Characterizing QSLVII Damage of Composite Sandwich Hulls

Claire De Marco Muscat–Fenech,*, Jeremy Cortis, Charles Cassar

*Department of Mechanical Engineering, Faculty of Engineering, University of Malta, Msida, MSD 2080, Malta
Buccaneer Boats Ltd., Tarxien Road, Gudja ZTN 04, Malta

Abstract

Damage on marine grade composite foam filled sandwich hull panels, fabricated according to BS EN ISO12215-5, using the traditional hand lay-up technique and cured under vacuum pressure is described. Damage test conditions are quasi static (QSI) and instrumented drop weight low-velocity (LVI) impact or quasi-static low velocity indentation impact QSLVII Tests are conducted in accordance to ASTM D7766-11, ASTM D6264-98 (QSI) and D7136/D7136M-05 (LVI). Various indentor geometries are employed during the studies, each simulate different intended damage scenarios. Various law contact responses are proposed for the force and energy absorbed, based on indentation displacement and impact time. Limitations to the QSI and LVI standards are described and improvements suggested.

Keywords: composite sandwich; impact damage; marine; quasi-static & low-velocity impact; QSLVII

1. Introduction

Laminated composite marine sandwich panels are susceptible to impact damage events with foreign objects occurs at varying speeds of impact. Damage on a composite panel is a dynamic event and is complex, due to the many constituents making up the part. Damage modes in the laminate skin may induce internal delamination, matrix cracking, fibre fracture and ply shear. Damage which may occur is not always clearly visible, however, it can cause a significant reduction in strength which can lead to premature failure of the laminate of the overall sandwich panel. Understanding the damage characteristics of a composite sandwich laminate is therefore essential in order to optimise their design against such failure. The events are modelled and tested in accordance to ASTM
D7766-11 [1] procedures A, B and C; ASTM D6264-98 [2] for quasi-static rigidly supported and simply supported panels and ASTM D7136/D7136M-05 [3] for an instrumented drop-weight test. The whole series of tests is called quasi-static low velocity impact indentation, QSLVII. Impact damage was sustained by the default hemispherical indenter and further geometrical conical, pyramid and flat-faced cylindrical indentors ‘rocks’, each produce their own characteristic damage mode. Various contact law responses are proposed for the force and energy absorbed, based on indentation displacement and impact time. Limitations to the QSI and LVI standards are described and improvement suggested.

2. Design, materials and fabrication of sandwich panels

The marine sandwich panels are designed in accordance to the small craft standard BS EN ISO 12215-5:2008 [4] for vessels of hull length less than 9mm, CE design category C, to operate in inshore seas with significant wave heights of up to 2m and a wind force of Beaufort Scale 6 or less. The panels are designed for unsupported panel areas ranging from 0.7m x 0.3mm to 2.1m x 0.9m. The design bottom pressures, subjected to the 6m craft at a maximum speed of 35 knots, in the planning mode in accordance to BS EN ISO 12215-5:2008 [4] range from 7.5 kN/m² to 36 kN/m². Seven certifiable sandwich panels with symmetrical skins of orthophthalic polyester, POLYLITE® M440-M850 resin and chopped strand mat/woven E-glass and Divinycell® H100 closed cell cross-linked PVC foam core have been engineered, based on the typical in-service hydrodynamic pressures. The designed panels are described in Table 1 [5]. The panels are produced in the traditional hand lay-up method and cured under a vacuum pressure of 0.5bar (or 14inches of Mercury) for 5 hours, with an additional 24 hours curing whilst encapsulated within the bag. The vacuum cured composite skins resulted in a 45% fibre volume fraction (65% fibre by mass) and 40% reduction in thickness when compared to natural curing.

3. Test methods regulating the impact damage resistance testing of sandwich constructions

ASTM under the jurisdiction of the D30.09 subcommittee published in 2011 the ASTM D7766 [1] standard, bringing together the standards ASTM D6264 [2] and D7136 [3], originally intended for single laminates but now applied to sandwich constructions and quasi-static low velocity impact indentation – QSLVII. ASTM D7766 [1] comprises procedures A, B and C. Procedure A is an indentation of a rigidly-backed specimen in which out of plane deformation is prevented, hence the flexural stiffness does not influence the sandwich damage initiation. Panels in procedure B are simply supported at the edges of a circular opening, which allows deflection under the action of a 12.7 mm hemisphere indenter, deemed to produce a significant amount of internal damage for a given amount of external damage, used mainly in the application of plastics. Damage suffered from both procedures is quantified by the depth and size of the indentation, the location and the type of failure observed at the skin and/or core. The final procedure C, is a drop weight impact test on edge supported sandwich specimens, using a 16 mm diameter hemisphere indenter.

![Indentors](image)

Shown in Fig. 1, in addition to the standard default EN24 (surface hardened to 60-62 HRC) alloy steel hemispheres other ‘standard’ rock geometries simulate grounding scenarios of a sharp tip cutting and bluff edges to push and open the laminate skin and core (conical, 30° apex angle, maximum dent depth 46.7mm), and both sharp tip penetration and cutting edges simulations (square based pyramid, 30° apex angle, 52.8mm maximum dent depth). In addition falling objects on the deck is simulated with a circular sharp laminate cutting edge and flat face to compress the skin and core material (cylindrical, 25mm diameter, maximum dent depth 40mm).
Fig. 2(a) shows the set-up for ASTM D6264 [2], procedures A and B. The load is applied at a rate of 1.25 mm/min for low compressive strength foams, such that the maximum force is attained between 1 to 10 min after the initial application of the load. Indentation is to within 50-80% through thickness displacement, before reaching the lower laminate skin. Sandwich hulls are designed to resist through thickness impact such that water ingress to the vessel is prevented.

Table 1. Certifiable hull sandwich panels & drop weight (LVI) settings [5,7]

| Panel | tskin (mm) | tcore (mm) | Fibre Sheets in each Skin | Mimpactor (kg) | Hdrop (m) | Vimpactor (m/s) | KEAvailable (J) |
|-------|------------|------------|---------------------------|----------------|-----------|-----------------|----------------|
| A     | 0.81       | 10         | 450CSM, 450CSM            | 5.782          | 0.59      | 2.74            | 21.70          |
| B     | 0.67       | 10         | 450CSM, 300CSM            | 5.782          | 0.59      | 2.74            | 21.70          |
| C     | 1.35       | 15         | 300CSM, 450CSM, 400w, 450CSM | 5.782          | 0.84      | 3.28            | 31.10          |
| D     | 2.03       | 15         | 450CSM, 450CSM, 600w, 450CSM, 450CSM | 5.782          | 1.41      | 4.12            | 49.07          |
| E     | 1.22       | 20         | 450CSM, 600w, 450CSM      | 5.782          | 1.29      | 3.99            | 46.03          |
| F     | 2.03       | 25         | 450CSM, 450CSM, 600w, 450CSM, 450CSM | 7.560          | 1.19      | 3.89            | 57.20          |
| G     | 1.86       | 30         | 300CSM, 450CSM, 600w, 450CSM, 300CSM | 7.560          | 1.19      | 3.89            | 57.20          |

Fig. 3. Catastrophic damage using ASTM D7136 recommended settings [7]

The ASTM D7136 [3] standard, procedure C testing is accomplished using the apparatus shown in Fig. 2(b). The standard dictates a ratio of impact energy to specimen thickness factor $C_e$ of 6.7J/mm. With the recommended minimum impactor mass of 5.762kg, the minimum drop height is evaluated to 1.18m. During pre-trial tests such settings produced catastrophic damage with complete panel penetration, producing lower face delamination, fibre pull out, core compression, shattering and flaking and face and core disbonding and becoming wedged within the panel, Fig. 3. Since such damage may probably cause vessel foundering, the standard designated setting were disregarded and the impactor and indentor mass and impact drop height, using pre-trial tests, was adjusted for a 50-80% through thickness penetration. For the default 16mm hemisphere, the final impactor mass and drop height is shown in Table 1. The velocity immediately above the panel surface, using the infra-red light gates, allowed the actual available kinetic energy ($= \frac{1}{2}mv^2$) to be evaluated. These settings were adopted for the other ‘standard’ rocks to enable the difference in damage incurred on the panels to be compared.
4. Results

The full regime of force vs indentor displacement experimental plots as first reported by [6,7] show that, each indentor geometry, produces similar characteristic plots. The initial stage of impact and the contact force is analysed according to Meyer’s law, \( F = k \alpha \) (where \( F \) (kN) is the contact force, \( \alpha \) (mm) the local indentation displacement, \( k \) is the contact stiffness (kN/mm\(^n\)) and \( n \) is a constant).
Although there are some reports that the application of the $F = k\alpha^n$ equation is limited to elastic contact analysis and that as the indentation contact area increases (as in the case of hemisphere indentors) significant deviations may arise. The other standard ‘rock’ geometries investigated here have controlled small incremental contact areas. The experimental data presented here indicates that the equation can be applied even up to the instances when the advancing indentor tips pierce through the top face and enters the core region. It will be shown, analysing the contact force response and absorbed energy, that the experimental data indicates that, $n \neq 1$ as often suggested for sandwich panels or $n \neq 1.5$ for monolithic laminates [8-14] but follows different power laws depending on the indentor geometry. Abrate [8,9] also suggests $n = 0.8$ for the standard default hemispheres. The contact stiffness coefficient, $k$ is found from the extensive experimental data.

During QSI, each indentor produces its own characteristic trend, in which the initial loading line shows that damage is occurring as the indentor advances, as reported in Table 2 & 3. Subsequent to each damage point a reduction in global stiffness is noted; signalling the elastic-plastic collapse of the core immediately below the top face; the bottom plies subjected to high in-plane tensile stresses due to the bending produce probable matrix cracking and fibre failure; matrix crushing through the thickness ensues due to the high localised contact forces, with delamination and fibre failure. Force vs indentation plots are shown in Fig. 4, 5, and 6.

ASTM D7136 dictates to report the maximum force, velocity, displacement and absorbed energy during the whole impact duration. During these simulations the 50-80% through thickness impact settings will always result in a rebound, therefore proper interpretation and application of the impact events is essential, Fig. 7. Total penetration impact duration (all panels, all indentors) is in the order of $0.001 < t_{\text{impact}} (s) < 0.02$; the absorbed energy and indentation displacement is evaluated from data acquisition; the absorbed energy during $t_{\text{impact}}$ is equivalent to the initial KE as measured from the velocity just above the panel; whilst the numerically computed total indentation
displacement is confirmed by visual displacement. Using the penetration impact duration time, the contact force and absorbed energy laws have been determined and compared with experimental data and reported in Table 3.

![Figure 6](image)

**Fig. 6.** Force (kN) vs indentor displacement (mm) - procedure A, panel F

Visual inspection, both surface and through thickness, damaged of the panels show all the main characteristic mechanisms usually associated with composites, mainly delamination, fibre failure, cracking and splits, face to core disbanding, core shattering and crushing and core densification, during the 50-80% through thickness penetration. All three procedures for each indentor geometry produced very similar damage, but the fact that procedures B and C allow panel deflection through the opening. Figs. 7 and 8 show the resulting damage in the sectioned panels.

![Figure 7](image)

**Fig. 7.** Force (kN), absorbed energy (J) vs indentor displacement (mm) - procedure C, panel D

Comparing force values and trends for each procedure, indentor and at which significant damage occurred; for the bluff hemispherical indentor the rigid backed and drop weight forces are comparable, indicating that for such round rocks strain effects may be ignored. For the simply supported condition, as in the case of hull panels, less force is required for the same damage; this indicates that the global flexure must be considered. [15] showed that whilst for laminates the hemisphere diameter to panel thickness ratio plays an important role between ‘thin’ to
‘thick’ impact response, [7] shows that for sandwich panels the flexural rigidity to thickness ratio has the greatest dominant effect. The other ‘rocks’, typical of sharp reefs and floating debris clearly show the difference between QSI and LVI responses - strain rate effects clearly effect the force values; that sharp cutting rocks can easily puncture the outer hull skins. The results presented here show that when characterising sandwich panels, it is important that a whole spectrum of impact standardised tests, ie all procedures A, B and C, are undertaken. Furthermore CAI testing is required to assess the residual strength of the damaged panels.

Table 3. ASTM D7766/ASTM D7136, procedure C – drop weight, LVI

| Indenter                  | Contact Force, \( F = k \alpha^p \) | Energy Absorbed, \( E = \int_0^T F \, d\alpha \) | Comments                                                                 |
|---------------------------|----------------------------------------|-------------------------------------------------|--------------------------------------------------------------------------|
| Hemisphere 16mm Ø         | \( 0 < \alpha < \alpha_c \): \( F = k \alpha \) | \( 0 < t < t_{\text{impact}} \): \( E = E_1 \alpha \) | \* \( F - \alpha \) plots follow two plots; an initially steep linear trend law; followed by a reduction in stiffness due to critical damage resulting from core and skin failure at \( t_c \), for and indentation \( \alpha_c \); the second linear with \( k_2 < k_1 \) to the maximum |
| Conical & Pyramid, (30° apex angle) | \( 0 < t < t_{\text{impact}} \): \( F = k \alpha^2 \) | \( 0 < t < t_{\text{impact}} \): \( E = \left( \frac{F_1}{1.8} \right) \alpha^{1.8} \) | \* \( E - \alpha \) plots show that a power law, \( n = 1.8 \), provides a good fit \( (r = 0.96) \), it follows that \( n = 0.8 \) \( (r = 0.8) \) for the \( F - \alpha \) history. Although \( n = 1 \), provides a reasonable \( F - \alpha \) fit \( (r = 0.65) \), the ensuing numerically integrated \( E - \alpha \) is not appropriate |

Fig. 8. Force (kN) vs indentor displacement (mm) - procedure C, panel F

5. Conclusions

Instrumented QSI and LVI or QSLVII on marine composite sandwich panels was successfully completed:

- ASTM D7766 originally intended for laminate impacts, however, the differences in response of sandwich panel to the overall panel rigidity, constituents and support configurations require updating.
- Various ‘rock’ geometries are required to simulate marine craft impacts since each standard rock produces it characteristic response and damage; 50-80% panel penetration is required, such that water ingress and vessel foundering not to occur; the \( C_F \) factor for drop height/total mass impactor calculation produces catastrophic damage, instead pre-trial tests should be incorporated to achieve the percentage through thickness penetration; support plate, simply supported, is to be thicker in accordance to the increased sandwich thickness; transversely sectioned panels is required to describe the damage of the skin and core; dent depth measurement as suggested masks the fractured skin and core damage, especially when considering other rock types.
- Smooth bluff hemisphere rocks, rigid backed and drop weight, show minimal strain rate effects; the diameter to panel thickness ratio describes the transition between ‘thin’ to ‘thick’ impact response; the flexural rigidity to thickness ratio has the greatest dominant effect.
• Force vs indentor displacement/impact time have been analysed, describing reduction in global panel stiffness at the various critical damage points; describing elastic-plastic core collapse at the interface; the high bending induced tensile stress, resulting in matrix cracking and crushing, fibre failure and delamination;

• Contact force equations are proposed based on an extensive curve fitting exercise analysing both the force and absorbed energy; each indentor and panel have different contact stiffness whose values depend on the skin composition, properties and thickness; for QSI the initial responses up to skin core penetration are described by: default hemisphere $n = 1.3$, conical and pyramid $n = 0.8$, cylinder $n = 0.7$ and confirmed by the absorbed energy traces; for LVI the default hemisphere a significant reduction in stiffness plot requires a two stage response bi-linear response; other geometrical rocks follow an $n = 0.8$ power law, also confirmed by the absorbed energy traces.

• Sharp edged/piercing rocks clearly indicated that: strain rate effects require consideration; force values for outer hull penetration under QSI conditions are easily attained.

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