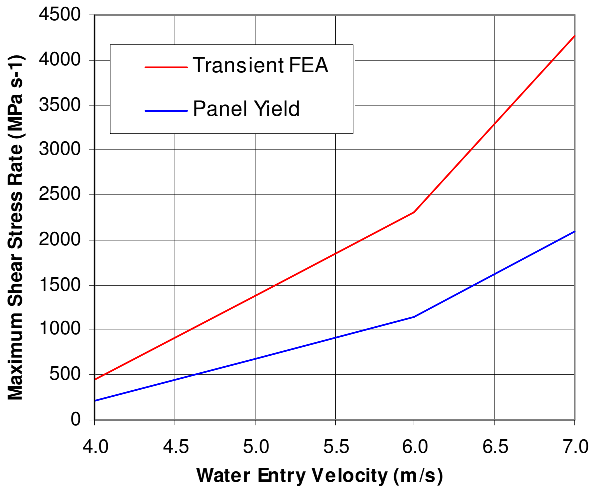

Fig. 12. Estimated core transverse shear stress rates from slamming data

2.6 Discussion of Core Shear Stress Rates

There is only very limited published data available for core transverse shear stress rates. Measurements undertaken by Hayman et al. are described in [7] and [8]. Their work included drop tests of a V shaped hull specimen, and some measurements taken on a 19.6m coastal rescue craft. In both cases strain gauges were embedded in the foam core to measure the transverse shear strains. Stress rates are not explicitly described, but interpretation of strain vs. time graphs suggests core shear stress rates of approximately 25 to 300 MPa/s depending on deadrise angle and impact velocity. Possible reasons for the lower values obtained than in this current work include:

- Differences in the panel materials, dimensions and boundary conditions.
- None of the strain gauges are situated close to the edge of the panel where the maximum shear loads are expected to occur. The closest gauge for the drop test appears to have been 115mm from the panel edge and on the actual vessel 220mm from the edge.
- In this author's experience, embedding of strain gauges in a foam core material typically underestimates core shear strain magnitudes due to local reinforcing of the core.
- Reductions in slamming velocity throughout the drop test event are evident in pressure traces included in [8]. This is also likely to be a reason for the maximum shear strains occurring near to the keel, rather than the chine as in this work.

3 Dynamic Testing of Sandwich Beams

3.1 Testing Method

The beam testing method used was based on that of the DNV Rules for High Speed, Light Craft and Naval Surface Craft [3]. This is based on an existing four-point sandwich beam testing standard, [4], but with a loading rate equivalent to a nominal core shear stress rate of 65 MPa/s. For a material of nominally 50 MPa core shear stiffness, this equates to a crosshead velocity of the order of several hundred mm/s depending on specimen dimensions, moment arm, and bending stiffness. This stress rate is applied to determine a specimen load application rate that achieves the correct stress rate in the initial linear region of the loading, before any yielding and subsequent non-linearity occurs for ductile core materials, or large geometric changes affect load distribution within the beams.

The DNV dynamic testing method provides a method of quantifying the effect of loading rate on core shear properties. However the analysis of the slamming test results presented in this paper suggests that actual shear stress rates in slamming can be significantly higher than 65 MPa/s. The aim of the beam testing was to investigate how the properties of the core material change at loading rates greater and equal to the DNV specified rate.

The testing of the four point loaded beam specimens was performed using a high speed four point bending test system. This system employs a computer controlled servo-hydraulic ram to apply the load, and records the ram displacement and applied load. The beams were tested in a quarter point loading situation with a support span of 300mm and a load span of 150mm. Tapered fiberglass pads were used to distribute the concentrated loads at the inner loading points.

Analysis of the beam stiffness and initial tests were undertaken to determine the loading rate that would achieve as close as possible to the DNV specified rate of 65 MPa/s for C70.130 foam core. The beams were then tested at a pseudo-static loading rate (0.3mm/s), at the rate that corresponded to the DNV rate (180mm/s), and twice and three times the DNV rate (360mm/s and 540mm/s). Because of the slightly different shear stiffness of each core the actual stress rate achieved varied between the materials, as shown in Table 2. While the 360mm/s and 540mm/s cases result in stress rates that are two to three times higher than the DNV specified 65 MPa/s rate, they are still not as high as those observed in the actual slamming tests. The maximum velocity was limited by the capability of the testing system.

Table 2. Core transverse shear stress rates achieved in beam testing (MPa/s).

Testing velocity	C70.130	R63-140	NH80
180 mm/s	65	55	76
360mm/s	120	90	155
540 mm/s	155	130	185

3.2 Specimen Details

Sandwich panels were manufactured using a wet hand lay-up technique and vacuum bagging. The skins consisted of two layers of 920gsm glass fibre triaxial stitched cloth (ETF920) at a nominal fibre weight fraction of 60% in West System 105 epoxy resin with 206 hardener, resulting in a skin thickness of 1.75mm. The core materials were nominally 20mm thick, and the beams were cut to dimensions of 75mm wide and 450mm long.

24 specimens were manufactured for each of the three core materials. This gave one set of six specimens for the pseudo-static tests and three sets of six specimens for the three different dynamic loading rates. One specimen of each set was used for initial setup and confirmation of loading rates, with five specimens used for the main test programme.

3.3 Specimen Failure Modes

All of the NH80 honeycomb and C70.130 cross-linked PVC specimens failed by shear fracture of the core material, sometimes at one end of the specimen, sometimes on both as shown in Figs. 13 and 14. This type of fracture occurred at all loading rates.

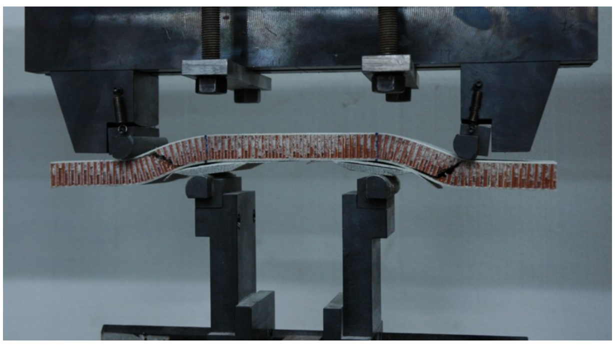

Fig. 13. Shear fracture of NH80 core beam specimen

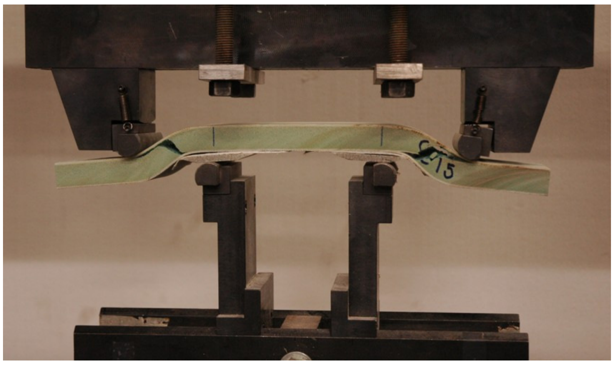

Fig. 14. Shear fracture of C70.130 core beam specimen

The specimens with the more ductile R63.140 core failed by plastic deformation of the foam core, leading to large deformations of the beams in transverse shear (Fig. 15), and significant local compression under the loading pads eventually leading to skin fracture at the inner loading points as shown in Fig. 16. This occurred at static and dynamic loading rates.

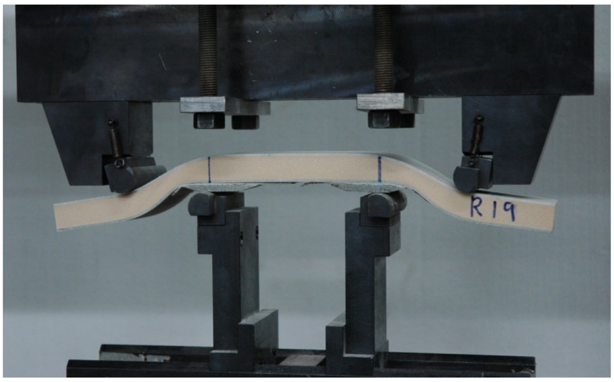

Fig. 15. Shear deformation of R63.140 core beam specimen

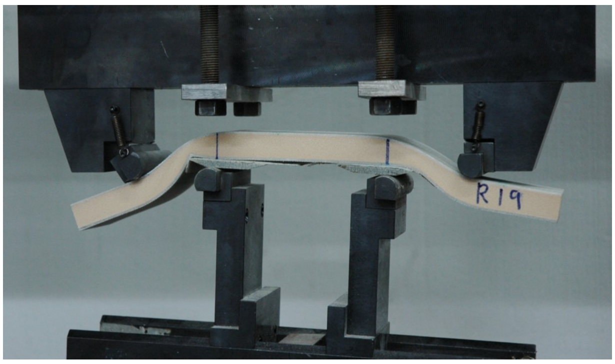

Fig. 16. Skin fracture of R63.140 core beam specimen

This type of failure involving large deformations followed by skin fracture is common for ductile cores under flexural loading, and can also occur for more rigid cores depending on the type of load pads and loading spans used. The extreme deformation of the specimens even before skin failure means that the methods used by typical test standards for calculation of core shear stress are no longer valid at this stage of the test because of changes to thickness of the specimens and geometric changes to load carrying in the beams. Care must be taken in interpreting results for such tests.

3.4 Effect of Loading Rate on Core Properties

Fig. 17 compares typical load-deflection curves at each of the loading rates for the NH80 honeycomb core beam specimens. There is no apparent difference in stiffness or strength between the loading rates. The stress-deflection curves are essentially linear to failure and the beams fail at relatively small deflections of 7 to 8mm, confirming the brittle nature of the honeycomb core.

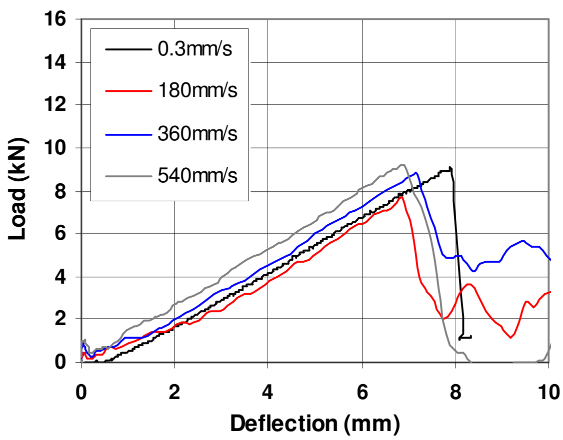

Fig. 17. Typical load-deflection graphs for NH80 honeycomb core beam specimens

Fig. 18 compares typical load-deflection curves at each of the loading rates for the C70.130 cross-linked PVC core beam specimens. These specimens show an initial linear region, progressive yield and then a region of plastic deformation at almost constant stress. The initial stiffness of the specimens appears to be similar; however there is a significant increase in both yield and ultimate strength of the core material at the high loading rates. There does not appear to be a significant difference in the strength of the core between the three high rate tests. The beams tested at low loading rates showed a longer region of plastic deformation than those tested dynamically, suggesting a reduction in ductility at the dynamic loading rates.

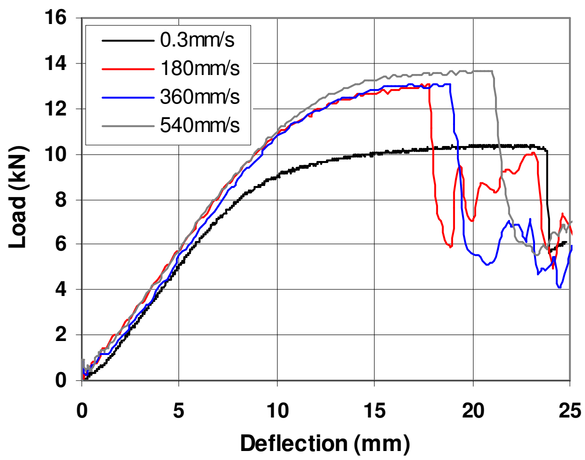

Fig. 18. Typical load-deflection graphs for C70.130 core beam specimen

The equivalent data is presented for the R63.140 core beam specimens in Fig. 19. The high ductility of this core is obvious in the large deformation of the beams. There appears to be a slight increase in initial stiffness of the dynamic beams compared to the static. There is a very significant increase in yield and ultimate shear strength for the dynamic beams. It is difficult to be conclusive about the limit of ductility for these specimens because the final failure is governed by skin failure; however the maximum displacement reached is similar for all of the loading rates.

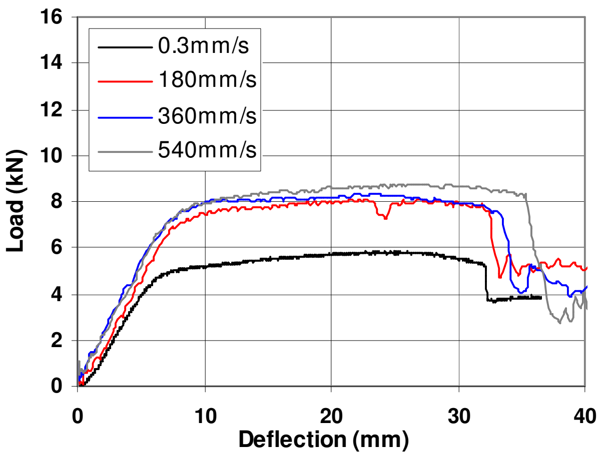

Fig. 19. Typical load-deflection graphs for R63.140 core beam specimen

The maximum shear stress value obtained from tests of this type is of questionable validity due to the large deformation of the specimens and sensitivity of the failure mode and stress to details of the exact loading method. The maximum shear stress is also of limited usefulness for design purposes. Calculation of the yield stress was undertaken for the two foam cores to provide a more meaningful comparison of their performance. The yield was determined by a 2% shear deflection offset of the linear portion of the load-deflection curve.

In the case of the NH80 Honeycomb core there was no apparent yield and only small beam deformations so the maximum stress achieved in the tests was used. Table 3 and Fig. 20 summarise the resulting core shear strengths at the different loading rates. The data points are plotted in Fig. 20 for all 60 specimens tested, with the lines defining the average strength values at each stress rate.

Table 3. Effect of loading rate on core shear strength

Loading Rate	0.3mm/s	180mm/s	360mm/s	540mm/s
Average strength (MPa) max. for NH80, yield for C70.130 and R63.140				
NH80	2.85	2.38	2.79	2.86
C70.130	2.74	3.57	3.56	3.62
R63.140	1.50	2.19	2.36	2.37
Standard deviation (MPa)				
NH80	0.23	0.23	0.42	0.08
C70.130	0.02	0.07	0.05	0.03
R63.140	0.06	0.08	0.10	0.03

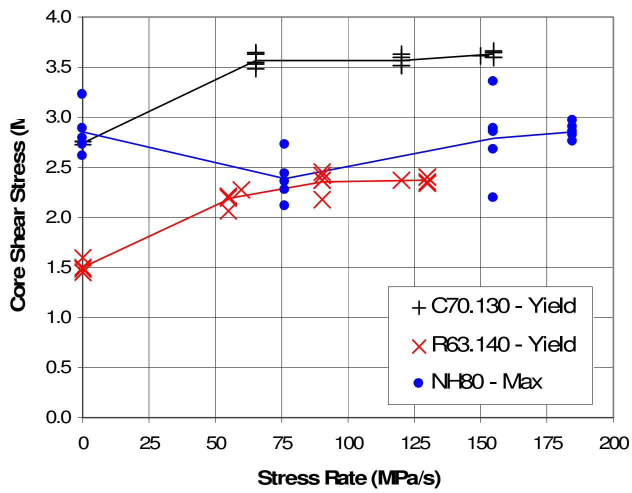

Fig. 20. Core shear strength vs. stress rate

The results confirm that the NH80 honeycomb is relatively insensitive to the loading rate, but is subject to much greater scatter in its strength data than the foam cores. The C70.130 and R63.140 PVC foam materials are significantly stronger in shear when loaded dynamically than at pseudo-static loading rates. The C70.130 material is approximately 30% stronger when loaded dynamically, while the R63.140 core has a dynamic shear yield strength that is approximately 60% stronger than its static strength. Over the range of loading rates investigated the yield strength of the C70.130 and R63.140 cores does not increase significantly at rates higher than the 65MPa/s specified by DNV for materials subjected to slamming.

4 Conclusions

Analysis of laboratory based slamming tests demonstrated that the transverse shear stress rates experienced by core materials in sandwich panels subjected to water slamming can be of the order of several thousand MPa/s for realistic slamming impact velocities. These rates are significantly higher than those prescribed by an industry standard testing method. While only one type of panel geometry and deadrise angle was investigated, the results suggest that further investigation of a wider range of slamming scenarios would be of value.

Dynamic testing was undertaken of four point loaded sandwich beams with Aramid honeycomb, cross-linked and high elongation PVC cores at four different loading rates. The results demonstrate that the Aramid honeycomb is relatively insensitive to the loading rate, while the cross-linked and high elongation PVC materials are significantly stronger when loaded dynamically than at pseudo-static loading rates. The foam cores are not very sensitive to the actual dynamic loading rate. The cross-linked PVC material has a dynamic shear yield strength 30% higher than its static strength. The high elongation PVC achieved a dynamic shear strength 60% greater than when loaded statically.

References

[1] Berger, L., Stadelmann, R. Dransfield, C., Loiselet, K., Derler, S. and Stanpfli, R. "Damage initiation during impact loading of sandwich panels". *Proceedings of 22nd SAMPE Europe conference*, Paris, 2001.

[2] R. Downs-Honey, S. Edinger, M. Battley, "Slam Testing of Sandwich Panels", *Proceedings of SAMPE 2005*, Long Beach CA, 1-5 May 2005.

[3] DNV Rules for High Speed, Light Craft and Naval Surface Craft "Core Material in Slamming Exposed Areas", *Det Norske Veritas*, January 2003, Part 2, Chapter 4, Section 2, D300.

[4] ASTM C393/C393M – 06, "Standard Test Method for Flexural Properties of Sandwich Constructions".

[5] S.-L. Chuang, Experiments on Slamming of Wedge-Shaped Bodies, *J. of Ship Research*, 1967

[6] Wraith R. G., *"Pressure Loads on Ship Hull Plating Caused by Slamming",* PhD Thesis, 1998, Dept. of Mechanical and Manufacturing Eng, University of Melbourne, Australia.

[7] B. Hayman, T. Haug and S. Valsgard, "Slamming drop tests on a GRP sandwich hull model", *2nd Int. Conf. on Sandwich Construction*, Florida, USA, 1992

[8] Hayman B., Haug T. and Valsgård S., "Response of Fast Craft Hull Structures to Slamming Loads", *FAST91*, Trondheim, Norway, 1991.

[9] G. Katsaounis and M. Samuelides, "Comparison of Structural Behavior of Wet Deck Panels Made of Different Materials Under Slamming Loads", *FAST99*, Seattle, USA, 1999.

[10] O. M. Faltinsen, Hydroelastic Slamming, *J. Marine Science Technology*, pp. 49-65, 2000.

[11] M. Battley, I. Stenius, J. Breder, S. Edinger, "Dynamic Characterization of Marine Sandwich Structures", *7th International Conference on Sandwich Structures*, Aalborg, Denmark Aug 2005.

[12] M. Battley, S. Lake, "Designing Composite Structures for Slamming Loads", *2nd High Performance Yacht Design Conference*, Auckland, 13-16 February, 2006.