A review of impact testing on marine composite materials: Part III - Damage tolerance and durability

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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 nature of the problem in terms of the distinct material and impact event parameters specific to marine applications has been discussed in parts I & II. Tolerance to impact damage is very often of greater concern than resistance to a catastrophic failure and hence the compression, flexural and other loading tolerance of marine composites to impact is reviewed here. Since in-service impacts will occur in the aggressive marine environment, studies on water absorption, temperature and repeated impact effects have also been discussed. Together with parts 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; Damage Tolerance; Durability; Water absorption; Temperature

1. Introduction

Laminated fibre-reinforced composite materials are commonly 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 is a known potential weakness of these materials when subjected to low-velocity impacts (LVI) with solid objects, as commonly encountered in a marine environment due to such events as collisions with floating debris, other craft, docks, and during production.

In Part I of the review [1] research on the impact on composite materials in general has been summarised, in-service 'marine impact' events described, comparisons of composites materials with other material systems were made, and the complexity of the problem discussed. Part II [2] concerned impact damage and the effects of both impact event and material parameters on impact behaviour.

Although for an extreme impact event the integrity and hence the impact resistance of the laminate to perforation is crucial to avoid potential loss of the vessel or structure, more often than not it is the reduction in structural properties after an impact event that is most dangerous, and hence their tolerance to impact damage is extremely important. Also, the marine environment is an aggressive one, both in terms of exposure to salt water and harsh temperatures, and in terms of a lifetime of dynamic loadings. Hence, marine laminates must be sufficiently durable to maintain their impact properties and so this third part of the review concerns the research on the damage tolerance and durability of marine composites.

2. Damage tolerance

The most obvious consequence of impact is the immediate failure of the structure, but more often minor failures that may lead to further damage and subsequent failure are more relevant [3]. Hence the tolerance of the structure to impact damage should be evaluated [4] with the residual strength remaining above a specified value. Damage tolerant materials also generally perform better in fatigue. Usually, the aerospace approach of using compressive strength after impact is assessed, but other residual strengths are also of relevance for marine composites where hull panels and other structures are often subjected to significant flexural loadings.

2.1 Compression after Impact (CAI) Tests

A significant failure mode of LVI is delamination which can greatly reduce in-plane compressive strength and hence, compression after impact (CAI) tests are especially relevant for structures which must be designed to withstand compressive loadings, such as decks. The impact damage may not be readily visible but the detrimental effect on residual strength may be significant [5]. These tests are generally carried out in accordance with three main steps [6]:

1. Inspection: specimen fabrication defects (and later, impact damage) are assessed with non-destructive evaluation (NDE) techniques.
2. Impact: the specimen is subjected to a controlled impact event.
3. Compression: the damaged specimen is subjected to in-plane quasi-static compression in a CAI support to prevent global buckling (Fig. 1).

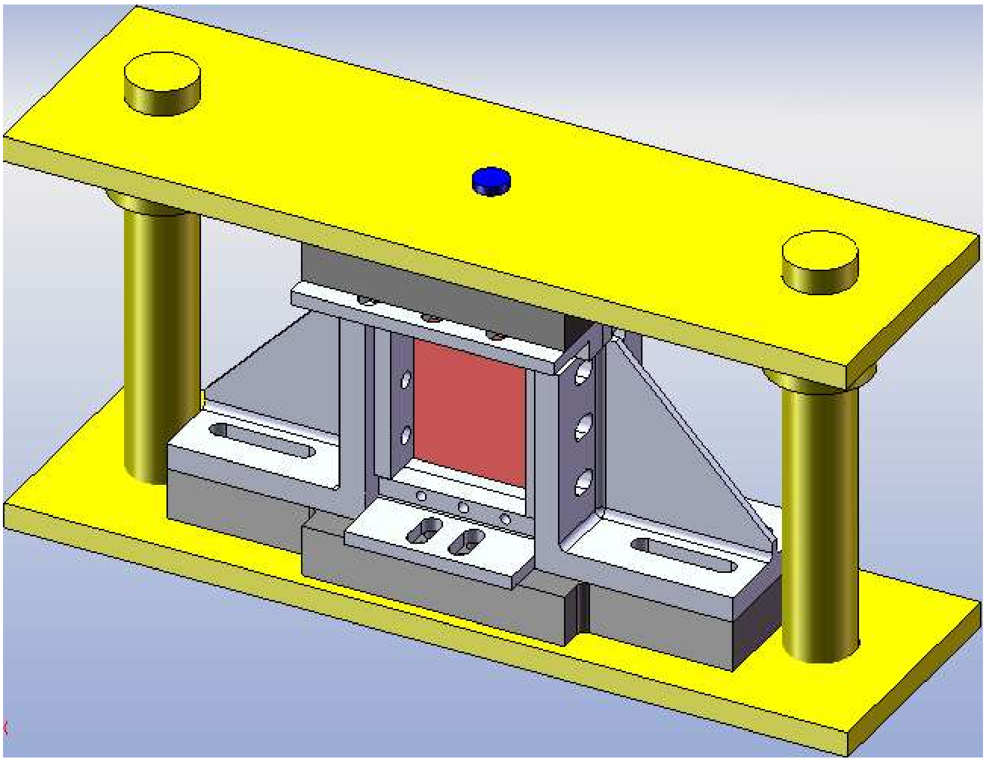

Figure 1: CAI Support (composite laminate in red)

The loaded edges must be exactly parallel to achieve a symmetric loading and avoid failure at the upper and lower edges where load is applied, and for thin laminates tabs to increase the loading area may also be required [7].

Davies et al. [8] found that residual compressive strengths of thick monolithic GRP laminates were greatly reduced by impact damage due delamination and a change of local fibre curvature in the vicinity of the contact area [9]. The use of the ratio of experimentally-determined impact forces as a damage measure could be used to give a useful alternative to residual compressive strength without the need of CAI testing [10]. Compressive strength was reduced more than was stiffness or residual far-field strains. Damaged panels failed via local delamination buckling and kink band formation, whilst compression / shear failure near to the specimen ends was seen for the intact panels. The residual CAI strengths of GRP panels after impact testing at three levels of incident energy were measured and then modelled numerically by Mouring et al. [11]. Two vinylester resins, one fire resistant but relatively brittle and one rubberised to enhance ductility, suffered significant, but similar, reductions in CAI strength [12].

Impact damage also changed the compressive failure mode of sandwich panels [13]; undamaged specimens suffered crimping of the foam core whilst after damage exceeded a critical size (irrespective of the impact energy) a sudden change to outer skin wrinkling was seen, resulting in large reductions in both stiffness and strength. Bull and Edgren [7] used a different CAI method for sandwich laminates where the two unloaded edges were left free. An inversely proportional relationship between CAI strength and incident energy was seen, which was stronger for a hemi-spherical indentor than for a pyramidal one.

A reduction of the CAI strength of sandwich panels was also seen by Shipsha and Zenkert [14], although this was not so significant. Failure was due to growth of the residual outer face dent inwards followed by sudden and complete separation of the face sheets, thought to be due to out-of-plane tensile fracture of the foam core. CAI strength reduction data for a set of sandwich materials representative of those used in the hull structures of naval vessels were obtained by Hayman and co-workers [15,16]. Impact damage due to sharp and blunt objects was simulated via machined cracks and circular holes in the face laminates and compared with real impact damage under compressive loading and strength reduction curves proposed for varying impact damage size.

CAI testing of sandwich laminates by Daniel et al. [5] showed that impact damage reduced the column compressive strength by more than a half, but that no significant strength reduction occurred up to a fairly high incident energy. Because of this 'susceptibility and sensitivity of sandwich structures to impact damage, and the possible loss in structural integrity', they recommend reliable NDE of such structures following impact events (see section 2.4). Other CAI tests on sandwich laminates [17] found that at low incident energies there was no reduction in strength, but as incident energy was increased CAI strength became inversely proportional to the impact energy before reaching a plateau at 60% of their original strength at relatively high impact energies.

Reuterlöv [18] reports on a study of the influence of the resin-filled ribs on face-sheets (of sandwich laminates infused using foam cores with channels for resin distribution) on the impact behaviour. No negative effect of the ribs were seen when compared to plain core material, and in fact the potential maximum load was increased by 20% for compressive loadings.

Various studies investigate the effects of water absorption on CAI strength, and these are included in Section 3.1.

2.2 Flexural after Impact (FAI) Tests

In a marine setting there are many structures subjected to bending loadings, such as hull panels, and hence the flexural after impact (FAI) residual strength is also of interest. Also, since marine laminates are often thicker than those used in aerospace applications (the main drivers for the development of standards and procedures) compression testing of marine laminates is not always very reliable or practical. Hence, easier to perform FAI tests are not only relevant but also attractive. Mines [19] notes that flexural testing is, '…also of use in assessing residual structural properties after some localized damage has occurred'.

The fact that Mouritz et al. [20] only observed slight reductions in the flexural strength of monolithic GRP specimens could be due to the fact that 3-point loading was used with the loading roller pressing onto the centre of the damaged (delaminated) area. A large reduction in interlaminar shear strength was seen, however. A four-point set-up avoids unwanted interaction between the loading rollers and the impact damage propagation, as described by Auerkari [21]. Also, since the compressive strength of the skins is most severely reduced by impact damage, the damaged outer skin was placed on the upper, compressive side of the flexural test. However, this work also noted problems with unwanted failure modes (at the supporting rollers) for undamaged specimens, underlining the need for correct specimen and loading dimensions in the flexural testing of sandwich laminates.

Bull and Edgren [7] considered using 4-point bending residual strength testing, but calculated that the specimens required to reduce edge effects to a minimum would be unfeasibly large. Santiuste et al. [22] investigated the influence of impact energy, beam width, and impactor geometry (Charpy and hemispherical) on the residual 3-point flexural strength of GRP. Residual flexural strength was lower in specimens with damage reaching the edges of the beam, and hence was lower for the wider Charpy impactor than for the hemispherical impactor, and also for the narrower specimens. However, much published CAI work also shows damage approaching the edges of either the impact supports and/or the specimen edges.

A 45% reduction in four-point flexural strength with the introduction of impact damage was due to failure at the 'bridge zone', i.e. the edges of the impact produced cavity under the upper skin [23,24]. A metal and rubber sheet gave protection under the loading rollers for the 4-point FAI tests on GRP PVC foam sandwich laminates of Singh and Davidson [25]. For these specimens designed to give core shear failure immediately followed by core-to-face sheet de-bonding, however, there was no effect of impact damage on the flexural strength. The continuation of the latter two studies on fatigue is discussed in section 2.3, and the effects of moisture and temperature addressed by Singh and Davidson included in sections 3.1 and 3.2, respectively.

2.3 Tolerance to other Loadings

Project CP299 'Damage Tolerance of Composite Pipes to Local Impact Loads' [26] found that impact damage to unlined pipes caused a five-fold reduction in residual strength (to either leakage or burst) and that a plastic liner delayed leakage failure until much higher energies. For composite cylinders subject to external pressure loadings (e.g. for underwater vessels) a critical impact energy level was seen, above which a significant drop in implosion resistance was related to the appearance of intra-laminar cracks [27].

The residual tensile strength of laminates designed for a high speed craft were reduced by up to 50% from that of the undamaged laminate [28]. It was concluded that laminates thin enough to support global loadings would have to be significantly reinforced to give acceptable impact tolerance.

The residual distributed transverse load strength of GRP balsa sandwich laminates for high-speed marine hulls was measured in static bag pressure testing from the side of the impact defects [29]. Large delaminated damage areas at the centre of the tested panels caused up to a 20% reduction in residual strength but as this was thought to be inseparable from scaling effects.

Although technically a form of damage tolerance, Aamlid [30] states that, 'the importance of secondary peeling of the sandwich skin after impact damage should be treated separately from impact'.

In Office of Naval Research (ONR) sponsored research, Kimpara and Saito [31] find a significantly reduced residual fatigue strength for both woven and stitched multi-axial CFRP laminates. The effects of water absorption on these effects is discussed in section 3.1. Shipsha [23,24] noted three main phases of post impact fatigue damage for 4-point flexure loaded sandwich laminates; rapid fatigue failure of the 'bridged zones' (at the edges of the cavity) at a very early stage (3–15% of cycles to final failure), initiation of a fatigue crack at the edge of the cavity, and propagation of this fatigue crack into the core at approximately 70°. Impact damaged fatigue threshold loads were approximately 35% of the ultimate static strength. Also for four-point flexural fatigue testing Singh and Davidson [25] found that impact damage caused a 36% reduction in fatigue life. The effects of water absorption and temperature on this effect is discussed in sections 3.1 and 3.2 respectively.

2.4 Non-destructive evaluation (NDE) and repair

Since the consequences of the impact damage is a main driver for research in the area it is important that this damage is quantifiable. Due to the complex natures of both the damage and composite materials, however, this is not a simple task and is the subject of much ongoing research. Hence, this section only aims to give a brief introduction to the field.

Simple and reliable visual observation of projected delamination area is possible with GRP monolithic marine laminates via simple backlighting [32–38] but for carbon or sandwich panels this is not possible. Bull and Edgren [21] note that for sandwich laminates no damage was observed visually with any certainty when there was an NDE determined damage area of less than 20 mm^2. Interestingly, they also find that although whereas visible delaminations were still evident after one year, in most cases visually identified indentation vanished in 6 months due to viscoelastic recovery.

An overview of NDE techniques, including ultrasonic scanning, X-ray Radiography, Acoustic emission, Thermography etc. is given by Wisheart [39], who explains that for the most common method, ultrasonic C-scan, a transmitter moves over the entire surface of the component providing a plan view projection of the area of damage, but that this cannot distinguish between delaminated areas on different interfaces through the laminate. Comparing ultrasonic inspection obtained projected damage areas with true damage area results obtained using a dye penetrant technique for thick GRP tubes, Gning et al. [27] showed that the true damage area was roughly 10 times the projected area. Imielińska and Guillaumat [40] saw a reduced projected impact damage area for specimens that had absorbed moisture (see section 3.1) but note that, 'This must not lead to the conclusion that wet samples suffered less damage than the dry, since the nature of damage was different. The projected damage area cannot be the only criterion of damage assessment'. However, Zhou [10] reasons that, 'although through-the-thickness distribution of damage in thick laminates is important, particularly in terms of impact energy absorption, the size of the largest delamination is still most critical in assessing residual compressive strength.'

Zhou and co-workers [41,42,10,9] also found that ultrasonic C-Scan could not detect the damage up to the initial delamination threshold even though limited matrix cracking and surface micro-buckling are likely to be visible on the impact surface. However, they considered C-scan to be the most powerful non-destructive tool for detecting and quantifying delamination impact damage, although thick and crimped fibre woven roving laminates presented a difficult challenge due to fibre crossovers and acoustic energy attenuation. Hence, a low frequency probe (0.5 or 1 MHz) in the through-transmission mode was used. Problems were also encountered when using a hand-held scanner since the laminate surface was very uneven and coupling between it and the transducer was problematic.

As part of the EUCLID project, the evaluation of NDE methods for single skin and sandwich composites [43] concluded that, 'Ultrasound techniques are generally the most accurate (in those cases where they work at all)' but were difficult for deep cores or when the inner skin was not accessible. Their use with balsa cores was found to be extremely difficult or impossible due to large density variations between core blocks masking all other effects. Later work [44], however, developed automated ultrasonic scanner equipment that made possible the detection of defects in GRP, CFRP, PVC foam and Balsa wood sandwich structures, 'mainly due to pulser and scanning optimisations such as probe frequency, pulser characteristics, frequency filtering on receiver amplifier, and coupling conditions'.

Far more in depth and practical application orientated information on the use of NDE for marine composites is to be found in both the U.S. Ship Structures committee report and summary by Eric Greene [45,46] and in a study by the Royal National Lifeboat Institution (RNLI) in which NDE techniques were trialled against typical methods used for the assessment of marine structures [47].

To develop a reliable low-cost NDE method for marine composites, especially composite sandwich structures Ayorinde et al. [48] investigated vibration-based techniques including low-frequency vibration, ultrasonic, acoustic absorption, thermosonic and acoustic emission (AE) methods. AE was found to be by far the most effective. A 3D optical scanner was used with success by Cucinotta et al. [49] to detect and model the shape of the plastically impact deformed outer skin of powerboat hull sandwich laminates.

NDE formed the backbone of a completely new approach to dealing with impact damage by Hayman, Zenkert and co-workers [50–53]. A purely damage inspection based approach, together with knowledge of exactly how damage affects the structural performance of marine laminates enables this method to elegantly sidestep the most challenging, expensive (and perhaps irresolvable, in terms of a complete solution?) parts of the impact problem - namely the selection of impact events and the prediction of the subsequent impact damage - whilst still enabling the safe operation of the structure via identification of any 'critical' damaged areas.

In fact, ease of repair to impact damage may be as important in terms of design criteria as impact resistance and/or tolerance. Cripps and co-workers address the problem of how decisions on when and how repairs to damaged lifeboat laminates should be made [54–56,47]. A successful impact damage repair method for a thermoplastic composite RIB was developed by Otheguy [57].

3. Durability

Laboratory impact testing and in-service impacts differ in that in-service laminates will have been affected by the marine environment, mostly by water absorption and temperature. Hence, work where these aspects have been investigated are included in this section. In-service impacts may also not just be confined to a single event, for example a vessel repeatedly hitting a dock wall or pontoon, and hence repeated impacts are also discussed here.

However, it is imperative that the results presented here are interpreted with the comprehension that a wide range of combinations of fibre materials (and no doubt sizings), resins, fabrication processes, saturation ageing methods (e.g. water salinity, temperatures and durations), and testing temperatures have been used, all which may well affect the behaviours seen, and explain the sometimes apparently even contradictory conclusions made.

Since the study of the effects of seawater ageing of glass-vinylester / rigid PVC foam sandwich laminates by Singh and Davidson [25] considers both the effects of temperature and water absorption on both impact damage and tolerance, it is described separately first.

Specimens were immersed in seawater until fully saturated (after approximately 4 months). All four combinations of undamaged and impact damaged, and dry and saturated specimens were tested both at room temperature and -20 °C both statically and in fatigue under four-point bending. For all conditions studied, a decrease in temperature from 20 to -20°C caused an average increase in static strength of 24%, and gave a small increase in static stiffness for all but the dry undamaged specimens. Seawater saturation had no significant effect on the reduction in FAI static strength due to impact at low or room temperatures, and at low temperature there was also no effect of saturation on the reduction in fatigue life due to impact (64% in both cases). However, at room temperature, impact damage decreased fatigue life by 36 % for dry specimens, and this increased to 64% with seawater saturation.

3.1 Water absorption

It is common when ageing laminates in terms of water absorption as described in this section to use a hygrothermal method with elevated temperatures to reduce the saturation period, and then testing is most often carried out at room temperature. The relatively rare work considering testing at elevated or reduced temperatures is discussed separately in section 3.2. The chapter, 'Moisture measurement and effects on properties of marine composites' [58] provides a good overview of water absorption and its damage, mechanisms and effects.

3.1.1 Water damage

The impact and post-impact performance of a composite material may be affected by water absorption through the degradation of the laminate to give damage such as the internal defects seen by Imielińska and Guillaumat [40] in glass–aramid / epoxy laminates placed in distilled water at 70 °C for 8 weeks. They also observed a slight reduction in projected damage area with water saturation, as described in section 3.1.3, but stressed that, 'This must not lead to the conclusion that wet samples suffered less damage than the dry, since the nature of damage was different. The projected damage area cannot be the only criterion of damage assessment.'

Berketis et al. [59] placed GRP non-crimp glass / polyester specimens in a hydrothermal environment (water baths at 65 °C) for up to 30 months and saw matrix dissolution and interfacial damage. Sample weight initially increased due to water absorption up to month 14 and then started to decrease due to material losses. Water absorption did not considerably increase the damage size but produced a greater density of through thickness damage, with consequences for damage tolerance as described in section 3.1.3. Evidence of interfacial deterioration caused by water absorption was also seen by Kimpara and Saito [31] for CFRP laminates. Hand laid-up glass-silk textile fabric reinforced epoxy laminates immersed in natural sea water at 28 °C [60] suffered matrix cracking and fibre/matrix de-bonding after just 16 days.

Gu and Hongxia [61] regarded peeling intensity as representative of the interlaminar bonding strength, which is important in the impact damage mechanisms of composite materials. Glass fabric polyester GRP infused specimens were immersed in distilled water for up to 21 days at 29 °C, after which the peel bond strength increased significantly, which, '… suggests that [the] water environment improves the bonding strength between the layers'. Interlaminar shear strength (ILSS) is also important in determining delamination, and immersion of glass / silk hybrid textile fabric reinforced epoxy hand laid-up (HLU) specimens in natural sea water at 28 °C for up to 16 days [60] reduced the ILSS by up to 70%. Izod impact tests on wet and dry specimens were also performed, but since the wet specimens were only immersed for 24 hours the results were (unsurprisingly) inconclusive.

In terms of sandwich laminates, Weitsman and co-workers [62,63] immersed glass-vinylester / PVC foam laminates in room temperature sea-water for over 2 years. The structure of the cellular foam was damaged and the delamination fracture toughness of the core/skin interface degraded, but these effects were confined to the core at the faces and in the vicinities of crack tips. Bull and Edgren [64] used a more aggressive aging environment of 72 hours under the steam of a 5% salt water (NaCl) solution at 50 °C in a Heraeus testing machine. The fracture toughness of fir wood- and plywood-cored GRP sandwich laminates were decreased, but conversely those of polyurethane foam and coremat were increased.

3.1.2 Damage threshold & energy absorption

The effect of water absorption on the impact resistance may be measured in terms of both the impact energy threshold to give first damage and energy absorbing capacity to failure. However, since the effects of water absorption on damage tolerance are often of the most interest, the effects on damage resistance are not so often addressed.

Strait and et al. [65] used immersion in synthetic seawater at 60 °C to investigate these effects for GRP with both standard and rubber-toughened epoxy resins. Matrix plasticization gave a significant increase in damage threshold energy for the standard epoxy after seawater immersion, but the energy absorbed to maximum load and the total energy absorbed were both substantially reduced due to moisture degradation of the fibres and the fibre-matrix interface for both GRP systems. Hence, it was concluded that moisture absorption can significantly reduce the impact resistance to failure of GRP composites, although resistance to initial damage could be increased. However, Imielińska and Guillaumat [40] saw no significant effects on the very low delamination threshold load or energy for glass–aramid /epoxy laminates immersed in distilled water at 70 °C for 8 weeks.

In ONR funded work Dale et al. [12] found that neither conditioning carbon - vinylester laminates for 400 days in seawater at room temperature, nor in seawater at 40 °C, nor in an environment chamber at 85% relative humidity and 50 °C significantly affected the impact forces recorded.

3.1.3 Damage tolerance

Damage tolerance was considered in section 2 and here the effects of water absorption on this aspect are also considered. Berketis et al. [59] exposed GRP non-crimp glass polyester laminates to hydrothermal environment (water baths at 65 °C) for up to 30 months. Impact damage projected size was not increased greatly but the through thickness damage density was, resulting in a decrease in CAI strength. This reduction in CAI reached a plateau after a certain time of exposure, irrespective of the incident impact energy and hence the exposure time was thought to be a more important factor than the level of delamination. However, for glass–aramid /epoxy hybrid laminates, submersion in distilled water at 70 °C for 8 weeks increased CAI strength [40]. This was thought to be because of a slight reduction in delamination area with water absorption, which was postulated to be due to energy normally available for interlaminar delamination being taken by propagation of water induced fibre-matrix interfacial damage.

Since for in-service examples such as a vessel's hull only one side of the laminate would be exposed to water, an approach where a simple water tank is made by sealing together (E-glass reinforced vinyl-ester) specimens has been used [66,67]. After filling the tank with artificial seawater for up to 30 months, it was dismantled and the specimens impacted and tested in compression to give CAI strength. Partially-saturated specimens gave a significant reduction in CAI strength, but some of this was recovered upon full saturation. A maximum CAI strength reduction of around 10% is compared to the 40% as reported by Imieliska and Guillaumat [40], but as noted by the authors, different materials and even impact energies were considered between the two studies and no comparison with fully submerged specimens was provided, making it very difficult to make any conclusions as to the effects of using this method over 'normal' full submersion of laminates.

The ONR funded work on carbon-vinylester composites of Dale et al. [12] discussed in section 3.1.2 found that although impact behaviour was not significantly affected, CAI strength was reduced by absorbed moisture, apparently due to degradation of the fibre/matrix interface. Other ONR work on carbon composites by Kimpara and Saito [31] found that, 'The effect of water absorption on CAI and post impact fatigue (PIF) performances were small in plain woven fabric CFRP laminates'. The CAI strength of multi-axial knitted carbon fabric laminates was also not affected by water absorption, but this did 'drastically' decrease their PIF properties.

The effects of artificial seawater immersion for up to 9 months on the impact behaviour and failure pressure of E-glass / epoxy filament wound pipes [68] showed that the seawater and transverse impact had significant effects on the failure pressures of the composite pipes

3.2 Temperature

In this section the effect of temperature of the testing environment, as opposed to the specimen conditioning temperature, is discussed.

The compressive through-thickness strength of sandwich laminates and cores is of interest in explaining impact behaviour. Mahfuz et al. [69] saw a decrease in PVC foam compressive strength with an increase in test temperature from room temperature to 110 °C for both quasi-static and high strain rate tests. For quasi-static tests this degradation in compressive strength was much more severe for linear foam than for cross-linked, but this relative performance was reversed at high strain rates. The high strain rate compressive strength of S-glass vinylester / PVC sandwich laminates was 'moderately' greater at sub-ambient temperature (when removed from liquid Nitrogen at -196 °C and tested immediately afterwards) than at room temperature, and this increase in strength was higher for sandwich laminates with linear cores. Despite this only a 'moderate' increase in strength at sub-ambient temperatures was seen, but the failure modes were completely different; impacts at low temperature gave complete pulverization and expulsion of the core materials accompanied by the separation of face sheets, whereas at room temperature the failure was dominated by delamination, core crushing, and partial core shear.

Liquefied natural gas (LNG) ships have a cryogenic containment system composed of structural sandwich laminates and chopped glass fibre-reinforced polyurethane foam (PUF) insulation. [70]. The impact resistance of PUF was investigated with respect to fibre weight percentage at the in-service operation temperature of -196 °C using liquid nitrogen and a drop-weight machine. The critical impact energy increased by up to 2.6 times with the addition of 10 % by weight of fibre and it was concluded that, 'chopped glass fibre reinforcement is vital for the retardation of cracks up to the critical impact load in the PUF under cryogenic environment'. Tensile testing after impact was found to be the most conservative and reliable damage criterion.

The work of Lopresto et al. [71] concerning carbon fabric vinylester laminates under both impact in air and water-backed impact found that maximum loads and initial rigidity were similar for air-backed impacts at room and low temperatures of -25 & -50 °C (in contrast to previous tests on epoxy laminates which exhibited a more brittle behaviour at low temperature). However, less energy was required for damage propagation at low temperature leading to larger internal damages for both the loading conditions.

Hybrid hand laid-up glass-silk textile fabric reinforced epoxy coupons were Izod impact tested at temperatures from 0 to 80 °C by Arun et al. [60]. Impact toughness increased with temperature up to 60 °C, followed by a slight decrease at 80 °C.

3.3 Repeated impact

Repeated impacts are analogous to fatigue for static loadings, with in-service examples such as impacts of a moored vessel with a dock wall and vessel collisions in waves [72]. Auerkari [21] assumes that the effect of repeated impacts is additive as in any fatigue damage and propose a simple analytical model where the damage area is proportional to the number of impacts raised to a fractional power.

Damage mechanisms in graphite, aramid, and glass / epoxy laminates due to repeated low-velocity impacts were investigated by Jang et al. [73] for a range of incident energies. By comparing failure modes with the loading-history, a critical incident energy (E_c) was identified above which a single, first impact gave internal delamination resulting in reduced stiffness (force-deflection gradient) and strength (maximum load) for subsequent impacts. These reduced strength and stiffness values were expressed as a function of the number of impacts; strength (normalized with respect to undamaged strength) plotted against the number of impacts - giving a linear relationship when plotted on a log-log scale. For initial impacts at energies less than E_c, no significant damage was seen until a critical number of impact cycles (N_c) was reached.

Repeated quasi-static indentation loading of thick GRP laminates using a flat-ended indenter showed that the local contact stiffness was influenced by delamination, but only during the unstable delamination initiation phase - as delamination started to propagate stably its effect on local contact stiffness gradually disappeared [42].

Mouritz et al. [20] found that the flexural (3-point) and ILSS (short-beam) test strengths of stitched GRP laminates reduced significantly with increasing number of impacts, consistent with the 'impact fatigue' studies of Jang et al. [73]. The degree of the reductions depended on the impact energy of individual impacts but a strong initial drop followed by an asymptotic approach to a minimum value was general. For a single impact there was a slight reduction in flexural strength but a large reduction in interlaminar shear strength. This large reduction in shear strength occurred since a single more severe impact creates damage inductive to shear failure, i.e. shear-induced matrix cracking, de-bonding and delaminations. Under repeated impacts the laminates then experienced a large deterioration in flexural strength due to fibre crushing beneath the impactor and then sub-surface fibre fracture.

The performance of HLU and vacuum infused GRP laminates were compared for repeated impacts by Belingardi et al. [74] who saw little difference in terms of force, energy curves and damage parameter (the ratio of irreversibly absorbed to incident energies, which increases with repeated impacts) for incident energies below that required for perforation. However, for higher energy impacts HLU specimens survived more impacts before perforating, absorbing more energy. For a given incident energy no significant difference between the two production process in terms of the rate of stable damage accumulation was seen, but the onset of unstable growth occurred with less repeated impacts for the infused laminates.

Sandwich GRP laminates, cored with PVC foam and Balsa were subjected to repeated impacts by Atas and Sevim [75]. The number of impacts to perforation, R_n, decreased with increasing incident energy, E_i, with a relationship of the same form for both cores:

$$E_i = 43{:}5\ R_n^{-0{:}3858} \text{ for PVC foam}$$

$$E_i = 46{:}7\ R_n^{-0{:}4053} \text{ for balsa}$$

Although the relationships appear very similar for both core materials, and for higher impact energy values both required a very similar number of impacts to perforation, as the impact energy is decreased Rn increases at a greater rate for foam-cored laminates compared to that for balsa ones.

The effects of repeated impacts in terms of damage and damage parameter are discussed by Cucinotta et al. [49] for powerboat sandwich laminates. Typically, at the first impact there was a total rebound of the indenter, although fibre damage was indicated by peaks in the force-displacement curve at higher loads. This fibre damage was not significant in subsequent impacts since fibre damage had already occurred. Further impacts led to a higher peak force, but the initial response stiffness (i.e. the slope at the origin) and the energy absorbed were lower. After many impacts, the peak force is very low due to perforation (and hence there is no rebound) and stiffness was reduced to an asymptotic low value. Overall, the composite stiffness decayed exponentially with a reduction of the peak force as the number of impacts increases, whilst the absorbed energy increased parabolically until total failure occurred.

4. Conclusions

The compression, flexural and other loading tolerance of marine composites to impact has been reviewed. By far the majority of the work considers compression after impact (CAI), no doubt since the available standards stipulate this loading case. However, marine structures are very often subjected to flexural loadings (e.g. hull panels) and there is little work considering this aspect. Also, compression testing of the usually thicker marine laminates, especially that of undamaged specimens, raises many practical problems (even to the extent that the standards suggests using different compression method for virgin and impacted specimens).

The relatively few studies on water absorption effects and the even rarer work on those of temperature and repeated impact damage have also been discussed. The scarcity of this type of investigation is exacerbated by the probable dependence of such behaviour on the many impact and material parameter combinations, and so it is not at all clear how applicable the available results would be to other marine composite material systems and / or impact events.

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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