A review of impact testing on marine composite materials: Part II – Impact event and material parameters

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Abstract: Composite materials are now used throughout the marine industry but their susceptibility to impact events is still an unresolved problem. The complex dependence of the impact behaviour and damage on the many material and impact event parameters discussed in part I means that impact testing must simulate the particular in-service case well. Hence, typical impact damage modes have been outlined for both monolithic and sandwich marine laminates, and the influence of impact indentor and target, and of material reinforcement, matrix, core and production process on impact behaviour are discussed. Together with parts I and III, this paper gives a comprehensive review of 'marine impact on marine composites', providing a valuable resource for the marine industry and research fields.

Keywords: Impact; Marine; Testing; Damage; Impact Parameters; Material Parameters

1. Introduction

Due to the many advantages of composite materials over the use of steel, aluminium or wood in marine applications, laminated fibre-reinforced composite materials are now common throughout the marine industry. However, these materials are very susceptible to impact damage, especially for high speed craft where the weight savings of composite construction are most beneficial, but also for other structures and vessels, for example in fishing boats where impacts between the fishing equipment and the structure are commonplace. Low-velocity impacts (LVI) with solid objects are considered here as representative of those most commonly encountered in a marine environment, such as collisions with floating debris, other craft, docks, and during production (e.g. 'tool drops').

In part I of this review [1] the huge amount of research in the general area of 'impact on composite materials' has been covered, and the specific in-service impact events common in a marine environment discussed. Comparisons of the impact behaviour of composites materials with other more 'traditional' material systems were made, and the complexity of the problem, especially with respect to the complex damage modes and the huge number of combinations of material and impact event parameters possible [2] is described.

Hence, in this second part of the paper, impact damage and the work investigating the dependency of the impact behaviour of marine composites on multiple material and impact event parameters are considered.

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2. Impact Damage

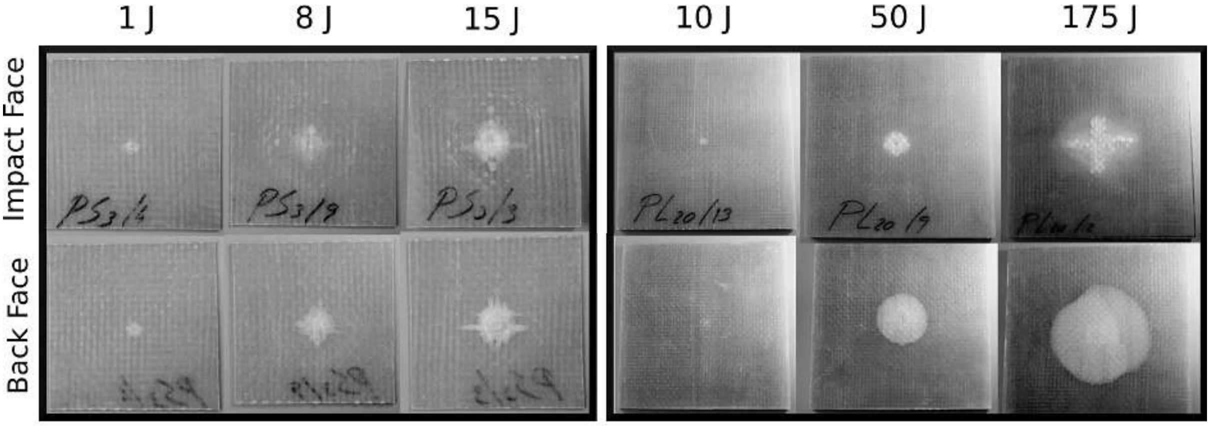
The LVI considered here is most often achieved through the use of an instrumented falling weight impact machine where a small impactor is dropped from a known height onto a horizontal target laminate. A much larger mass is attached to the impactor and a load cell between the two gives the variation of impact force with time which may be post-filtered to remove noise from the signal. A device, often an optical gate, gives the incident velocity and hence the impactor displacement and velocity and the energy it imparts may be calculated from the force-time data by successive numerical integrations [3]. An alternative, easier to set up variation is that of a swinging pendulum impacting on a vertically mounted target [4].

As discussed in part I [1], the damage modes suffered by the target laminates are complex, interacting and highly dependent on the exact combination of material and impact event parameters making a comprehensive detailed discussion of all of them here impractical. However, general trends in this damage progression have been characterised in the literature.

Importantly, for the low fibre fraction thicker glass-polyester hand laid up laminates of the marine industry damage is already incurred at extremely low incident energies [5].

Zhou and Greaves [6] characterise the damage behaviour into three stages for thick GRP laminates and the same three separate 'regimes' were seen by the author [5] for both thick and thin plates with subtle differences as discussed in Section 3.2.1 (Fig. 1):

1. 'Un-delaminated': At extremely low incident energies damage is slight and mainly restricted to matrix cracking.
2. 'Delaminated': At a low critical incident energy delaminations suddenly appear, which then spread with increasing impact severity.
3. 'Fibre damage': At higher energies fibre failure occurs, leading to perforation.



(a) 'Thin' plates (b) 'Thick' plates

Figure 1: Impacted laminated GRP plates.

As well as similar damage to the skins, the core of a foam sandwich laminate may also undergo local compression damage. Zenkert [7] characterises two main such failure types;

permanent skin indentation with core crushing (Fig. 2.i) and surface void crack with core crushing (Fig. 2.ii).

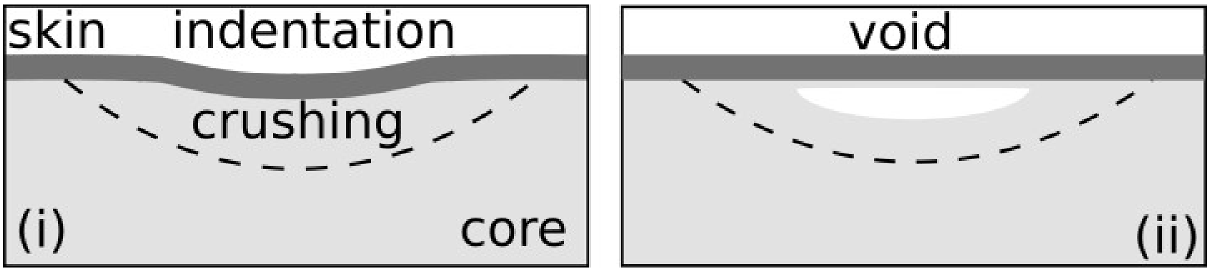


Figure 2: Foam sandwich failure modes [7]

More compliant foam cores were compressed but not cracked and on unloading the face sheet remained bonded to the deformed core giving an indentation in the sandwich surface. For more brittle cores unloading after core compression fractured the core in tension leaving a cavity in the core below the face sheet which returned to its original position. The extent of the crushed core was larger than either that of the indented face sheet or of the cavity.

Wiese et al. [8] described an additional core shear failure mode for a more brittle cross-linked PVC core which, 'cracks in a circular manner under the point of impact, and the crack develops in a conical shape as it expands through the core'. A further, different failure mode for an end-grained balsa core was reported, 'The balsa fails in shear resulting in a small diameter cylinder of core material acting as an internal ram on the back skin'. These failure modes were also reported by Hayman and McGeorge [9], as illustrated in Fig. 3.

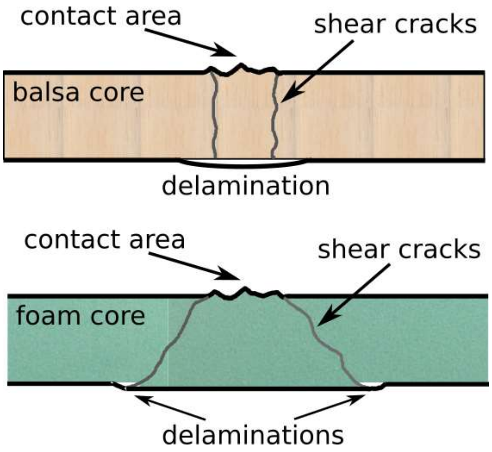


Figure 3: Balsa and cross-linked PVC foam core shear failures [9]

3. Impact event parameters

As discussed in Part I [1], since the impact behaviour, resistance and tolerance all strongly depend on the many impact event parameters in a complex way, the influences of those used in testing and their relationships with in-service impact events are fundamental to any research in the field.

3.1 Indentor Parameters

A most important aspect of any impact method is the shape (and size) of the impactor. The author [10] compares impact on single skin GRP plates using flat and hemispherical-ended impactors, amongst other test parameters, using an experimental design approach [11,12]. Generally the flat indentor gave higher forces and lower irreversibly absorbed energies, but, very importantly, the significance and nature of these relationships were strongly influence by the values taken by the other test parameters as was the projected damage area. These 'interactions' between test parameters show that when interpreting results concerning the effect of a given parameter these results may only be quantitatively and perhaps qualitatively true for the given test setup - the trends may change, disappear or even reverse if other test setups are used. Hence, the conclusions of the research discussed below should be interpreted with this in mind, i.e. conservatively appreciating that a change in test setup (or materials etc.) may well affect the results and hence conclusions made.

Quasi-static indentation tests on GRP monolithic laminates using hemispherical indentors of diameter 10mm, 20mm and 30mm [13] showed that a Hertzian contact law fitted well the initial response, although considerable material variability was seen for woven roving (WR). The irregular resin-rich surface was influential at initial contact and was thought to reduce the contact stiffness for smaller diameter indenters and obtaining the power law parameters was extremely sensitive to the initial few data points due to this surface layer. At higher loads the response became linear as delamination damage became significant, and the slope of this linear response increased approximately linearly with indenter radius. Good correlation of the transition load with indenter radius was obtained using a simplified shear delamination model. Despite their significantly lower fibre volume fraction, chopped strand mat (CSM) laminates exhibited a slightly higher contact stiffness than did the WR laminates.

Santiuste et al. [14] compared the impact damage of monolithic GRP beams supported in three point flexure for both a hemi-spherical and a Charpy impactor. In tests with the Charpy impactor damage reached the edges of the beam at lower incident energies than it did in those with the hemi-spherical impactor. However, although both the absorbed energy and the residual flexural strength were affected by indentor shape, the relationship between absorbed energy and residual strength was not.

As part of 'The cost effective use of fibre reinforced composites offshore' Joint Industry Project, [15] Project CP04 'Impact response of thick composite laminates and sandwich structures' found that, for sandwich panels with a range of core materials and for impact set-ups where the main mode of deformation was local indentation rather than global bending and shearing, 'Indentor shape and size are important in determining failure mode and energy to failure. The flat indentor produced a shear plug penetration failure while the hemisphere failure was due to a tensile bending. The failure load of the flat indentor was higher than that of the hemisphere'. Further, Project CP202 'Design and performance of panel elements for energy absorption and resistance to penetration and impact' also found that both loads and energies to first penetration were highest with the flat indentor, where, 'the energy to first penetration also corresponded to total penetration'.

In fact, a large majority of the studies into marine impact has defaulted to the use of a hemispherical-ended cylinder or ‘rounded’ impactor. As discussed previously, although this does introduce some standardisation it has the serious flaw of not being particularly relevant to a ‘typical’ marine impact event [16]. Noting that ‘edge’ and ‘corner’ impacts are likely in a marine setting (e.g. semi-submerged containers, deck-dropped fish boxes etc.) work at VTT [17,18,16,19–21] developed the use of a square based pyramid impactor, which they considered to be the best solution for determining the impact strength of sandwich laminates due to its ability to give multiple failure modes and consistent results (and is later referred to by other authors as a ‘VTT pyramid’ impactor). The main conclusions of this work are:

- The impactor geometry greatly effects the nature of the impact and failure modes
- For the pyramid, projected area grows with indentation and hence the nature of penetration is completely different from that where the projected area is constant (cylinder). This is especially true at the inner face as a pyramid, unlike a cylinder, will still be affected by the outer face on contact with the inner face.
- The constant projected contact area of the cylinder mean that core thickness and material have very little influence.
- Penetration force and energy are proportional to impactor tip radius, meaning that the sharp pyramid may penetrate thin faces at very low, even unmeasurable values. A modified pyramid with a larger tip radius would produce easier to read results, but must remain indicative of probable in-service events.
- Cylinder impactors cause shear-dominated failure modes, whilst those using a pyramid are manifold.
- Total delamination of the inner face may occur before penetration. Increasing the panel size may change this, but delamination may also be a large and valid energy absorbing mechanism.

Mines et al. [15,22] used the same approach of using pyramidal (and conical) impactors for fire resistant sandwich composites in the offshore industry (as part of Project CP08 ‘Impact behaviour of fire resistant twin skinned laminates and panels’). They also found that failure modes were dependent on indentor geometry with the cone and pyramid geometries causing more localized damage and the cone penetrating the panel more easily.

Bull and Edgren [23] utilised a hemi-spherical and a pyramid shaped impactor, the latter defined by Nordtest [24] and referred to as ‘VTT-type’ indicating that the Nordtest standard was based on the previously discussed work of Hildebrand et al. At the same energy level the damage from the pyramid were ‘slightly easier to spot’ than those from the hemi-spherical impactor. Zenkert and co-workers [7,25] carried on this work on ‘blunt’ (hemi-spherical) and ‘sharp’ (pyramidal) impactors. A low and a high incident energy was used to give a barely visible damage (BVID) and a clearly visible damage (VID), respectively. Blunt impact damage consisted of a very small dent BVID damage plus minor surface fibre breakage in the VID case. Otherwise only slight core crushing was observable, but ultrasonic C-scan revealed significant overlapping delaminations. Sharp impact created a slit in the face sheet, which lengthened with increasing impact energy.

The effect of impactor (which they refer to as 'rock') geometry was investigated by Muscat–Fenech et al. [26–28], comparing hemi-spherical as that prescribed in the standards with cylindrical (flat-ended), conical and pyramidal impactors since, 'Marine hulls commonly suffer impact from pointed bluff and sharp edge objects not only from objects which fall on the deck, but also from grounding and impact incidents when underway'. These comparisons are made on each of seven different marine sandwich panels.

Quasi-static indentation tests lead to the postulation of different 'Hertzian' contact laws for the different 'rock' geometries of the form $F = k\alpha^n$, where F is the contact force, k is the contact stiffness, α the indentation displacement and n is a constant. For the initial responses up to outer skin penetration: $n = 1.3$ for hemispherical, $n = 0.8$ for conical and pyramid (which give very similar results generally), and 0.7 for the cylinder. The same approach was then also used to model the absorbed energy behaviour.

Drop weight impact tests also showed large differences between the behaviours seen using the different impactors, although conical and pyramidal impactors generally gave very similar results. Trends were generally stable across the different types of panel (although exceptions were seen):

Maximum Force:	Cylindrical >> Pyramid ≈ Conical > Hemispherical
Maximum Displacement:	Pyramid ≈ Conical > Hemispherical > Cylindrical

The failure modes were manifold and varied in a complex way with impactor geometry, and are described in detail in the paper. However, at the impact energies used, the irreversibly absorbed (effectively by the specimen via damage) energy was fairly constant between impactors.

Impacts with a completely different class of objects, those of ice, have been considered by Niclassen and co-workers [29,30]. This is an extremely challenging undertaking since the impactor itself is both fragile and extremely diverse in terms of both shape and fragility. A model for calculation of ice impact force and energies was established and used to plan a plausible (in terms of in-service energies) initial test series using fabricated conical impactors of ice for drop weight tests on CFRP sandwich (and aluminium). They conclude that the failure of the ice itself limits the impact energy suffered by the structure. They note that although the damage suffered by the aluminium panels were not critical, the CFRP panels would need to be reinforced (although it must be said that this is obviously highly dependent on the initial panel designs considered, and of the size, shape and strength of the ice impactors used).

3.2 Target Parameters

3.2.1 Monolithic laminates

Since impact behaviour is a structural response, the nature of the target is highly important, often in terms of the structural stiffness. Panel thickness is an obvious contributor to stiffness and was discussed in terms of the influence of flexural rigidity and membrane effects by Zhou and Davies [31–34] for thick monolithic GRP laminates They warned that, 'It is thus very important to note, in order to avoid an unnecessarily conservative design, that the ultimate load threshold is dependent on the laminate in-plane dimension. This has particular significance for design based on data of small thin coupon tests.' Delamination onset and load bearing force were seen to increase with thickness, with the obvious drawback of an increase in weight [6]. However, delamination area did not vary with thickness, although only the projected area of damage was measured. An increase of plate diameter from 100 to 500 mm increased the influence of membrane forces, but the delamination threshold forces were unaffected. In terms of impact penetration strength, Arvidson and Miller [35] confirmed that a laminate with more reinforcement fibre will fare the best.

Most of the author's work [3,5,10,36–49] addresses the influence of specimen thickness for single skin GRP, and categorises this into 'thin' and 'thick' (or more accurately low and high thickness to diameter ratio) behaviours. The transition between these two types of behaviour was seen to be around a diameter to thickness ratio of around 15, *for these particular materials and test set-up*:

'Thin' plates (Fig. 4) suffered internal delamination but this was not seen to affect the response significantly. High deflections gave a membrane stiffening effect until at high incident energies back-face fibre failure led to perforation.

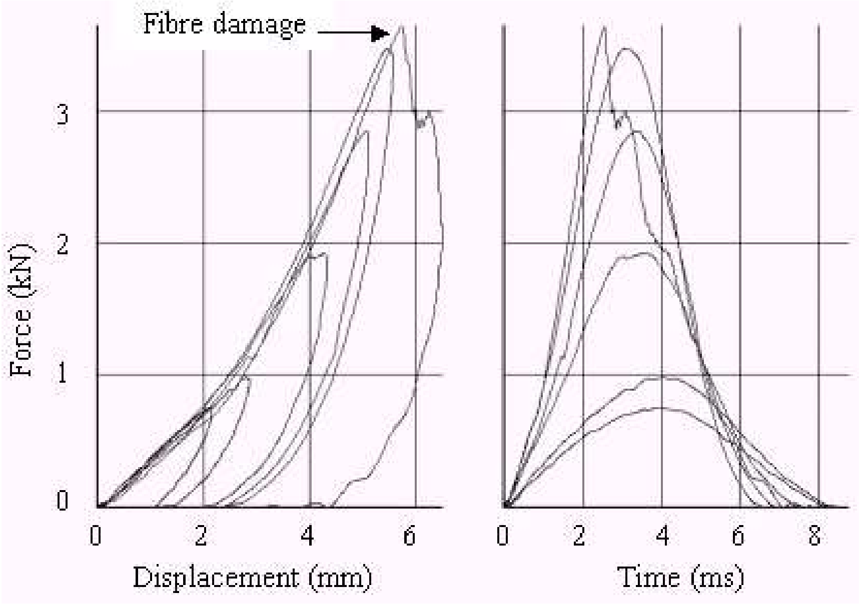


Figure 4: Typical impact response of 'thin' laminates (plots for a series of identical tests at increasing incident energies)

'Thick' plates (Fig. 5) showed both significant shear and indentation deformation. A bi-linear force-displacement response as delamination led to a significant stiffness reduction was seen, followed by front-face initiated fibre failure leading to perforation and/or shear failure.

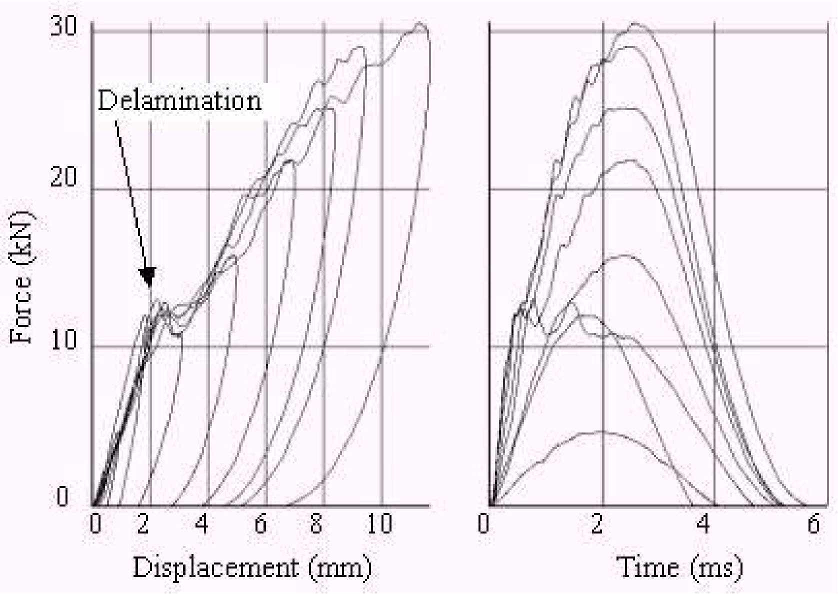


Figure 5: Typical impact response of 'thick' laminates (plots for a series of identical tests at increasing incident energies)

In terms of in-service examples, Echtermeyer et al. [50] identify bending as critical for full size single skin panels of a surface effect ship (SES) impacted at the centre. Aamlid and Antonsen [51] saw an increase in penetration strength with single skin thickness as expected, but the trends seen suggest that, 'the impact strength of aluminium and multi-axially reinforced panels, both glass and carbon, seems to merge at about t = 2mm'.

Hayman et al. [52] report an increase in the critical (to penetration) impact energy with thickness, but only a relatively small increase in this energy for single skin GRP when the impact is moved from the panel centre to the edge.

Santiuste et al. [14] studied two widths of monolithic GRP beams supported in three point flexure in impact. Damage reached the edges of the narrow beams at lower incident energies. However, although both the absorbed energy and the residual flexural strength were affected by beam width, the relationship between absorbed energy and residual strength was not.

The main applications of composites in the offshore and underwater industries use tubular forms fabricated by filament winding and hence various investigations into impacts on tubular targets have been completed [50,53–59]. Uralil [53] refers to two criteria for the impact resistance of FRP piping; the onset of cracking of the inner layer which require only low impact energy levels, and loss of ability to maintain function until replacement for which substantially higher impact energies may be required. He also quotes drop weight tests of the Ameron International Corrosion Resistant Piping Division (Technical Data Report No. EB-15) showing that failure energy (to cracking of the inner liner) increased linearly with wall thickness at constant diameter, but that only slight increases in failure energy were required for increasing pipe diameter at constant wall thickness.

Stokke, et al. [60] found that impact damage was independent of (a) the impact location (at a support or in between supports) and (b) whether the pipe was empty or filled with water.'

However, Reid and Corbett [61] measured less impact delamination area for oil filled pressurised pipes than for empty pipes since some impact energy was absorbed and distributed by the bulk compression of the fluid in the pipe. Conversely, the pipes were stiffened by the pressurised oil and were hence perforated at far lower energy levels than were the empty pipes. The inclusion of an internal liner increased resistance to impact.

Carbon fibre yacht masts are also tubular in form, and the work of Miller [62] loaded proposed America’s cup mast sections to 120% of their maximum design load and used impact tests to confirm that a dramatic decrease in wall thickness achieved by improvements to lay-up and tube curvature did not compromise the impact resistance of the spar.

3.2.2 Sandwich laminates

For sandwich laminates the core and face sheet thicknesses are considered as structural parameters here and as such are addressed in this section, whilst the other sandwich laminate variables (such as core and face sheet materials, and lay-up) are discussed in section 4.

Project CP04 ‘Impact response of thick composite laminates and sandwich structures’ [15] found that for sandwich panels with a range of core materials, ‘Over the range of parameters tested the main mode of deformation was local indentation rather than global bending and shearing. Hence skin thickness (and reinforcement weight) was the major panel parameter determining panel strength and energy absorption’, and the core properties, ‘had significantly less influence on panel performance than the skin’. However, when core thickness was reduced enough to change the global behaviour and give core densification before skin fracture with larger radii indentors, the core material became influential.

In terms of the design of panel thickness, for a given expected impact severity (usually estimated from the vessel size and speed) stiffener spacing (giving panel size) and panel thickness will vary inversely between the two extreme cases of small thin and large thick panels. Muscat–Fenech et al. [26–28] designed seven different GRP foam sandwich panels according to BS EN ISO 12215-5 [63] with core thicknesses ranging from 10 up to 30 mm stating that, ‘These panels represent the different design panel areas used in order to reduce the number of wooden stiffeners and hence total craft weight’.

Procedures A & B of the ASTM D7766-11 [64] ‘Standard practice for damage resistance testing of sandwich constructions’ were used for quasi-static indentation tests. ‘Procedure A: Rigidly backed specimens’ stipulates a 200 x 200 mm specimen supported on a solid 300 x 300 mm steel support. However, smaller specimens of 75 x 75 mm were used since this smaller size still ensured that damage remained away from the specimen edges. ‘Procedure B: Edge supported specimens’ was also followed with 152 x 152 mm specimens supported on a 200 x 200 mm steel plate with a central 127 mm diameter hole. They compare the two support configurations and the major differences are discussed in terms of panel flexure and damage delay.

Falling weight impact tests following Procedure C with a 150 x 100 mm supported on a plate with a 125 x 75 mm cut-out were then performed. The standard stipulated incident energies gave catastrophic through thickness damage, and since consequences of hull puncture are possible foundering and loss of life at sea a 50 to 80% through thickness penetration testing criteria was suggested. Due to the increased panel flexural rigidity compared to single skin laminates, a ratio of flexural rigidity to panel thickness ratio (D/t) of 10 was proposed as the criteria for transition between 'thin' to 'thick' impact response (in terms of force-time history) for sandwich panels.

Procedures B and C are designed to allow the specimens to deflect under load, although this highlights the limitations of standards most likely developed with thinner aerospace laminates in mind since marine panels of the thicknesses considered here would definitely only significantly deflect with a much larger panel size than the support spans prescribed by the standard. Also, the use of toggle clamps may well stop the specimen moving, but the degree of clamping is not well controlled even if the maximum clamping force is prescribed as this will also depend on the friction between specimen and support [10] and the surfaces of marine laminates (especially hand laid up ones) are not always smooth and regular.

Hildebrand [16] investigated the effects of varying the sandwich laminate parameter face thickness ratio (between outer and inner). A thicker outer face was found to improve both outer and inner face impact penetration strength, and this arrangement is commonly found in boat-building practice. Compared to equal face thicknesses, a ratio of 70% / 30% increased impact strength by 65% and 24% for the penetration of outer and inner faces, respectively. An increase in penetration impact strength of both inner and outer faces was also seen with an increase in core thickness, the latter increase being much larger than expected. An increase in core thickness from 50 to 75 mm gave an increase +9% and +81% for the penetration strengths of the outer and inner faces, respectively. The influence of core thickness on repeated impact behaviour for power boat designs reported by Cucinotta et al. [65] is discussed in part III of this review [66].

An important yet hardly considered aspect for marine laminates is that for impacts below the waterline (or on water filled protection compartments on naval vessels) the presence of the water constitutes an 'added mass' that will change the impact behaviour from that of the same laminate in air. Kwon et al. [67] found that the fluid structure interaction (FSI) effect on sandwich composite structures was very significant, giving generally much greater impact force, strain response, and damage size, some changes in damage location and also damage initiation at much lower impact energies. Hence, 'Neglecting to account for FSI effects on sandwich composite structures results in very non-conservative analysis and design.' Lopresto et al.[68] call this condition of impact on a hull panel in contact with water 'water backing' and simulate this using a silicon membrane over a water reservoir to support their carbon fibre / vinylester samples. As did Kwon et al., they again observe completely different behaviour both in terms of load-displacement response and damage when using their water-backed setup compared to standard 'in air' impact.

4. Material Parameters

It is important to stress here, since all aspects of impact behaviour are very likely to be influenced by the exact nature of the impact event considered, that any conclusions on the effects of using different material combinations must be interpreted strictly on the basis of the test conditions used in the specific study. The previously discussed interactions between the impact-event and material parameters [1] may well mean that different or even contradictory conclusions would have been reached for other impact events.

4.1 Reinforcement

4.1.1 Reinforcement material

The impact resistance of surfboard sandwich laminates was improved by replacement of E-glass fibres with those of S-glass by Manning et al. [69].

To investigate the effects of various parameters, Hildebrand [16,19,21] completed a large test series on 26 different sandwich laminates of basically similar geometry based on a reference panel of E-glass-epoxy faces on an aluminium honeycomb core. The material parameters fibre material, reinforcement architecture, stacking sequence, matrix material, and core material and density were all varied, and hence reference is also made to this work in the following sections. Substituting E-glass reinforcements with an aramid-glass hybrid reduced the impact strength for penetration of both outer and inner face, by 60% and 11%, respectively and it was suggested that for transverse shear dominated failures only one type of fibres was carrying the load. Glass outperformed aramid and polyethylene fibres, giving the highest impact strength in terms of absorbed energy. However, the alternative fibre materials better resisted the propagation of damage. The use of aramid reduced the outer and inner skin specific penetration strength by 6 & 9%, respectively.

Aamlid and Antonsen [51,70] found that a pure aramid laminate, ‘exhibits a surprisingly low impact strength, significantly lower than all other FRP panels except for the spray-up panel’ even when considering a specific strength based comparison. A 50% by weight hybrid laminate with glass improved the impact strength significantly but this ‘is still considerably lower than for comparable lay-ups with glass fibres only. No positive synergy effect is observed by combining aramid and glass fibres’.

The accomplished yacht and boat designer Rolf Eliasson [71,72] also states that aramid laminates do not always give good impact behaviour. Both Arvidson and Miller [35] and Sutherland and Guedes Soares [43] found that an aramid/glass hybrid laminate performed no better than an equivalent all glass laminate.

Hildebrand [16,19,21] found the use of carbon fibres in an aluminium honeycomb sandwich laminate reduced the outer and inner skin specific penetration strength by 8 & 18%, respectively. Bi-axial carbon fibre single skin panels gave a lower resistance to impact than the equivalent glass fibre laminates but comparable to that of the woven roving glass fibre laminates with the same thickness [70]. However, a carbon epoxy foam sandwich panel gave comparable impact resistance and water-tightness to a ‘traditional’ GRP monolithic sandwich for under half the weight [4].

4.1.2 Reinforcement architecture and stacking sequence

An increase in impact strength of 70-80 % (with equal thickness) was achievable for glass single skin laminates by replacing a traditional woven roving glass fibre with a knitted glass reinforcement [70].

The author [39] presents various aspects of the impact behaviour of WR, CSM and 'combi-mat' WR/CSM E-glass/polyester single skin laminates. For both fibre architectures delamination occurred at very low incident energies and very similar responses were seen at incident energies up to fibre damage. However, fibre damage was most severe for CSM and CSM/WR laminates [43]. Despite their significantly lower fibre-volume, CSM laminates exhibited a slightly higher contact stiffness than those of WR [13]. For WR, the degree of fibre-crimp was more influential than the type of polyester resin (ortho or iso-phthalic) [45].

Different internal 3-dimensional damage distributions were seen between woven and multi-axial carbon single skin laminates [73], although the specimen thicknesses were different at 2.0 and 2.5 mm, respectively. Similarly, for sandwich laminates, multiaxial stitched (knitted) reinforcements gave improved specific impact strength compared with CSM or WR [16,19,21].

Echtermeyer et al. [50] suggested ways of improving single skin laminate impact behaviour without knowing the impact loads a priori through consideration of the stacking sequence, including keeping Kevlar plies in the centre of the laminate. Reducing the angle between subsequent reinforcement layers also gave a 12% improvement in the impact strength of sandwich laminates with respect to outer face penetration [16,19,21].

The effect of stacking together plies of the same orientation ('clustering') was investigated for R-glass epoxy single skin laminates by Perillo et al. [74,75]. Three different cross plied laminates were tested, each with the same eight plies, 6.8 mm thickness and in-plane properties but differing number of interfaces between same-orientated plies, n_d (where delamination can propagate); L1 [0,0,90,90]s ($n_d = 2$), L2 [0,90,90,0]s ($n_d = 4$) and L3 [0,90,0,90]s ($n_d = 6$). When impacted at the same energy there was almost no variation in the impact load versus displacement curves between the three laminates, but the projected area and shape of delamination was significantly influenced by n_d and delamination area varied linearly with n_d. However, neither force nor time to threshold damage initiation varied with n_d.

After extensive comparative impact testing of candidate single skin laminates for a yacht hull Miller et al. [76] found that alternating plies of ±45° multi-axial with 0/90° woven rovings were more resistant to impact damage than other laminate stacks.

Adding a surface elastomer coating significantly increased the impact penetration strength of sandwich panels, particularly of the outer face [16,19,21]; a 2 mm thick coating increasing the strengths of the outer and inner face by 100% and 21%, respectively. This was much more efficient than an extra 1mm additional laminate to the outer face (c.f. improvements of 24 % and 8% for outer and inner faces, respectively). The same authors also used a similar strategy to try to improve impact resistance by adding a secondary thinner sandwich layer to the surface of the outer skin which they call a ‘double sandwich’. An upper core of denser PVC increased the penetration strength of the inner face by 10%, but it was unclear whether this increase was due to the ‘double-sandwich effect’ or simply due to the higher strength of the denser PVC-foam at the surface.

Suvorov and Dvorak [77–80] used thin ductile ‘interlayers’ inserted between face and foam core to absorb face sheet deflection and hence prevent or reduce damage to the foam core. Two different interlayer materials were used; a stiff and incompressible polyurethane (PUR), and a compliant and compressible elastomeric foam (EF). PUR successfully reduced global and local face deflections, local foam core compression and post loading residual stresses. EF gave much improved protection against core compression, whilst increasing overall and local deflections.

Concerning composite pipes for the offshore industry, CSM had much lower strength, stiffness and energy absorption capabilities compared to filament wound pipes and suffered very localised impact damage with no sign of delamination [15] (Project CP299 Damage Tolerance of Composite Pipes to Local Impact Loads).

4.2 Matrix Material

The impact resistance of a surfboard was improved by the use of epoxy over polyester resin [69], and Findon and Lee [4] saw a trend of improved impact resistance and water-tightness with the use of epoxy over polyester. The author [47] noted subtle differences between the damage modes of the epoxy and polyester laminates; the epoxy laminates suffered more back-face fibre damage, but less internal delamination, but the type of polyester resin used (ortho or iso-phthalic) was not very influential [45].

Project CP04 ‘Impact response of thick composite laminates and sandwich structures’ [15] found that, ‘the choice of resin type (polyester or phenolic) had little influence on performance’ for impact events where local indentation dominated over global bending and shearing. They note, ‘… that this result is true for normal resins but experience in the design of armour shows that resin properties and particularly the fibre / resin interface may play an important role’.

Miller and co-workers selected vinyl ester resin was selected for construction of a yacht hull for its excellent impact damage resistance due to its high elongation which was close to that of more expensive and more time-consuming to repair epoxy [35,76].

The use of more flexible resins improved the impact strength of glass-epoxy aluminium honeycomb sandwich panels at the expense of other material properties [16,19,21]; a flexible epoxy matrix (15% elongation at break) gave 80% higher inner face impact penetration strength compared to standard epoxy, but that of the outer face was not affected. However, a very flexible matrix together with CSM as a core-bedding layer increases the specific impact strength without any significant decrease in in-plane strength and stiffness (see section 4.4). A rubber modified vinylester resin increased the outer face specific impact penetration strength by 28% compared to that of the standard epoxy, and this gave a unique total outer face de-bonding final failure mode (occurring at the same specific energy as for inner face penetration in the reference panel).

Two vinylester resins, one fire resistant but relatively brittle and one rubberised to enhance ductility had similar impact performance [81]. Perrot et al. [82] investigated the impact damage resistance of GRP using low styrene emission resins, finding that the low failure strain of the low styrene emission resins studied resulted in significantly lower impact damage resistance. Impact tests on GRP (CSM) / Rigid PVC foam sandwich laminates fabricated using both a conventional vinylester and a bio-resin [83] showed a slight improvement in impact resistance for the latter.

A comparative study of the static and dynamic interlaminar fracture toughness of glass-fibre marine composites with epoxy, vinylester and iso- and ortho-phthalic polyester resin matrices [84] provides much information that is highly relevant to impact on marine composites.

As further described in the next section, Castilho et al. [85] compared the impact behaviour of GRP sandwich laminates with various core materials. Interestingly, an unintended incomplete curing of the vinylester resin for one of the core materials (thought to be due to chemical 'poisoning') led to a greatly increased ability to absorb impact energy through an extra and much elevated peak in the force deflection behaviour during the penetration of the first skin. This also, however, led to a severely reduced flexural sandwich flexural stiffness.

A very severe (32 kJ) large scale 'dynamic impact loading which is typical of the marine environment' simulated via a 500kg steel weight dropped from 6.5m onto a RIB (rigid inflatable boat) fabricated using a thermoplastic composite (TPC) [86] 'dramatically demonstrated the toughness of PP-glass structures'. It was noted that away from the locally perforated region the remainder of the hull largely recovered its original shape with only very little cosmetic damage, and states that, 'This tough recovery is characteristic of thermoplastic composites, and differs greatly from that of thermosetting composites, which are usually much more brittle'.

4.3 Core Material

Hildebrand [16,19,21] found that for larger panels the effect of core density on impact strength was more significant than that of the material parameters of the face laminates. Aamlid [87,70] found that both sandwich outer skin penetration strength and damage development at higher energies were far more severe for denser rigid PVC (Divinycell H200) panels. For a constant impact energy, Daniel et al. [88] recorded peak loads and impact event durations that were roughly proportional to and inversely proportional to the core density, respectively. Laminates with denser cores absorbed more energy and were thus more resistant to skin failure. PVC cores gave better results than did other materials, absorbing more energy through indentation. For GRP / Rigid PVC sandwich laminates a doubling in impact resistance energy was seen for an increase in core density of 50 to 75 kg/m^2, although it must be noted that the core thicknesses were also different at 10 and 12 mm respectively [83].´ Findon and Lee [4] saw that a higher density and thicker core 'certainly aided in the impact tolerance of this panel'.

However, project CP04 'Impact response of thick composite laminates and sandwich structures' [15] considered impact events where the main mode of deformation was local indentation rather than global bending and shearing and in this case saw that the core properties were not as important as those of the skin. However, 'An exception is the case of thin cores and large indentor radii, which could result in core densification before skin fracture, or alternatively where the core has very high compressive strength and stiffness'.

Collombet et al. [89] compared crosslinked (rigid) and linear (ductile) PVC foam cores. Local crushing was similar for both cores and after perforation of the outer skin neither foam offered significant resistance to indentation. However, the type of foam had a significant influence on damage development and mechanisms with no shear cracks observed in the ductile foam. Zhou et al. [90] impacted GRP laminates with nine different foam cores; 5 of crosslinked PVC (60 to 200 kg/m^3), 2 of linear PVC (90 and 140 kg/m^3) and 2 of PET (105 and 135 kg/m^3). Since perforation resistance was strongly correlated with core shear fracture properties they postulated that shear fracture is important in determining the perforation resistance of thin-skinned sandwich structures. Impact testing by Miller and co-workers showed that both linear PVC and Corecell (SAN, Styrene acrylonitrile) foam cores showed high impact toughness and would have provide acceptable service for the topsides of a yacht [35,91], and in the end the Corecell option was taken purely because of better availability [76], a common design decision in the marine industry.

Continuing the work of Hildebrand, Wiese et al. [8] found that damage to balsa sandwich was less severe than for H200 PVC laminates. The Office of Naval Research (ONR) sponsored research of Daniel et al. [88] found that although balsa sandwich performed well under static loading, they failed 'catastrophically under impact loading due to the low fracture toughness along the grain direction'. Hildebrand [16,19,21] found that the outer face penetration strength of balsa sandwich was 75 - 100% higher than that of the PVC cored laminate, and 10 - 40% higher than that of those with aluminium honeycomb cores. Similarly for the penetration of the inner face, balsa cores were stronger by 50 - 100% compared with the aluminium honeycomb cores and by 10 - 70% compared with the PVC foam cores.

Atas and Sevim [92] noted that balsa-cored laminates were stiffer than those of PVC but that the main impact damage mode to the outer skin was delamination for the balsa whereas it was local damage for the PVC. This was also true for the inner skin; the weaker skin-core bond of the balsa leading to de-bonding between core and face-sheets. Findon and Lee's [4] balsa-cored aramid / E-glass laminate suffered the worst damage of all panels at all incident energies, and the most severe loss of water integrity at higher energies. However, it must remembered that other factors such as core thickness and skin materials were changed between panels and hence the effect of the core is not easily isolated.

PVC, Balsa and Amorim Corecork (agglomerated cork granules) cored GRP sandwich laminates were compared in impact by Castilho et al. [85]. For the small (150 x 100 mm) simply supported specimens considered, the balsa sandwich outer skin was perforated at an energy of two-thirds that required for the PVC sandwich, but the energy to perforation of the inner skin was similar for both laminates. The cork cored laminates gave an outer skin perforation energy very similar to that of the PVC sandwich, but offered 40% more energy absorption in resisting perforation of the inner skin.

The choice of the core bedding (adhesive) can considerably increase the impact strength [16,19,21]. The use of a syntactic foam of laminating resin and glass microspheres led to an increase of 31 and 22% for the penetration at outer and inner face, respectively. Further, using a flexible resin for the syntactic foam bedding resulted in an increase of 25% and 73%, respectively.

The approach advocated by Mines [93] of using sandwich beam flexural tests to approximate the impact event and hence explore the relative impact responses and performances of candidate sandwich configurations is a very practical approach, especially during initial design stages.

4.4 Production Process

It is important to remember that the effects of changes in production process are normally actually due to changes one or more of the previously discussed parameters (for example, a change from hand lay-up to infusion will give thinner and higher fibre volume fraction laminates) and also that the materials used for a more 'hi-tech' production process will generally be more 'exotic' – for example chopped glass and polyester is used for spray-up, epoxy or vinyl ester and glass or carbon for infusion, and pre-preg is most often of carbon and epoxy). Hence, the effect of production method on the impact behaviour of a laminate is most often confounded (inseparable) from the effects of secondary parameters.

As expected, spray-up fabricated laminates performs poorly in impact since the low fibre-fraction and short fibres inefficiently distribute the forces [70]. The author [40] found that the effect of laminator on the impact response of woven-roving E-glass/polyester laminates did not appear to be large (although both were working under laboratory conditions). Findon and Lee [4] showed that the move from hand lay-up (HLU) to infusion and on to using SPRINT materials (consists of a layer of fibre reinforcement either side of a pre-cast, pre-catalysed resin film with a very lightweight tack film on one face) gave a trend of both improved impact damage resistance and damaged laminate water-tightness.

Belingardi et al. [94] found no significant differences between the force, energy curves and damage parameter between HLU and infused laminates for tests in which no perforation occurred. However, HLU laminates required more energy to perforate them.

A wet-lay-up face/core bonding performed better in impact than bonding the face to the foam core using an adhesive, since it provided improved face/core adhesion resulting in less transverse core fracture [95]. Adhesive bonding reduced the outer skin delamination area compared to wet lay-up bonding through impact energy absorption mechanisms such as crack arrest at the adhesive's filler particles. The delamination threshold load was unaffected by the face-core bonding method, depending only on the face laminate properties.

Pultruded sections have been found to be very resistant and tolerant to impact damage [96,97,15] especially as an alternative to steel structures.

4.5 'Confounded' material parameters

If two or more material parameters are varied between different tested laminates then only comparisons between the two specific configurations may be made since the effects of each of the separate parameters are inseparable from (or 'confounded' with) each other.

Laminates of multi-axial unwoven E-glass fibres and conventional epoxy were compared with woven E-glass fibres with a rubber toughened epoxy (formulated specifically for marine applications) by Strait et al [98]. The former had a 20% higher damage initiation energy, but absorbed only 50% of the energy to peak load of the latter which had a 15 to 23% greater overall energy absorption. It is impossible to separate the effects of fibre architecture and matrix in these effects however, and only direct comparisons between the two laminates can be made.

Zhou [6,32,33] compared the impact damage thresholds of thick E-glass/polyester and S-glass/phenolic laminates. Impact resistance to delamination was not sensitive to impactor mass or target plate diameter for both laminates, nor to impact velocity for E-glass/polyester. However, the delamination threshold was 'modestly' proportional to velocity for S-glass/phenolic. Ply shear-out impact resistance was significantly and 'modestly' proportional to velocity for the E-glass/polyester and S-glass/phenolic laminates, respectively. The effects of target geometry on ply shear-out resistance were greater for E-glass/polyester than for S-glass/phenolic. The effects of resin and reinforcement are confounded here.

Two very different sandwich laminates typical of general engineering applications; woven glass vinyl ester / Coremat core and woven glass epoxy pre-preg / honeycomb core were compared by Mines et al. [22]. Via experimental observation and analytical modelling they concluded that core density influenced failure progression, and suggested that the use of high ductility skins, the use of multiple layers and the tailoring of the multi-axial crush behaviour of the core could increase the panel perforation energy.

With the aim of introducing aluminium foam sandwich (AFS) into ship construction comparisons between impacts on GRP/PVC foam sandwich yacht laminates and two types of AFS laminates were made by Crupi et al. [99]. More energy was required for complete failure of the PVC foam sandwiches, which suffered predominantly elastic failure, compared to the ductile fracture with large out-of-plane displacements of the AFS specimens. Further work [100] investigated the mechanical behaviour under bending and impact loading of aluminium honeycomb sandwich (AHS) panels reinforced by GFRP outer skins compared with the AHS panels (without GFRP skins) where much more energy was absorbed by the GRP reinforced laminates.

5. Conclusions

Typical impact damage modes have been outlined for both monolithic and sandwich marine laminates and studies investigating the effects of a number of types of both impact event and material parameters have been discussed. However, given the significant and interacting effects of many of these parameters on impact behaviour it would be dangerous to try to extract simplistic trends from this discussion. Hence, only information most relevant to the specific materials and impact event combination to be considered should be referred to for guidance, but the safest approach is still one of a testing programme specifically tailored to simulate the specific case considered.

It is also important to consider exactly which aspect(s) of impact behaviour (response, resistance and / or tolerance) is (are) most important before attempting to optimise the laminate and structure for impact.

Together with parts I and III of this review, this paper has identified, characterised and discussed of a large (and often not easily sourced) body of 'impact' work specifically considering marine applications of composite materials, providing a valuable hitherto unavailable specific source of reference for the marine industry and research fields.

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References

[1] L.S. Sutherland, A review of impact testing on marine composite materials, Part I: Marine impacts on marine composites, Compos. Struct. (2017).

[2] R.M. Cripps, Design and Development of Lifeboats - Damage Evaluation and Repair of Composite Structures, Appl. Mech. Mater. 3–4 (2005) 3–8.

[3] L.S. Sutherland, C. Guedes Soares, Impact on marine composite laminated materials, in: Mar. Technol. Eng., Taylor & Francis Group, London, UK., 2011.

[4] E. Findon, S. Lee, Impact Testing of High Technology Laminates and Structures, in: Amsterdam, NL, 2005.

[5] L.S. Sutherland, C. Guedes Soares, Impact characterisation of low fibre-volume glass reinforced polyester circular laminated plates, Int. J. Impact Eng. 31 (2005) 1–23..

[6] G. Zhou, L.J. Greaves, Damage resistance and tolerance of thick laminated woven roving GFRP plates subjected to low-velocity impact, Impact Behav. Fibre-Reinf. Compos. Mater. Struct. Camb. Woodhead Publ. Ltd. (2000) 133–185.

[7] D. Zenkert, Damage tolerance of Naval sandwich panels, in: Major Accompl. Compos. Mater. Sandw. Struct., Springer, 2005: pp. 279–303.

[8] M. Wiese, A. Echtermeyer, B. Hayman, Evaluation of oblique impact damage on sandwich panels with PVC and balsa core materials, in: Fourth Int. Conf. Sandw. Constr., EMAS Publishing, Stockholm, Sweden, 1998.

[9] B. Hayman, D. McGeorge, Dynamic Response of Sandwich Structures, in: Theory Appl. Sandw. Struct., R.A. Shenoi, A. Groves, and Y.D.S.Rajapakse (Eds), University of Southampton, Southampton, UK, 2005.

[10] L.S. Sutherland, C. Guedes Soares, The effects of test parameters on the impact response of glass reinforced plastic using an experimental design approach, Compos. Sci. Technol. 63 (2003) 1–18.
[11] L.S. Sutherland, R.A. Shenoi, S.M. Lewis, Size and scale effects in composites: II. Unidirectional laminates, Compos. Sci. Technol. 59 (1999) 221–233.
[12] L.S. Sutherland, R.A. Shenoi, S.M. Lewis, Size and scale effects in composites: III. Woven-roving laminates, Compos. Sci. Technol. 59 (1999) 235–251.
[13] L.S. Sutherland, C. Guedes Soares, Contact indentation of marine composites, Compos. Struct. 70 (2005) 287–294.
[14] C. Santiuste, S. Sanchez-Saez, E. Barbero, Residual flexural strength after low-velocity impact in glass/polyester composite beams, Compos. Struct. 92 (2010) 25–30.
[15] A.G. Gibson, D.A. Spagni, The cost effective use of fibre reinforced composites offshore, HSE Books, Sudbury, 2003.
[16] M. Hildebrand, Improving the impact strength of FRP-sandwich panels for ship applications, VTT, 1996.
[17] P. Auerkari, P.H. Pankakoski, Strength of sandwich panels with impact defects, VTT, Epsoo, 1995.
[18] M. Hildebrand, A comparison of FRP-sandwich penetrating impact test methods, VTT, 1996.
[19] M. Hildebrand, Improving the impact strength of FRP-sandwich panels for ship applications, Part 2, VTT, Espoo, Finland, 1997.
[20] M. Hildebrand, Penetrating impact strength of sandwich panels—meaningful test method and simplified prediction, in: Mech. Sandw. Struct., Springer, 1998: pp. 247–254.
[21] M. Hildebrand, The effect of raw-material related parameters on the impact strength of sandwich boat-laminates, VTT, 1994.
[22] R.A.W. Mines, C.M. Worrall, A.G. Gibson, Low velocity perforation behaviour of polymer composite sandwich panels, Int. J. Impact Eng. 21 (1998) 855–879.
[23] P.H. Bull, F. Edgren, Compressive strength after impact of CFRP-foam core sandwich panels in marine applications, Compos. Part B Eng. 35 (2004) 535–541.
[24] Nordtest, Sandwich panels: Local impact strength of frp-sandwich panels, Nordtest, Espoo, Finland, 1998.
[25] D. Zenkert, A. Shipsha, P. Bull, B. Hayman, Damage tolerance assessment of composite sandwich panels with localised damage, Compos. Sci. Technol. 65 (2005) 2597–2611.
[26] C. Muscat–Fenech, J. Cortis, C. Cassar, Impact damage testing on composite marine sandwich panels. Part 1: Quasi-static indentation, J. Sandw. Struct. Mater. 16 (2014) 341–376.
[27] C. Muscat–Fenech, J. Cortis, C. Cassar, Impact damage testing on composite marine sandwich panels. Part 2: Instrumented drop weight, J. Sandw. Struct. Mater. 16 (2014) 443–480.
[28] C. Muscat–Fenech, J. Cortis, C. Cassar, Characterizing QSLVII Damage of Composite Sandwich Hulls, Procedia Eng. 88 (2014) 141–148.
[29] M. Burman, N. Niclasen, Ice impact on sandwich panels for light weight marine vessels, in: Florida Atlantic University, Fort Lauderdale, USA, 2016.
[30] H. Herrnring, J.M. Kubiczek, S. Ehlers, N.O. Niclasen, M. Burmann, Experimental investigation of an accidental ice impact on an aluminium high speed craft, in: Lisbon, Portugal, 2017.
[31] G.A.O. Davies, D. Hitchings, G. Zhou, Impact damage and residual strengths of woven fabric glass/polyester laminates, Compos. Part Appl. Sci. Manuf. 27 (1996) 1147–1156.
[32] G. Zhou, Static behaviour and damage of thick composite laminates, Compos. Struct. 36 (1996) 13–22.
[33] G. Zhou, Prediction of impact damage thresholds of glass fibre reinforced laminates, Compos. Struct. 31 (1995) 185–193.
[34] G. Zhou, G.A.O. Davies, Impact response of thick glass fibre reinforced polyester laminates, Int. J. Impact Eng. 13 (1995) 357–374.

[35] M.H. Arvidson, P.H. Miller, Hull material evaluation for Navy 44 sail training craft, Nav. Eng. J. 113 (2001) 71–78.

[36] L.S. Sutherland, C. Guedes Soares, Impact on Marine Laminates, in: Proc. RINA Conf. Mod. Yacht, RINA, Southampton – UK., 2007.

[37] L.S. Sutherland, C. Guedes Soares, Scaling of impact on low fibre-volume glass–polyester laminates, Compos. Part Appl. Sci. Manuf. 38 (2007) 307–317.

[38] L.S. Sutherland, C. Guedes Soares, Scaling of Impact on Glass-Polyester Laminated Plates, in: Marit. Ind. Ocean Eng. Coast. Resour., Taylor & Francis, London, UK, 2007: pp. 293–300.

[39] L.S. Sutherland, C. Guedes Soares, Effects of laminate thickness and reinforcement type on the impact behaviour of E-glass/polyester laminates, Compos. Sci. Technol. 59 (1999) 2243–2260.

[40] L.S. Sutherland, C. Guedes Soares, Impact tests on woven-roving E-glass/polyester laminates, Compos. Sci. Technol. 59 (1999) 1553–1567.

[41] L.S. Sutherland, C. Guedes Soares, The use of quasi-static testing to obtain the low-velocity impact damage resistance of marine GRP laminates, Compos. Part B Eng. 43 (2012) 1459–1467.

[42] L.S. Sutherland, C. Guedes Soares, Impact behaviour of GRP, aluminium and steel plates, in: Anal. Des. Mar. Struct., Taylor and Francis Group London, 2009: pp. 293–300.

[43] L.S. Sutherland, C. Guedes Soares, Impact behaviour of typical marine composite laminates, Compos. Part B Eng. 37 (2005) 89–100.

[44] L.S. Sutherland, C. Guedes Soares, Impact on low fibre-volume, glass/polyester rectangular plates, Compos. Struct. 68 (2005) 13–22.

[45] L.S. Sutherland, C. Guedes Soares, Impact on single-skin marine composites, in: C. Guedes Soares (Ed.), Marit. Transp. Exploit. Ocean Coast. Resour. Proc. 12th Ie 11th Int. Congr. Int. Marit. Assoc. Mediterr. IMAM 2005 Lisb. Port. 26 - 30 Sept. 2005, Taylor & Francis, London, 2005.

[46] L.S. Sutherland, C. Guedes Soares, Characterisation of impact on low fibre-volume woven roving E-glass polyester composites, in: Actas 5º Encontro Nac. Análise Exp. Tensões E Mec. Exp., Universidade de Coimbra, 2004.

[47] L.S. Sutherland, C. Guedes Soares, Effect of laminate thickness and of matrix resin on the impact of low fibre-volume, woven roving E-glass composites, Compos. Sci. Technol. 64 (2004) 1691–1700.

[48] L.S. Sutherland, C. Guedes Soares, Transverse impact on circular marine composite plates., Mec. Exp. – Rev. APAET. 10 (2004) 83–93.

[49] L.S. Sutherland, C. Guedes Soares, Impact behaviour of low fibre-fraction glass / polyester laminates., Mec. Exp. – Rev. APAET. 7 (2002) 53–59.

[50] A. Echtermeyer, R.F. Pinzelli, K.A. Raybould, N. Skomedal, Advanced composite hull structures for high speed craft, in: Toulouse, France, 1994.

[51] O. Aamlid, G. Antonsen, Oblique impact testing of single skin, aramid fibre reinforced plastic panels, DNC, 1997.

[52] B. Hayman, A. Echtermeyer, D. McGeorge, Use of Fibre Composites in Naval Ships, in: Warsh. Proc. Int. Symp., RINA, London, UK, 2001.

[53] F.S. Uralil, Impact damage tolerance of FRP composites in offshore applications, in: S.S. Wang, D.W. Fitting (Eds.), Compos. Mater. Offshore Oper. Proc. First Int. Workshop Oct. 26-281993, NIST Publications, Houston, Texas, 1995: pp. 185–192.

[54] P. Davies, P. Chauchot, Composites for Marine Applications Part 2. Underwater structures, in: Mech. Compos. Mater. Struct., Springer, 1999: pp. 249–260.

[55] P. Davies, Scale and size effects in the mechanical characterization of composite and sandwich materials, Mechanics. 8 (1999) 10.

[56] P.B. Gning, M. Tarfaoui, F. Collombet, L. Riou, P. Davies, Damage development in thick composite tubes under impact loading and influence on implosion pressure: experimental observations, Compos. Part B Eng. 36 (2005) 306–318.

[57] M. Tarfaoui, P.B. Gning, P. Davies, F. Collombet, Scale and Size Effects on Dynamic Response and Damage of Glass/Epoxy Tubular Structures, J. Compos. Mater. 41 (2006) 547–558.

[58] M.E. Deniz, O. Ozdemir, M. Ozen, R. Karakuzu, Failure pressure and impact response of glass–epoxy pipes exposed to seawater, Compos. Part B Eng. 53 (2013) 355–361.

[59] A.T. Echtermeyer, Integrating Durability in Marine Composite Certification, in: P. Davies, Y.D.S. Rajapakse (Eds.), Durab. Compos. Mar. Environ., Springer Netherlands, Dordrecht, 2014: pp. 179–194.

[60] R. Stokke, The Norwegian Approach, in: IBC Technical Service Ltd., 1992.

[61] S.R. Reid, G.G. Corbett, Performance of GRP pipe Under Impact Loading, in: IBC Technical Service Ltd., 1992.

[62] P.H. Miller, Design, verification, and forensic correlation of composite yacht structures, DTIC Document, 2003.

[63] British Standards Institution, Small craft - Hull construction and scantlings - Part 5: Design pressures for monohulls, design stresses, scantlings determination., International Organisation for Standardisation, 2008.

[64] ASTM, ASTM D 7766 -11 Standard practice for damage resistance testing of sandwich constructions., American Society for Testing and Materials, Philadelphia, PA, 2011.

[65] F. Cucinotta, A. Paoli, G. Risitano, F. Sfravara, Optical measurements and experimental investigations in repeated low-energy impacts in powerboat sandwich composites, Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ. (2017) 147509021772061.

[66] L.S. Sutherland, A review of impact testing on marine composite materials, Part III: Damage tolerance, durability, and strain rate and scaling effects, Compos. Struct. (2017).

[67] Y.W. Kwon, M.A. Violette, R.D. McCrillis, J.M. Didoszak, Transient Dynamic Response and Failure of Sandwich Composite Structures under Impact Loading with Fluid Structure Interaction, Appl. Compos. Mater. 19 (2012) 921–940.

[68] V. Lopresto, A. Langella, I. Papa, Dynamic load on composite laminates in the presence of water, Polym. Eng. Sci. (2017).

[69] J.A. Manning, A.G. Crosky, S. Bandyopadhyay, Flexural and impact properties of sandwich panels used in surfboard construction, in: Adv. Compos. 93, Wollongong (Australia), 1993.

[70] O. Aamlid, Impact properties of different shell structures in relation to rule requirements, in: Stockholm, Sweden, 1997.

[71] R. Eliasson, Building Fully-Cored Rescue Boats, in: Seattle, Washington, USA, 2006.

[72] L. Larsson, R. Eliasson, Principles of yacht design, 2nd ed., Adlard Coles Nautical, London, UK, 2000.

[73] I. Kimpara, H. Saito, Post-Impact Fatigue Behavior of Woven and Knitted Fabric CFRP Laminates for Marine Use, in: Major Accompl. Compos. Mater. Sandw. Struct., Springer, 2009: pp. 113–132.

[74] G. Perillo, N. Vedivik, A. Echtermeyer, Damage development in stitch bonded GFRP composite plates under low velocity impact: Experimental and numerical results, J. Compos. Mater. 49 (2015) 601–615.

[75] G. Perillo, J.K. Jørgensen, Numerical/Experimental Study of the Impact and Compression after Impact on GFRP Composite for Wind/Marine Applications, Procedia Eng. 167 (2016) 129–137.

[76] P. Miller, D. Pedrick, G. Schweikert, Development and Initial Review of the Mark II Navy 44 Sail Training Craft, in: Annapolis, Maryland, 2009.

[77] A.P. Suvorov, G.J. Dvorak, Dynamic Response of Sandwich Plates to Medium-velocity Impact, J. Sandw. Struct. Mater. 7 (2005) 395–412.

[78] A.P. Suvorov, G.J. Dvorak, Enhancement of low velocity impact damage resistance of sandwich plates, Int. J. Solids Struct. 42 (2005) 2323–2344.

[79] G.J. Dvorak, A.P. Suvorov, Protection of Sandwich Plates from Low-velocity Impact, J. Compos. Mater. 40 (2006) 1317–1331.
[80] G.J. Dvorak, Y.A. Bahei-El-Din, A.P. Suvorov, Impact and Blast Resistance of Sandwich Plates, in: Major Accompl. Compos. Mater. Sandw. Struct., Springer, 2009: pp. 625–659.
[81] M. Dale, B.A. Acha, L.A. Carlsson, Low velocity impact and compression after impact characterization of woven carbon/vinylester at dry and water saturated conditions, Compos. Struct. 94 (2012) 1582–1589.
[82] Y. Perrot, C. Baley, Y. Grohens, P. Davies, Damage Resistance of Composites Based on Glass Fibre Reinforced Low Styrene Emission Resins for Marine Applications, Appl. Compos. Mater. 14 (2007) 67–87.
[83] D. Ghelli, O. D'Ubaldo, C. Santulli, E. Nisini, G. Minak, Falling Weight Impact and Indentation Damage Characterisation of Sandwich Panels for Marine Applications, Open J. Compos. Mater. 02 (2012) 8–14.
[84] P. Compston, P.-Y.B. Jar, P. Davies, Matrix effect on the static and dynamic interlaminar fracture toughness of glass-fibre marine composites, Compos. Part B Eng. 29 (1998) 505–516.
[85] T. Castilho, L.S. Sutherland, C. Guedes Soares, Impact resistance of marine sandwich composites, in: Marit. Technol. Eng., Taylor & Francis Group, London, UK, 2014: pp. 607–618.
[86] M.E. Otheguy, Manufacture, repair and recycling of thermoplastic composite boats, PhD, University of Newcastle, 2010.
[87] O. Aamlid, Oblique impact testing of aluminium and composite panels, DNV, 1995.
[88] I.M. Daniel, J.L. Abot, P.M. Schubel, J.-J. Luo, Response and Damage Tolerance of Composite Sandwich Structures under Low Velocity Impact, Exp. Mech. 52 (2012) 37–47.
[89] F. Collombet, S. Pecault, P. Davies, D. Choqueuse, J.L. Lataillade, A.T. Marques, Contribution of the Response Surface Methodology to the Study of Low Velocity Impact on Sandwich Structures, in: Mech. Sandw. Struct., Springer, 1998: pp. 255–262.
[90] J. Zhou, M.Z. Hassan, Z. Guan, W.J. Cantwell, The low velocity impact response of foam-based sandwich panels, Compos. Sci. Technol. 72 (2012) 1781–1790.
[91] P.H. Miller, Student Research Projects for the New Navy 44 Sail Training Craft, in: Annapolis, Maryland, 2003.
[92] C. Atas, C. Sevim, On the impact response of sandwich composites with cores of balsa wood and PVC foam, Compos. Struct. 93 (2010) 40–48.
[93] R.A.W. Mines, Product case studies for polymer composite sandwich beam construction, Int. J. Mech. Eng. Educ. 27 (1999) 126–144.
[94] G. Belingardi, M.P. Cavatorta, D. Salvatore Paolino, Repeated impact response of hand lay-up and vacuum infusion thick glass reinforced laminates, Int. J. Impact Eng. 35 (2008) 609–619.
[95] K. Imielińska, L. Guillaumat, R. Wojtyra, M. Castaings, Effects of manufacturing and face/core bonding on impact damage in glass/polyester–PVC foam core sandwich panels, Compos. Part B Eng. 39 (2008) 1034–1041.
[96] M. Wisheart, Impact properties and finite element analysis of a pultruded composite system, \copyright M. Wisheart, 1996.
[97] D. Choqueuse, R. Baizeau, P. Davies, Experimental studies of impact on marine composites, Proc ICCM12. (1999).
[98] L.H. Strait, et al, Effects of seawater immersion on the impact resistance of glass fiber reinforced epoxy composites, J. Compos. Mater. 26 (1992) 2118–2133.
[99] V. Crupi, G. Epasto, E. Guglielmino, Low-velocity impact strength of sandwich materials, J. Sandw. Struct. Mater. 13 (2011) 409–426.
[100] V. Crupi, E. Kara, G. Epasto, E. Guglielmino, H. Aykul, Theoretical and experimental analysis for the impact response of glass fibre reinforced aluminium honeycomb sandwiches, J. Sandw. Struct. Mater. (2016).