A review of impact testing on marine composite materials: Part IV – Scaling, strain rate and marine-type laminates

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Abstract: Although composite materials are now used throughout the marine industry their susceptibility to impact events is still an unresolved problem. The complex nature of the problem in terms of the distinct material and impact event parameters specific to marine applications, damage tolerance and durability has been discussed in parts I, II and III of this review. Here, work addressing marine composite impact scaling and strain-rate effects, and impact studies not explicitly concerning marine applications yet considering laminates typical of the marine industry have been reviewed. Together with parts I, II 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; Scaling; Strain Rate

1. Introduction

Laminated fibre-reinforced composite materials are now used in many areas of the marine industry, mainly due to their resistance to the aggressive marine environment, ease of fabrication and potential high specific material properties. However, damage due to low-velocity impacts (LVI) with solid objects is a known potential weakness of these materials. The objective of this review is to bring together the work concerning 'marine impacts on marine composites'. Part I [1] summarised research on the impact on composite materials in general, described in-service 'marine impact' events, made comparisons of composites materials with other material systems, and discussed the complexity of the problem. In Part II [2] impact damage and the effects of both impact event and material parameters on impact behaviour were considered and Part III [3] concerned impact damage tolerance and durability aspects.

The present paper considers the work addressing two aspects which are critical to ensuring that impact testing represents in-service impact behaviour, i.e. scaling and strain-rate effects. Finally, investigations that, whilst not explicitly concerning marine applications, do consider composite materials typical of the marine industry (e.g. glass/reinforced, hand laid-up or infused single skin or sandwich laminates with foam or balsa cores) are described.

2. Scaling

Zhou and G.A.O. Davies [4] state that, '… impact testing of full-scale structural components (prototypes) under various impact conditions is very expensive, and is seldom carried out. Instead, the small coupon tests are conducted in the laboratory, and their data are used for the design evaluation of prototypes in conjunction with the consideration of physical similarity. To this end, scaling laws must be developed to ensure that the behaviour of a coupon is representative of the prototype and to allow the extrapolation of results for changes in scale.' They also note that the development of such scaling laws become 'almost impossible' when damage occurs. Peter Davies and co-workers [5] [6] also pose the question, 'Is it possible to scale impact tests, to predict the behaviour of large structures based on smaller scaled-down specimens?', also noting that scale effects in impact are extremely complex. There is a wealth of published studies of scaling with respect to composite materials, but few studies address the scaling problem for impact and only a handful of these studies concern marine composites, which are described below.

2.1 Similitude scaling models

The concepts of similitude and dimensional analysis are often used to develop scaling laws [7,8] in terms of scaling factors (λ) of the relevant variables - defined as the ratio of the parameter at prototype and model scales.

Peter Davies [9] used the scaling laws developed by Qian et al. [10] to model drop weight scaling tests on Rovimat (combined chopped strand mat, CSM, and woven roving, WR) polyester - Airex 80 kgm^{-3} PVC cored sandwich laminates. 'Small' (1-ply/10 mm core/1-ply) and 'Large' (2-plies/20 mm core/2-plies) simply supported square panels dimensioned for both shear and flexure dominated behaviours (with small and large length/thickness ratios, respectively) were tested. Large panels were twice the size of the relevant small panels ($\lambda = 2$) and were geometrically similar. The contact force predictions of the scaling model followed the experimental results, scaling as λ^2, i.e. increasing by a factor of 4 from small to large panels. The contact time was also roughly twice as long for the larger panel as predicted. The scaling laws predicted that peak strains are the same at both scales, which was in reasonable agreement with experiment for the shear dominated cases (small length/thickness ratio), but for bending dominated cases (large length/thickness ratio) the small panel strains were only roughly half those seen for the larger panels.

The same scaling laws were then applied to ±55° filament wound glass/epoxy cylinder specimens with diameter to wall thickness ratios of 9 at small (diameter 9 mm, thickness 1 mm) and large (diameter 175 mm, thickness 20 mm) scales to investigate any effects of scale on impact damage. Since the tubes were not exactly geometrically scaled in terms of diameter and thickness (due to practical manufacturing difficulties) the scaling factor λ was 3.0 and 3.2 with respect to thickness and radius, respectively. A value of λ of 3.0 was used for the tests (to scale tube length and impactor diameter by λ, and impactor mass by λ^3) but some additional tests using $\lambda = 3.2$ confirmed that this did not lead to significant differences in results. Cylinders were supported in a cradle, subjected to a single impact and then inspected for damage via ultrasound, sectioning and microscopic examination. At intermediate incident energies more cracks were seen at the small scale, and only the large scale cylinders showed an undamaged region at the centre of the damage cone. Projected damage area did not scale particularly well. In later work [11] loads, maximum displacement and contact duration were seen to scale well but larger tubes suffered more damage, although the type of damage was, in general, consistent. It was concluded that, 'Hence, today it is still necessary to test the structures in their final configuration to determine their damage behaviour; subscale testing may seriously underestimate damage tolerance.'

The author used a dimensional analysis approach to develop scaling laws for impact on marine composite materials and then verified them experimentally for the transverse impact of a hemispherical ended impactor on fully-clamped circular hand laid-up glass–polyester plates at three different scales [8]. Although the model was a simplified one, the tests showed that it scaled the impact responses well for the elastic response. However, some small 'size effects' were observed, especially for the damaged response, but the mechanisms behind these effects were not explained. Further investigation has favoured the hypothesis that slight discrepancies in the scaling of the supports may have been responsible for some of these effects, although this has not been confirmed.

2.2 Analytical and numerical scaling models

Since the different sizes of specimens considered by Zhou and G.A.O. Davies [4] were not geometrically similar (in this case of different thickness but equal in other dimensions) they proposed an empirical scaling rule assuming that the impact delamination is shear controlled ('terminal shear' model). They concluded that the incident kinetic energy (IKE) required for delamination initiation should be scaled by the thickness ratio, and that the resultant maximum impact force would also scale by the same factor.

$$\frac{(mV^2)_2}{(mV^2)_1} = \frac{t_2}{t_1} \quad (1)$$

Where, *m* and *V* are the impact mass and velocity, respectively, *t* is the laminate thickness and the subscripts *1* & *2* refer to thickness' 1 & 2.

For the residual strength of impacted GRP (glass reinforced plastic) balsa sandwich laminates for high-speed marine hulls measured using a static pressure bag Auerkari and Pankakoski [12] conclude that since the tested panels were much smaller than actual marine hull panels the latter are unlikely to suffer from the edge delamination problems they saw in the laboratory and hence panels with different core/face dimensioning and wider edge regions at and beyond the support frame were advocated.

Sutherland and Guedes Soares [13,14] apply a simple mode II fracture analysis to describe the critical load for the unstable onset of a single circular delamination in an isotropic material proposed by G.A.O. Davies and co-workers [4] which predicts proportionality with thickness$^{3/2}$.

$$P_c = \frac{2\sqrt{2\pi}}{3}\left(\frac{EG_{IIc}}{1-\upsilon^2}\right)^{1/2} h^{3/2} \quad (2)$$

Where *E* is Young's modulus, G_{IIc} is the mode II strain energy release rate, υ is Poisson's ratio, and *h* is laminate thickness.

'Large' and 'small' (50 and 100 mm diameter) specimens were impacted with an instrumented falling weight test machine using scaled impactors (10 & 20 mm hemi-spherically ended cylinders). Various thicknesses were considered within each specimen size and impact mass was not scaled systematically, but was larger for the large tests (10.85 kg c.f. 2.85 kg for the small specimens). The model gave excellent agreement with experimental results in allowing for plate thickness, irrespective of plate diameter

A numerical modelling approach was used by Zenkert et al. [15] to scale the effects of damage. They considered a CFRP (carbon fibre reinforced polymer) sandwich for the Visby class corvette, performing quasi-static indentation both at the panel centre and edge with both blunt and sharp indentors to simulate impact damage, followed by compression after impact (CAI) tests. Firstly, small scale (300 x 300 mm) panels were indented on a solid flat bed and since clear evidence of progressive microbuckling failure was observed from fractographic investigations, the code 'Composite Compressive Strength Modeller – CCSM' [16] was calibrated to the experimental data for blunt impact cases by assuming an equivalent hole representing the damage (assessed with C-scanning). CCSM was also used for sharp impact tests, but since damage was a clear crack an equivalent crack model was used in this case. Predictions for a set of larger panels were then made using the calibrated code and these predictions verified experimentally. Two types of larger panels were tested; (i) a scaled-down typical wet deck panel consisting of an 800 x 800 mm flat plate with two longitudinal stiffeners, and (ii) panels simply supported on a 980 x 625 mm frame and loaded hydrostatically with a water-filled rubber bag. The numerical analyses closely predicted the experimental data.

Johnson et al. [17,18] also used numerical analyses, in this case FEA (Abaqus/Explicit and the user material subroutine VUMAT), to predict the scaling of low velocity impact on infused vinylester woven roving E-glass panels. A delamination model using energy failure criterion applied at inter-ply non-linear elastic resin-rich layers. Matrix and fibre damage is modelled using Hashin's 2D stress based failure criteria. The FEA model was calibrated experimentally at two scales, 'large' - 1.5 x 1.5 x 0.038 m (5 x 5 ft x 1.5 in), and 'small' - 0.23 x 0.18 x 0.006 m (9 x 7 ft x 0.25 in).

From the above it could be inferred that both simple analytical and numerical methods have been successful. However, it must be remembered that the analytical methods are simplified ones and as such can only be relied upon to give indications of scaling trends. Conversely, the more complex numerical methods have been successfully fitted to experimental data, but it must be remembered that there is no certainty that these models may be extrapolated to other impact events on different materials, and the financial, time and practical resources will almost certainly not be available for obtaining the required material property inputs. Hence, in terms of the practicalities faced by the marine industry (i.e. limited resources) simple analytical approaches may not only be the safest but also the only feasible option.

3. Strain rate

The effect of strain rate (in the sense of 'loading rate') on impact behaviour is of interest in terms of several aspects of impact, including:

1. 'Simulation' of impact behaviour using simpler, more accessible and cheaper quasi-static equivalent tests [19]. As can be seen below, the great majority of the work in this area falls into this category.

2. The sensitivity of impact behaviour to the (relatively small) changes in strain rate when different impact mass and velocity permutations are used to give the same impact energy.
3. Whether for design decisions or for (numerical or analytical) mathematical modelling reliable, accurate and *relevant* material properties are required. Maximum vessel speeds, and hence in service impact velocities usually vary between around 5 and 40 knots depending on the vessel type (and racing or naval vessels may even exceed this upper limit). Which of these properties must be obtained at the relevant strain rates and when will the quasi-static ones be acceptable? For example, 'The loading rate must be considered when the choice of core material is made, as a foam may show superior properties at high rate but not satisfy a stiffness requirement under long term loading or vice-versa'. [20]

The work investigating strain rate effects is summarised below, categorised by composite laminate type. As for all other aspects of impact behaviour, it must be remembered that the exact nature of the composite materials and test set up considered may well change any strain rate effects seen. As discussed in the first and second papers of this review [1,2], due to the prevalence of low-velocity impact in a marine setting these studies use a drop weight impact set up when simulating in-service impact events (with a typical maximum drop height of 2 m corresponding to an impact velocity of around 6 m/s).

3.1 Sandwich laminates

Uralil [21] summarises the 'Project CP-08' results by Marinetech North West [22] of a large number of impact tests on sandwich panels thus, 'Comparison of load-deflection curves has shown that the sandwich panels failed at similar loads and deflections in both static and impact tests, thus suggesting the use of static tests for predicting performance'. However, subsequent studies as described below, showed that this was perhaps an oversimplification of more complex behaviour.

Nilsen et al. [23] found that the force seen in quasi-static tests on FRP/PVC sandwich plates was 50-65% lower than that for drop weight dynamic tests. The panels consisted of 600 x 600 mm sandwich panels (supported on a 530 x 530 mm frame) of glass-polyester face laminates (of 1.7 and 3.5 mm thickness) cored with 80 and 200 kg/m^3 PVC (of 25 and 50 mm thickness). The absorbed energy to penetration of the outer, impacted face was between 18 and 62 % of that for the dynamic, impact tests [24].

In a comparison of three impact test methods on various FRP sandwich panels, Hildebrand [24] uses a 'slow impact' (quasi-static indentation) test based on the approach proposed by Grenestedt and Kuttenkeuler [25]. Hildebrand compares the standard ISO 6603 test with a very similar quasi-static tests (at 15 mm/min). The quasi-static force for penetration of the impacted 'outer' face was between approximately 20 and 55 % of that for the equivalent dynamic (impact) drop weight test, depending on the nature of the sandwich panel impacted. However, it must be noted that except that for the slow impact tests the hemispherical ended cylinder indentor diameter was 10 mm (c.f. 20 mm for ISO 6603) and the support diameter was 36 mm (c.f. 40 mm for ISO 6603). Further, he concludes that, '…

the laminate shear strength, being matrix-dominated, is affected more by varying loading rates than is the laminate flexural strength, which is more fibre-dominated' and further that the speed of testing, '… can affect the impact strength in different manners, depending on which is the domination strength value involved in the failure mode.' Further work specifically addressed strain-rate dependency of the strength of FRP-sandwich face (glass, carbon or aramid fibres laminates with polyester, epoxy or phenolic matrices) and core (crosslinked and linear PVC foams, end-grain balsa, aluminium and aramid paper honeycomb) materials [26]. Strain rate was found to increase strength in most cases; typically between 10 and 80% depending on the material system for a four-fold increase in impact strain rates.

Peter Davies and colleagues at IFREMER [27] [20] studied loading rate effects on glass Rovimat (WR / CSM) polyester PVC foam (both 'ductile' and 'rigid' 80 kg/m^3) sandwich panels. A slight increase with strain rate of facing tensile stiffness was seen and core shear moduli increased by 12 and 20% with a triple order of magnitude increase in strain rate for the rigid and ductile foams, respectively. However, these latter test rates were much slower than those expected in drop weight impact tests and so a drop weight shear test was developed. Preliminary results showed that, '… the shear moduli values of both foams at the strain rates of interest for the drop weight impact tests on sandwich panels are significantly higher than those measured in quasi-static tests. Failure behaviour is not discussed here but that also evolves with rate.'

Next, simply supported 300 mm square sandwich panels were impacted using a 100 mm diameter 10.9 kg steel hemispherical impactor and the resultant behaviour modelled analytically. The model gave good correlation with experiment for the rigid PVC sandwich using quasi-static shear properties, but it was necessary to use the higher shear modulus value obtained from higher strain rate tests for the ductile foam sandwich, '… suggesting that rate dependence of properties must be taken into account.'

Further work [28] measured shear stress-strain behaviour of foam cores for marine sandwich structures at loading rates encountered by racing yachts. Initial results for high density foams indicated that quasi-static testing may be sufficient design purposes. However Baral et al. [29], investigating an improvement to yacht sandwich panels through the use of a foam core reinforced in the thickness direction with pultruded carbon fibre pins, suggested that, 'Quasi-static test results cannot be used to predict impact resistance here as the crush strength of the pinned foam is more sensitive to loading rate than that of the honeycomb core.

Static and drop weight impact three point bending tests on polymer composite sandwich beams were compared by Mines et al. [30]. Woven glass, carbon and aramid fibre, and glass CSM reinforced polyester and epoxy resin face sheets were cored with both Coremat and aluminium honeycomb. Much lower failure forces, displacements and energies were seen for impact tests on Coremat-cored beams than for static tests, which was thought to be, '… due to there not being enough time for the upper skin damage to distribute, and then increase, due to finite damage time effects.' Strain rate effects were less severe for the honeycomb beams. Mines and Jones [31] then include strain rate dependence of both core crushing stress and lower face failure strain in their elastic-plastic analysis of the static and impact behaviour of sandwich beams, allowing for the increase in material strength with strain rate improving the impact energy absorption capacity. Further work [32] [33] found that energy absorbing capacity increased with the velocity of impact, which was thought to be due to an increase in the core crush stress and skin failure stress at higher strain rates. It was shown, '… that the increase in perforation energy from static to dynamic loading can be due to a change in deformation geometry as well as material strain rate effects'. Later work [34] considers the crush behaviour of structural foams at various strain rates and calibrates numerical models with dynamic data for PVC foam, PMI foam and aluminium foam.

In the review of the 1990-2003 research programme into the cost effective use of fibre reinforced composites offshore programme [35], Project CP04 'Impact response of thick composite laminates and sandwich structures' found that the low velocity dropped object impact loads and energies to both first failure and complete perforation were higher than those for quasi-static loading. Project CP202 'Design and performance of panel elements for energy absorption and resistance to penetration and impact' also found that, 'At low velocities the laminate and sandwich behaviour was similar and conservative to that observed in quasi-static tests'.

The necessity of using material properties obtained at the relevant strain rates for sandwich structures is considered by Hayman and McGeorge [36], where they note that, 'It is important to bear in mind that the effective properties of materials may change with increasing strain rates. This applies to both the elastic properties and the failure stresses or strains.' When discussing the through thickness properties of foam cores they note that in a panel the foam is restricted in the plane of the panel, which is not the case for most test standards, and this can effectively double the core through-thickness stiffness. Hence, they advise that, 'When performing dynamic tests on these materials it is thus extremely important to distinguish between effects that are genuine strain rate effects and those that are due purely to restriction of the deformation in the direction transverse to the loading.' As an indication of the dependency upon many parameters, and hence complexity, of strain rate dependency for impact with solid objects their only comments on this subject are, 'Strain rates for situations involving solid objects can vary enormously depending on the speed of the impact, the panel lay-up, and the type and location of the strain that is of interest. Each case must be considered in relation to these parameters.'

The behaviour of PVC foam cores at quasi-static and high strain rate (HSR) loadings were compared by Mahfuz et al. [37], who saw a moderate increase in compressive strength with an increase in strain rate. However, cross-linked and linear PVC foams showed very different strain rate dependencies, e.g. at higher rates of strain linear outperformed cross-linked, but under quasi-static loading the reverse was true.

Suvorov and Dvorak [38] investigated the inclusion of a polyurethane (PUR) interlayer between the carbon-vinyl ester face sheets and the H100 PVC foam core of marine sandwich plates to mitigate impact damage. They found that the effect of the PUR interlayer under impact did not have as much effect as it had in quasi-static contact tests. The very short duration of the impact was thought to be at least partly responsible for this, when more of the kinetic energy was absorbed by the soft core and less by the face-sheet and interlayer. Rather than the stiff and incompressible interlayer used, a more '… compliant and compressible interlayer would increase the duration of impact, allow time for absorption of the kinetic energy, and reduce the strain energy of the underlying core.'

Very similar far-field deformations were seen for quasi-static and drop weight tests by Daniel et al. [39] in their study of unidirectional and woven carbon/epoxy and woven glass/vinylester composite laminates with cores including various density PVC foams and balsa wood. However, damage was less severe for impact than for equivalent quasi-static tests.

Ghelli et al. [40] compared drop weight impact with equivalent quasi-static tests for E-glass CSM, vinyl ester or polyester, rigid PVC foam-cored sandwich laminates. Higher resistance to penetration was seen for impact tests, and quasi-static indentation generally did not fully reproduce the impact loading, giving different hysteresis cycles.

For PVC, balsa and NL20 Corecork (agglomerated cork) cored WR E-glass polyester sandwich panels, Castilho et al. [41] measured drop-weight impact maximum failure forces of around 1.5 times higher than equivalent quasi-static ones, but undamaged and the overall impact behaviour was well predicted by the quasi-static tests. Interestingly, a problem with the cure of the NL10 laminates led to overly flexible (and hence extremely resin controlled) laminates which absorbed 3 times more energy to failure under impact than for quasi-static tests.

Quasi-static and drop weight impact tests at the University of Malta (with hemispherical, conical, pyramid and cylindrical indentors on marine grade WR/CSM E-glass polyester - linear PVC foam sandwich panels) [42–44] gave similarly damaged panels. The hemispherical indentor gave similar forces for quasi-static and impact tests, but the sharp-edged 'piercing' indentors, 'clearly indicated that: strain rate effects require consideration'.

3.2 Single skin laminates

Gibson and Spagni [35] also report higher loads and energies to failure for dropped object impact tests compared to quasi-static tests for single skin laminates in their summary of the 1990-2003 research programme into the cost effective use of fibre reinforced composites offshore programme.

Zhou [19] states that, '… simplifying a low-velocity impact event to a quasi-static process allows the development of simple analytical techniques needed for material selection, reduction of the number of tests, and preliminary design purpose'. Strain rate effects for the drop weight impact of a flat ended cylinder on thick E-glass fibre reinforced polyester laminates were investigated [4] by comparing dynamic with quasi-static tests; the former giving 36 and 22% higher maximum forces for thin and thick plates, respectively. However, the critical delamination threshold forces were less strain-rate sensitive.

Further work was reported by Zhou and Greaves [45] where S-glass/phenolic laminates were also studied. The effect of loading rate on damage was first examined by comparing quasi-static and impact tests (with velocities of 8.3 x 10^{-5} ms^{-1} and 8 ms^{-1}, respectively). The force at the onset of damage (delamination and ply shear-out) for E-glass/polyester laminates was independent of impact velocity, but the S-glass/phenolic impact tests gave, 'a modest increase in the threshold forces (over 20%) for both thicknesses with reference to the quasi-static values'. However, for 'failure' (ply shear-out or laminate load-bearing capability) this behaviour was reversed; a significant and 'modest' force increase was seen for the E-glass/polyester and S-glass/phenolic laminates, respectively. Secondly, both the impact velocity and impactor mass were varied simultaneously whilst IKE was kept constant to give much smaller (20%) variations in velocity between equivalent impact tests, and producing correspondingly small differences in delamination area

The similitude scaling model used by the author [8,46] for dropped weight impact on low fibre-volume glass–polyester laminates did not allow the correct scaling of strain rate (as scale was increased strain rate had to decrease, i.e. λ_t = s). This was thought to be responsible for a delay in the onset of fibre damage seen for increasing incident velocity for the thinner WR laminates (i.e. an apparent 'scale effect' could actually have been due to a velocity scaling distortion in the scaling model invoking a strain-rate effect).

Equivalent drop weight impact and quasi-static tests were also compared by the author [47,48] to explore the use of the latter to predict the dynamic impact behaviour of marine GRP (E-glass/polyester) laminates. Static tests predicted well the initial impact behaviour and onset of delamination damage, and the lack of signal vibrations in static results made identification of damage onset both much easier and more accurate (since there were no data filtration shift effects). However, static tests significantly underestimated final fibre failure and total energy absorption capacity, except for the thickest specimens where fibre damage occurred at similar loads for both static and impact tests. It was inferred that the 'undamaged' response and initiation of and delamination were not strain rate dependant, but that the fibre failure mechanisms were.

Johnson et al. [17,49] discuss the importance of using high strain-rate material properties in the numerical modelling of impact on infused E-glass vinyl ester laminates. They justify their exclusion of strain rate sensitivity, '… primarily due to the lack of robust test methods. Secondly, due to the conflicting test results. Thirdly, the impact velocities used in the present work are very low and the plates demonstrate a flexural response as opposed to a dilatational wave response seen with very short impact times.' However, they postulate that the very conservative FEA out-of-plane small plate displacements and out-of-plane stresses and strains could be improved with a strain rate model, and state that, '… strain rate sensitivity is an issue which still needs addressing'.

The stiffness and initial damage force of infused thick non-symmetric glass-fibre-reinforced plastics intended for nautical application were found to be not constant at different drop weight impact velocities by Belingardi et al. [50], which they thought likely to be due to resin-rich nature of the laminates.

Quasi-static indentation tests on plain weave T700 carbon/vinylester laminates by Dale et al. [51] gave reasonable estimates of the threshold impact damage force for equivalent falling weight impact tests. Also, quasi-static and impact loaded specimens (which were equivalent in terms of maximum impact force) gave similar compression after impact (CAI) strengths.

3.3 Filament-wound tubes

As part of the 1990-2003 research programme into the cost effective use of fibre reinforced composites offshore programme [35], Project CP299 'Damage Tolerance of Composite Pipes to Local Impact Loads' found that, 'There was a pronounced velocity effect on the energy absorption mechanism and the pipes could absorb significantly more energy under dynamic than quasi-static loading'.

Quasi-static indentation and drop weight impact tests on thick ±55° filament wound glass/epoxy tubes intended for underwater applications were compared at IFREMER [52]. Since above a critical impact energy level a significant drop in implosion resistance was noted, any relevant rate effects on damage were considered important. Whilst damage mechanisms were the same for quasi-static and impact tests, slight differences in the relative dimensions of the various damage modes were seen. The mean damage threshold values were 3 and 4 J for static and impact tests, respectively, suggesting that, '… even for low velocities, impact speed has an effect on the response of thick composite cylinders'. Static damage was both smaller and less variable than equivalent impact damage, which was postulated to be due to differences in energy dissipation mechanisms. Ultrasonic inspection, and then sectioning, polishing and dye penetration were used to determine projected and total damage areas, respectively. The total damage area was found to be 12 times the projected area for static and 10 times larger for impact.

3.4 Pultruded laminates

An apparent rate effect seen by Wisheart [53] for equivalent IKE impacts on pultruded glass fibre/polyester composites for the construction of freight containers at different incident velocities was found to actually be due to the omission of the KE gained by the mass as it dropped from the contact to maximum plate deflection positions. The term 'total impact energy (TIE)' was defined to include this in the IKE calculation (the author had also noted that this same small omission was present in the software supplied with the instrumented falling weight impact test machine at IST, which he corrected when re-writing it). When peak force and peak deflection were plotted against TIE the rate effects disappeared, or at least were greatly reduced, and it was concluded that (over the velocity and mass range tested), 'there were no detectable strain-rate effects, either in elastic stiffness response or in damage initiation/propagation levels'.

Project CP01, 'Impact behaviour of pultruded gratings' (part of the 1990-2003 research programme into the cost effective use of fibre reinforced composites offshore programme [35]) found that quasi-static tests underestimated impact strength.

Although the author's work [54,55] actually studied impact events (such as high-heels) on a footbridge deck, the pultruded sections considered would be equally appropriate for use in marine applications. Quasi-static test results were successfully used to estimate the drop weight impact incident energies required for perforation (by scaling by a factor of approximately 1.5) and force-displacement behaviour was similar for impact and quasi-static tests. Only sections with a resin-rich coating showed a strain rate effect before significant damage occurred, with the impact response stiffer than the equivalent quasi-static one. However, a similar stiffening strain rate effect was seen for all specimens after the onset of damage, which was believed to be due to rate sensitive damage propagation. Perforation responses were also higher for impact tests (by a factor of between 1.2 and 1.6 for uncoated specimens).

4. Marine-type laminates

In both the previous sections and the previous parts of this review [1–3] the studies that explicitly consider impact on composites for the marine industry are reviewed. However, within the rest of the literature is a relatively small number of papers that whilst not specifically aimed at the marine industry, do consider composite materials typical of the marine industry; e.g. glass/reinforced, hand laid-up or infused single skin or sandwich laminates with foam or balsa cores. The information from these studies may also be relevant to the marine industry, and hence they are reviewed below. Again, due to the importance of low-velocity impact in a marine setting the studies use a drop weight impact set up when simulating in-service impact events.

4.1 Single skin laminates

All of the studies in this section concern Glass Reinforced Plastic (GRP) laminates, but more specific details of these materials are given in Table 1. The variation in reinforcement architecture, matrix and production method between the individual studies should be taken as a warning against generalising their conclusions as discussed in the following subsections.

4.1.1 Impact event parameters

Guillaumat [62] shows the importance of impactor mass and velocity, and the target dimensions on the impact responses of contact force, target displacement and impact damage using a methodology based on an experimental design approach [82–84].

Cantwell [61] also investigates the effect of target geometry and size on the impact resistance; for circular and square plates with characteristic dimensions from 50 to 300 mm. The degree of damage seen was related to the force generated and simple analytical energy balance and interlaminar shear stress models successfully correlated the maximum force and damage initiation energy with the size and geometry of the target. This critical impact damage initiation threshold force, P_{crit} is further investigated [79] and found to conform very well to a model predicting proportionality to laminate thickness$^{3/2}$ [85]. P_{crit} was also found to be proportional to projectile diameter but was not influenced by target size.

The influence of laminate thickness on impact resistance was also addressed by Broughton [86]. Whilst damage resistance increased with laminate thickness, residual compressive strength and delamination propagation was not sensitive to panel thickness over the range of 5 mm to 25 mm because the flexural deformation was generally negligible compared with through-thickness shear deformation for thick laminates. He also recommends that future work focuses on impact resistance of non-aerospace materials and that damage characterisation/modelling is still far from satisfactory, particularly for non-aerospace materials.

Reference	Reinforcement		Matrix	Production
	Glass	Architecture		
[56]	E	Woven	Epoxy	Infused
[57]	E	Multi-axial	Epoxy	Infused / HLU
[58]	E	Multi-axial/ CSM	Epoxy / PE /VE	Infused / HLU
[59]	S2 *	Woven	Epoxy	Infused
[60]	E	Multi-axial	PE	HLU
[61]	E	Woven	PE	HLU
[62]	E	Multi-axial	PE	HLU
[63]	E	Multi-axial	VE / Urethane	Infused
[64]	E	Multi-axial	Epoxy	Infused / HLU
[65,66]	E	Woven	VE	HLU
[67]	E	Woven	PE	Infused
[68]	E	Multi-axial	Epoxy	Infused
[69]	E	CSM	PE	HLU
[70]	E	UD	Epoxy	Infused
[71]	E	Multi-axial	Epoxy	Unknown
[72]	E	Woven	Epoxy	Vacuum bagged
[73]	E	Multi-axial	Epoxy	Pre-preg?
[74]	S2 *	Woven	VE	Press
[75]	E	Woven	Epoxy	Vacuum bagged
[76]	E	Woven / Multi-axial	Epoxy	Infused
[77]	E	Multi-axial	Epoxy	Pre-preg
[78]	E	Woven / CSM	PE	HLU
[79]	E	Multi-axial	Epoxy	Press
[80]	E	Woven	VE	Infused
[81]	S	Multi-axial	PE	HLU

* - and Aramid, CSM – Chopped Strand Mat, UD – Unidirectional,
PE – Polyester, VE – Vinylester, HLU – Hand laid up

Table 1: Details of GRP single skin laminates

The hull of a marine vessel will have curved laminates, especially at the bow where impacts are most likely, and the effect of curvature of the target laminate was studied by (Short et al. [77]. They found differences in impact response, impact damage area and post-impact buckling behaviour between flat and curved targets. However, 'perhaps unexpectedly, the post-impact compressive strength for a curved laminate was found to be similar to that for a flat laminate.'

In terms of a typical marine vessel hitting a floating object, the impact event is very likely to be at an oblique angle to the hull laminate. Oblique impacts at angles from 0° (perpendicular) to 30° were considered by Madjidi et al. [69] for CSM (Chopped Strand Mat) laminates. Delamination area and permanent indentation depth were seen to be lower at more oblique angles, leading to the observation that residual tensile strength was at a minimum for perpendicular impacts, especially at higher impact energies.

4.1.2 Damage resistance and tolerance

Resistance to damage will be a desired characteristic (except for cases where impact energy absorption is required to mitigate injury of personnel or damage to other parts of the structure). This may be in terms of the extreme case where lack of impact resistance leads to complete perforation and hence breaching of the hull, but also in terms of how far the load bearing capacity of a laminate is reduced due to the damage; its damage tolerance.

Madjidi et al. [63] investigated the effect of resin and glass reinforcement micro-structure on the impact performance of GRP in terms of damage resistance, depth of penetration and energy absorption. A urethane matrix performed better than the vinyl esters considered, as did a finer glass structure.

In an experimental and numerical study of aramid and S2-glass reinforced laminates (Berk et al. [59] saw that the glass laminates absorbed more energy before perforating than did the aramid ones. An FEA analysis was made to replicate the experimental results with some success, using experimentally obtained material properties. Zouggar et al. [81] also impacted S-Glass reinforced GRP, and again an FEA model was successfully made to replicate the experimental results of three impact tests (on a single laminate at 3 energy levels), although this time with no reference to the source of the material properties used. The FEA model was then used for a small parametric study concerning orientation and number of plies and the target dimensions. Unfortunately no experimental validation of the numerical parametric study were reported to indicate if the probable changes in failure modes and/or mechanisms invalidated any of the assumptions of the FEA model used.

A detailed numerical investigation of compression after impact (CAI) response, validated against glass-vinylester experimental data by Yan et al. [80] found that the numerical model underestimated the critical energy release rate of delamination. This was thought to indicate that impact-induced damage beyond the initial impact-induced damage zone was influential, and that delamination propagation is the critical mechanism that lowers the buckling strength of impacted specimens. However, it must be noted that the numerical model relies on the identification and modelling of the specific damage modes and mechanisms from these specific experiments, and that this type of approach may not be safe if the same model is applied to different materials and/or impact events where these mechanisms and modes may well differ.

Atas et al. [57] ground channels out of the top six plies of infused GRP plates which were then filled with either hand laid-up or infused replacement laminates. These ‘repaired’ laminates were then subject to three point bending and drop weight impact tests. The flexural stiffness of the infusion repaired specimens was over 50% higher than their hand laid-up counterparts and this explains the stiffer impact response of the former at lower energies. However, at higher energies where damage (mostly at the bond-line between the repair and substrate laminate) became significant, both repair methods showed extremely similar impact response and degrees of damage. Perforation of the intact and repaired samples were approximately 120 and greater than 150 J, respectively.

The effect of the addition of a carbon fibre nanofiller to the matrix material was found by Hossain et al. [67] to increase the peak impact force, but also to reduce the irreversibly absorbed energy and the extent of damage. Similar results were obtained by [75] for the addition to the matrix of Cloisite 30B nanoclay, with increases in maximum load and elastic recuperation and the associated reductions in displacement and damage. Subsequent exposure to fire decreased the maximum load and elastic recuperation, the latter of which was marginally less sensitive to fire damage for the nano-reinforced matrix material. Cloisite nanoclays were also studied by Heydari-Meybodi et al. [64] via LVI tests on GRP beams, who concluded that, 'the use of nanoclay significantly improved the response of the composite beams under the LVI test'. Infused specimens suffered less damage area yet more energy absorption than those which were hand laid up. Increasing the nanoclay content reduced the delamination area by up to one third, but peak loads were unaffected. Impact peak loads were always higher than the equivalent quasi-static values; for the hand laid up specimens this ratio increased with nanoclay content, although no significant corresponding increase was seen for the infused beams. Cloisite 15A reinforced beams were less stiff than those of Cloisite 30B, and hence absorbed more energy.

In terms of the measurement of the impact damage suffered by GRP, Meola and Carlomagno [71] found that the onset of heat generation loci corresponded to the onset of Charpy pendulum impact damage using infrared cameras. Infrared thermography was used for non-destructive evaluation of damage and analysis of temperature maps gave information about the damage threshold and extension. Mahdian et al. [70] characterized impact damage with a combination of equivalent quasi-static tests and the analysis of acoustic emission signals to identify the distinct damage mechanisms and then to predict the total damage area. Threshold impact energies were estimated from quasi-static tests.

The residual compressive and tensile residual strengths of GRP laminates have already been mentioned in the previous section [77,69]. Hirai et al. [65,66] showed that the CAI strength of glass-vinylester laminates was improved by increasing the γ-MPS concentration of the fibre surface treatment, and reduced by an increase in temperature. A similar detrimental effect of U.V. light on CAI strength was also recorded by Pang et al. [73]. Various surface treatment additives have successfully improved the Charpy impact strength of GRP, with polyalkenyl-polymaleic-anhydride-amides the most successful [78]. Fibre surface treatments were also used by Park and Jang [74] to reduce the impact damage area of thin GRP/aramid hybrid laminates, and conversely they found that the greatest damage area and hence energy absorption occurred when the impacted surface ply was of aramid.

The inclusion of thermoplastic (Poly Propylene, PP) fibres in GRP to improve the impact damage resistance and damage tolerance (CAI) was studied by Selver et al. [76]. Total absorbed energy was increased by 22% and non-crimp laminates absorbed more energy at low velocity impacts in comparison to woven laminates. The significantly reduced impact fibre damage was thought to be due to a 'cushioning effect' of the lower modulus PP fibres, and hence, in CAI tests, pure GRP, woven GRP/PP and non-crimp GRP/PP laminates retained 45, 83 and 60% of compressive strength respectively.

4.1.3 Durability

A service life in a marine environment entails repeated cyclic wave and docking induced loads, and hence the impact durability of the materials used is an important issue [3].

Repeated impact tests by Belingardi et al. (Belingardi et al., 2009) used their damage index (DI - a damage variable to quantify the penetration process in thick laminates) to investigate the rate of initial steady damage accumulation and the onset of severe damage modes. For very low incident energies repeated impacts did not significantly increase the initial damage. For intermediate energies repeated impact tests gave an initial region of steady damage accumulation before a sudden increase in damage growth just before perforation. For higher energies severe damage mechanisms already occurred after the first impact.

Kosmann et al. [68] studied the reduction in GRP fatigue lifetime due to impact damage. Specimens were damaged at different impact energy levels after 50 fatigue load cycles (to simulate impact on materials already exposed to in-service loads) and then fatigue tested until failure. More than 85% of the samples failed at the impact damage. A critical impact energy giving a dramatic decrease in fatigue life was seen.

The marine environment is also a very harsh one, combining the effects of exposure to water, heat and Ultraviolet (UV) radiation. Boukhoulda et al. [60] showed that the hygrothermal ageing of GRP at elevated temperatures led to a decrease in impact force and delaminated area, and an increase in plate deflection and contact duration. Okeson et al. [72] investigated the effects of moisture on the delamination damage growth under subsequent low temperature thermal cycling and found that moisture led to up to double the damage growth of dry samples. UV exposure of GRP by Pang et al. [73] increased the severity of impact damage and hence significantly reduced CAI strength, and these effects interacted with and were exacerbated by water absorption. However, the impact responses were less degraded by ageing than were the static ones.

A critical impact damage force – laminate thickness model [47,85] has been shown to apply for test temperatures between 23 and 90 °C [79]. They suggest that though the influence of test temperature on damage initiation is complex, the evidence does suggest that initiation force increases with temperature for thinner laminates. Akderya et al. [56] investigated impact on thermally aged (at -18, 25 and 70 °C) adhesively bonded GRP single lap joints, finding that impact, and elevated and reduced temperatures all significantly reduced the load bearing capacity.

4.2 Sandwich laminates

Details of the sandwich laminates of the studies reviewed below are given in Table 2.

4.2.1 Sandwich laminate parameters

The complexity of the impact response due to the number of material parameters is compounded by the additional variables introduced (such as core thickness and material) when sandwich laminates are considered.

Reference	Reinforcement		Matrix	Core	Productio n
	Material	**Architecture**			
[87]	E-glass	Multi-axial	Epoxy	PVC	Infused
[88]	E-glass	Multi-axial	Epoxy	PVC, PET	Infused
[89]	E-glass	Multi-axial	Epoxy	PVC	Infused
[90]	E-glass	Woven/CSM	PE	PVC	HLU
[91]	Carbon, E-glass	Multi-axial, Woven	Epoxy, PE	Syncore	Pre-preg
[92]	E-glass	Woven / CSM	Epoxy	Balsa, PVC, PET	Infused
[93]	E-glass	Woven	Epoxy	PVC, PET	Infused
[94]	E-glass	Woven	VE	PMI	Infused
[95]	E-glass	Woven	Epoxy	PVC, PU	Vacuum
[96]	E-glass	Woven	Epoxy	PU	HLU
[97]	E-glass	Woven	Unknown	PU	Unknown

CSM – Chopped Strand Mat, PE – Polyester, VE – Vinylester, PVC – Plolyvinylchloride,
PET – Polyethylene, PMI – Polymethacrylimide, PU – Polyurethane, HLU – Hand laid up.

Table 2: Details of sandwich laminates:

Lopresto and Caprino [91], in a summary of studies of the impact behaviour of sandwich laminates over a number of years, characterised the complex mechanisms of damage initiation and propagation by proposing semi-empirical and analytical models for the prediction of the residual strength. Static and low velocity impact tests were carried out on various composite laminate systems and under different tests conditions. Damage initiation followed a power law to the exponent of 1.5 suggesting that delamination was mainly due to shear stresses. An elastic solution for circular isotropic plates, modified to allow for indentation, accurately described the elastic behaviour of the plates and the first failure energy. The penetration energy was predicted by an empirical equation insensitive to matrix type and content, and mainly dependant on the areal fibre weight. A simple model predicting the impact energy by a simple indentation measurement was found to be insensitive to many other parameters for a given fibre/resin system. An analytical model predicting residual tensile strength as a function of indentation depth also resulted in good agreement with experiment.

The relative performances of balsa, PVC and PET cores were evaluated by Massüger et al. [92] with balsa outperforming the foams with respect to energy absorption, but not as clearly as could be expected on the basis of its shear strength and modulus (although the small number of panels tested and the need to investigate the influence of skin parameters was noted). Through-stitching of the skins with polyester fibres was found to improve the impact resistance of GRP Urethane sandwich laminates for various combinations of drop height, impactor shape and weight and core thickness by Yoon et al. [97]. The effect of core thickness was also investigated for PVC & PET by Ozdemir et al. [93]; very thin cores behaved in a similar way to a single-skin laminate with a longer elastic response period and decreasing forces and increasing contract times, deflections and energy absorption as the core thickness was increased. Thin and thick cored laminates had very similar loading behaviour, but the unloading behaviour differed due to differences in the damage mechanisms. Corresponding to its higher compression modulus, laminates cored with PVC exhibited a stiffer behaviour than did those with a PET core. PVC and PET cores were also compared by Atas et al. [57] and, in spite of their differing densities, tensile and compressive strengths and stiffness's, there was little difference in perforation threshold between the two sandwich laminates, probably because of the similar material properties in shear of the two cores. They also found that, for a constant foam core thickness, perforation threshold increased in a fairly linear fashion with an increase in face-sheets thickness.

By dividing up a PVC core into up to 3 layers separated by thin GRP sheets Al-Shamary et al. [87] succeeded in simultaneously reducing the peak impact force and increasing the energy absorbing capacity. Similarly, the effects of graded (multilayer combinations of 55, 90 and 200 kg/m^3 PVC foam) cores and panel curvature on the impact force, deflection and perforation energies were investigated by Baba [89]. Generally, as expected, the presence of a foam layer with higher mechanical properties close to the impacted surface led to higher stiffness, peak load and perforation energy. A slightly higher (7%) perforation energy was required for the curved panels. They conclude that, '… this study indicates that the use of layered cores is a good way of increasing the impact performance and minimizing the impact failure of sandwich panels', presumably because the better impact resistance of higher density foam can still be taken advantage of at the impact face whilst using lighter foams for the rest of the core. However, no account of how this approach affects other (such as flexural and shear) properties of the sandwich laminate was given.

4.2.2 Impact parameters

As discussed previously [1–3], the effect of the nature of the impact event (e.g. impactor shape, target properties, etc.) on the impact behaviour is of utmost importance since any testing must replicate in-service impact events as well as possible. An experimental design based response surface approach allowed Collombet et al. [90] to investigate the effects of target span and impact velocity and mass on the impact response of sandwich panels. They conclude that the experimental design method allows not only the influence of impact parameters to be measured, but also of any 'coupling' (interaction) between these parameters. Since there was interaction between mass and velocity for most of the responses studied they concluded that this implies that the energy parameter will not always be sufficient to describe an impact loading, but that both mass and velocity must be specified. The nature of the foam core was found to play an important role for lower skin damage, but did not have a strong influence on local crushing under the impactor.

Srivastava [96] investigated the effect of the impact test used (Charpy, Izod or falling weight) on the impact behaviour of GRP / polyurethane foam laminates and found a significant variation in the energy absorption between the three test methods (as confirmed in a recent review article [98]), and that Charpy tests gave higher dynamic fracture toughness values.

A clear difference between an impact on single skin and that on sandwich laminates is that the indentation into the latter is likely to be more significant due to the thin face-skin laminates. Sadighi and Pouriayevali [95] explore theoretically and experimentally the contribution of indentation to the impact response of single skin and foam sandwich GRP laminates and find that whilst for single skin laminates indentor diameter (for the 10 and 20 mm values considered) has a clear effect on the response, for sandwich laminates it has no obvious influence. Analytical and FEA models using the indentation results produce results in keeping with the experimental ones. Experimental quasi-static indentation tests were also performed on GRP foam cored sandwich laminates by Rizov et al. [94] and an FEA model developed. They conclude that, 'It is clear that the residual dent, predicted in the second step of the finite element analysis, will play a very important role in the modelling of the post-indentation load-bearing capacity of sandwich panels.'

5. Conclusions

The studies addressing marine composite impact scaling and strain-rate effects, and studies not explicitly concerning marine applications yet considering laminates typical of the marine industry, have been reviewed.

Simplified similitude scaling analyses seem to work very well for the undamaged response and can reasonably predict the onset and severity of damage. However, in terms of damage resistance there is still a need for larger scale validation testing.

Strain rate effects depend on the exact composite / impact event considered, but, *in general*, the following observations appear to be applicable:

- Generally, strain rate effects due to the relatively small differences in impact velocity between different velocity-mass permutations for a given LVI incident energy appear to be correspondingly small.
- Quasi-static tests may be used to give valuable information about the impact response.
- There appears to be relatively little strain rate effect between quasi-static and dynamic tests for the undamaged response of monolithic laminates, up to and including the onset of delamination.
- Laminates are generally more resistant to impact than to quasi-static loadings in terms of perforation – by between approximately 10 and 100%, depending upon the specific laminate and impact event / test set-up considered.
- At least some of the damage mechanisms appear to be significantly strain rate dependant in terms of propagation.

Together with parts I, II 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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