A review of impact testing on marine composite materials: Part I – Marine impacts on marine composites

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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. There is a huge body of work in the area, succinctly summarised here, but the great majority concerns impact events and composite materials more relevant to the aeronautical industry. A discussion of the complexity of the problem in terms of damage and dependence on the many material and impact event parameters shows why there is a need for a review of work specifically considering 'impact on marine composites' due to the distinctive impact events and materials of marine applications. Marine impact scenarios are discussed and comparisons between composite and other construction methods made. 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; In-service events

1. Introduction

Laminated fibre-reinforced composite materials are now used throughout the marine industry; composites are ubiquitous in pleasure boat and racing yacht construction, are widely used in the construction of fast ferries, naval and coastguard patrol craft, fishing and work boats, and also in the offshore oil and gas industry [1]. This is because composite materials promise many advantages over the use of steel, aluminium or wood, such as resistance to corrosion and rot, ease of forming complex seamless shapes, and high specific material properties.

However, these materials are known to be very susceptible to impact damage especially that due to out of plane impact events. An impact on a composite material is a complex, structural event involving multiple and interacting failure modes. This is further complicated by the fact that there are many parameters defining both impact event and composite material, and the effects on impact behaviour of almost all of these parameters are large *and* interdependent. There are also various facets of impact behaviour to consider; Impact response (force, deflection and energy absorption), impact resistance (to damage) and impact tolerance (residual properties). Finally, the definition of 'good' impact behaviour will depend on the application and its impact requirements, and different aspects of this may well be in conflict (e.g. energy absorption and damage resistance and/or tolerance) [2,3].

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Hence, there has been a huge amount of research in the area of 'impact on composite materials' in general. Although these studies consider a range of impact events and materials, the great majority of this work concerns carbon pre-preg autoclaved laminates for the aerospace industry and not the lower fibre-fraction glass, often manually fabricated, composites still ubiquitous in this area [1,4]. Marine composite materials are also far more variable and not at all standardised as they are in the aerospace industry. A lack of available resources, both financial and regulatory, mean that impact studies for marine composites are relatively rare, and not easily encountered and / or accessed, or remain unpublished since the work was often of a sensitive military or commercial nature. The effect of this on design is summarised by Mouritz et al. [5], 'To overcome the lack of information, it is common practice to design composite ship structures with safety factors that are far higher than when designing for metals [6]. Most composite structures are designed with safety factors between 4 and 6, *although values up to 10 are applied when the structure must carry impact loads* [7]. The high safety factors result in structures that are heavy and bulky, and this seriously erodes the strength-to-weight advantage offered by composites.'

Also, the impact events likely to be seen in the marine environment are clearly not the same as those to be expected for aircraft or space vehicles, and as a consequence most standard test methods, which have been developed mainly with aerospace materials and impact scenarios in mind, are not necessarily applicable. In a marine environment, common impact events include collisions with floating debris, other craft, docks, grounding, and during production (e.g. 'tool drops') all of which are low-velocity impacts, and are hence those considered in this review. Further, only impacts with solid objects, focusing on those with smaller objects are considered; i.e. the areas of wave impact and slamming, and grounding are not included here.

The typical approach in most standards is of a predefined impact event on the full-scale component, but this is expensive and, '… can only evaluate a few selected events and not the much wider spectrum of expected scenarios. A calculation approach would be easier and would give more insight into the failure mechanisms involved' [8]. The main problems with the numerical approach no longer include that of computational power, but those of the effort and expense of obtaining all the required material property inputs, especially through thickness properties for delamination modelling (which is particularly critical for the marine industry where materials are extremely unstandardized), and of the need to know and model the complex interacting failure modes a priori. Calculations based on relatively easy to obtain test material data are possible, e.g. [9] but require a complicated, large 3-D model and progressive failure analysis and as one of the authors of that work concludes, 'Due to the complexity of modelling impact it may take a while until testing can be replaced by calculations in design standards' [8]. Shipsha and Zenkert [10] concur that in general numerical approaches have great potential, but only, 'provided that the damage parameters and damage configuration can be characterised'. Hence, there is still a big leap from the current ability to identify and map the failure modes from impact tests and then to fit a numerical model to the data, to producing a useful reliable design tool to predict unknown impact behaviours. However, much progress has been made in this direction through various studies modelling the impact on marine composites, both in terms of numerical [11–16,10,17–31,9,32] and analytical models [33–49,15–18,21,50,24,51,52,27,53–62].

Hence, given the dependency of impact behaviour on multiple material and impact event parameters, the fact that both the materials and the impact events encountered in the marine industry are different and distinct from those found in other industries, and since testing is still currently the most practical and reliable option, the objective of this review is to bring together all of the experimentally based work explicitly addressing the problem of impact on marine composites in one document. These studies are characterised, outlined and discussed as a useful resource to those working in both the research and design fields.

However, aspects of the general 'impact on composites' work may still be of interest, and hence the main review papers concerning all of this vast volume of work to date are outlined in section 2.1, providing a source of well over 1500 relevant references. In section 2.2 the complexity of the problem and how this leads to the idiosyncrasies of 'marine impacts on marine composites' are discussed. Section 3 addresses the need for any impact testing to replicate real 'in-service' marine impact scenarios and highlights work where practical comparisons between 'traditional' construction methods and those using (the relatively new) composite material systems in terms of impact are made. In part II of the paper [63], impact damage, and impact and material parameter effects are covered, and finally, in part III [64] impact damage and durability issues are addressed.

2. 'Impact on Composite Materials'

There are far too many papers on impact on composite materials for them all to be reviewed in a publication of this format and so the reader is directed here directly to a small number of excellent review papers which will provide details of over 1500 categorised references.

The impact problem is characterised into the two separate regimes below [65], of which the former, low velocity impact (LVI), is the subject of this review:

1. Low velocity impact by a large mass (e.g. tool drop), generally simulated using a falling weight or a swinging pendulum. This has been defined as for incident velocities of 1 to 10 ms^{-1} where 'the contact period is such that the whole structure has time to respond to the loading' [66].
2. High velocity (ballistic) impact by a small mass (e.g. runway debris, small arms fire), generally simulated using a gas gun.

2.1 State of the Art

In their early review of the field Cantwell and Morton [65] provide an extremely good holistic overview of how the impact behaviour, resistance, tolerance and other related aspects of a composite material can be related to design requirements. As such the main conclusions of this study warrant detailing here, since they are still very relevant to the marine industry.

Firstly, impact testing techniques were discussed, noting right from the outset that, '*Ideally, the impact test fixture should be designed to simulate the loading conditions to which a composite component is subject in operational service and then reproduce the failure modes and mechanisms likely to occur*'.

Charpy or Izod pendulum tests were only thought suitable for ranking impact performance as a first step in determining dynamic toughness because the short, thick test specimen geometry is not typical of engineering components and absorbed energy varies with specimen geometry [67].

Instrumented falling weight testing, where a weight falls from a pre-determined height to strike the test specimen or plate supported in the horizontal plane, was hence preferred since a wide range of test geometries can be tested. The use of high strain rate test machines to give the rate dependency of basic material properties such as tensile strength, modulus and interlaminar fracture toughness was advocated. Importantly, they noted that due to a lack of experimental standards a wide variety of testing techniques made direct comparison between separate studies difficult.

The effects of various material parameters were then discussed, resulting in the following six conclusions which between them still constitute a good guide to the planning and interpretation of impact test results and to the relevant design considerations

1. Fibres that have a large area under the stress/strain curve tend to be better suited to energy absorbing applications, and increase the subsequent load-bearing capacity of a composite structure.

2. Good matrix Mode II (forward shear) properties (which should be obtained at the relevant strain rates, c.f. point 6 below) reduce impact damage and hence raise residual compressive properties.

3. ‘Good’ impact behaviour may refer to stopping a projectile (where residual properties are not important) or to reducing damage. The strength of the fibre/matrix interphase region can be adapted to the required application; to be weak to encourage failure through gross splitting and delamination for the former case, and stronger for the latter.

4. The energy absorbing capability and failure mode are determined by the stacking sequence. Large changes in fibre orientation between plies and unidirectional laminates should be avoided. The use of woven fabrics, hybrid composites or stitching supress damage (woven, and in particular hybrid woven laminates have a primary and secondary failure mode due to the difference in moduli between the types of fibres which increases catastrophic impact resistance, and this realisation later paved the way for construction of the first fully CFRP ocean-going racing yachts [68]).

5. Geometrical effects are significant (only) for low velocity impact loading. Impact resistance varies with the target's geometry and hence its ability to store energy. Large targets are not necessarily better energy absorbers than small coupons. Care should be taken, therefore, when interpreting data from tests on laboratory-size specimens. Beams tend to be capable of absorbing more energy than larger structures such as circular plates.

6. Both the material's basic properties and / or the target response may be sensitive to the impact velocity and hence strain rate. Low velocity impact loading by a heavy object induces an overall target response (which may be identical or very similar to the static case), whereas high velocity impact by a light projectile induces highly localized target

deformations and energy dissipations, despite the fact that impact energies may be identical. Matrix dominated fracture modes are rate dependent and care should be taken when using static tests to characterize dynamic behaviour (c.f. point 2. above).

The paper and subsequent books by Abrate [69–71] should be the first ports of call for anyone interested in this area. An extensive review of the field is categorized into sections concerning; experimental studies, simplified analyses, indentation laws, analysis of LVI, scaling, experimental studies of impact damage, damage, effect of material properties, effect of stacking sequence and target geometry, damage prediction, and residual properties.

Richardson and Wisheart [66] categorise four major damage failure modes (matrix mode, delamination mode, fibre mode, and penetration mode), then discuss the influences of constituents and geometry on impact response before addressing residual tensile, compressive, flexural and fatigue strengths. They conclude that progress is required both for more complex target geometries and for materials other than just those used in the aerospace industry.

Through their review of 'The role of reinforcement architecture on impact damage mechanisms and post-impact compression behaviour' Bibo and Hogg [72] also provide a wealth of references addressing many aspects of impact on composites, concluding that, 'By providing a route to controlling fibre architecture, textile forms offer a route to controlling damage tolerance'.

The book 'Impact behaviour of fibre-reinforced composite materials and structures' edited by Reid and Zhou [73] brings together 8 monographs (from 14 contributors) covering a wide range of areas, each with its own list of references. Chapter 5, 'Damage resistance and tolerance of thick laminated woven roving FRP plates subjected to low-velocity impact' [74], is of particular interest to the marine industry.

The review of the impact damage of composite materials by Bartus and Vaidya [75] brings together a large number of studies on this most complex phenomenon, and aims to build upon the previous reviews of Cantwell and Morton [65], Abrate [70], and Reid and Zhou [73]. Given that delamination plays such an important part in the initiation and development of impact damage, the 'review of delamination predictive methods for low speed impact' by Elder et al. [76] also provides valuable guidance and sources.

Resnyansky [77], [78] references over 500 sources in his extensive literature review of impact on composites involved in helicopter vulnerability assessment for the Australian Department of Defence. Part 1 includes an outline of the paper, structure certification and classification of threats, material characterisation and general impact experimental techniques and theories. Part 2 reviews literature on; damage response to low-velocity impact and to ballistic impact; after-impact damage tolerance and repair, and finally summarises trends and technology gaps in the area.

Given that the last of these reviews was completed over ten years ago, there is a large number of studies that have been published in the meantime. Although the focus of this review is on marine composites and given that to review all of this work here is not possible, a bibliography of recent work on impact on composites in general is provided in order to provide a useful update to the afore mentioned reviews.

A more recent review paper, although restricted to impact on sandwich laminates, may also be relevant to the marine industry where these laminates are often used where weight savings are paramount [79].

2.2 A Complex Problem

The fact that there is such a large number of studies in the area of 'impact on composite materials' demonstrate that it is a complex problem. Two of the main reasons for this are outlined below:

(i) The problem involves complex behaviour and damage mechanisms.

In terms of the driver for impact on composites research, i.e. a material / structure's impact performance, one or more of the (structural) *impact response* (to an impact event), the *impact resistance* (to impact damage) and the *impact tolerance* (residual properties) may be important dependant on the application considered. As an illustration, when suffering an impact event it may be required that a ship's deck panel must not deflect so far as to cause consternation to the crew (response), must not be damaged at everyday impact energies (resistance), and must also not collapse under normal loadings after a significant impact has induced damage (tolerance). However, conflicts between these three aspects of impact behaviour are common; for example a material good at absorbing impact energy may well do this via extensive damage mechanisms, which will lead to very poor impact damage resistance and tolerance. An excellent example of this is the common belief that Kevlar (aramid) fibres are used in bullet-proof vests so they are 'good' in impact and hence should be included in hull laminates, when in fact a different type of Kevlar without any resin matrix is actually used to 'catch' the bullet [80] (this is not to say there are not advantages of using this material, just that the reasoning is naïve and misinformed).

Further, In terms of impact response there are many potential possibly relevant measurable variables ('responses'), such as contact force, deflection and absorbed energy. Also, global deflections may be large, and membrane effects or shear deflections are usually significant, e.g. [81], and concentrated local forces at the impact point give a complex non-linear contact behaviour, e.g. [82].

Last, but certainly not least, there are multiple and *interacting* failure modes (including matrix micro-cracking, internal delamination, ply shear-out and fibre fracture [74] and damage may occur both due to global deflections and due to local contact forces, [66] which may well already occur at very low incident energies [49,51].

(ii) The problem covers a wide range of both impact event and material parameters.

Despite many references to 'impact properties', 'Impact' is a structural event, where any of the many structural and geometrical parameters, such as target and impactor geometries, impactor velocity, mass and incident angle, target clamping conditions, etc. may well influence the impact behaviour, both quantitatively and qualitatively [83,65,84].

The composite material itself has an internal micro-structure, and the exact combination of many material parameters such as resin and matrix material, interface properties, and internal geometry may well significantly influence the impact behaviour.

Hence, the various response and damage modes will almost certainly vary (both quantitatively and qualitatively) with changes in the type and nature of both the specific composite material considered and of the exact nature of the specific impact event considered.

Further, multi-parametric studies of impact of composites [83] using systematic and statistically based design of experiment (DOE) techniques [85–87] have clearly shown that the effects of almost all of these (material and impact) parameters nearly always depend on all of the other parameters involved. That is, the effect of a given parameter does not remain constant as a second parameter is varied. In the language of DOE this is called an 'interaction effect' or just an 'interaction'. Further, the nature of such a 'two-way' interaction effect (i.e. between two parameters) may vary with the value of a third parameter (a 'three-way' interaction), and this concept can be extended up to an 'n-way interaction. Experience has shown [83] that for impact on composites these interactions are usually significant up to the highest level studied (e.g. if three parameters are studied, then 3 way interactions are usually significant).

Hence, given these interactions, 'conflicting results' may well surface between studies that set one or more parameters that are not equal. A simple, and obvious, illustration would be that two otherwise identical studies using carbon pre-preg in one case and hand laid-up GRP in another may well provide different, or even conflicting results. However, even far more subtle discrepancies may result in different results, for example the degree of crimp of two nominally identical GRP laminates [42]. Hildebrand [84] quotes eight different test impact set ups that had been used in the literature to investigate impact on marine impact literature, and he then compares 3 of these and obtains not only quantitatively, but also qualitatively different results.

The two points above are extremely relevant when considering the relevance of the available literature to a given impact problem. As discussed before, by far the great majority of the literature available concerns high fibre volume fraction, autoclaved pre-preg carbon composites destined for the aerospace industry. Far fewer studies have concerned the lower fibre-fraction, often hand laid-up glass composites still ubiquitous in the marine industry [1,4] (because of the much tighter financial restraints of the marine industry). These points also explain the lack of coherence between the separate studies since they mostly concern separate and distinct specific cases of the overall problem.

Further, in the marine industry materials are not at all standardised; the preferred laminates will vary from shipyard to shipyard, and even when nominally identical lay-ups are prescribed, differences between materials suppliers and/or (often manual) production techniques and expertise will produce different materials. Another highly relevant point that compounds this lack of standardisation is that far tighter financial restraints mean that only the minimum of material testing is feasible (usually only that required for classification). This means that impact data for these materials is not only extremely rare, but that if available it is far less likely to be of any practical use to another project.

Finally, but perhaps most importantly, the impact events likely to be seen in the marine environment are not the same as those to be expected for aircraft or space vehicles. An illustrative example is that the gas gun firing of frozen poultry at a structure may be relevant in terms of bird-strikes for an aircraft, but does not represent a realistic impact event for a ship, even a very fast one. Similarly, the use of a hemispherical indenter in standards designed to replicate hail or runway stone strikes at aircraft speeds do not necessarily make these standards relevant to the marine industry.

3. Impact on Marine Composites

As discussed above, since the impact behaviour, resistance and tolerance all strongly depend on the many impact event parameters, the nature of the expected in-service impact events are fundamental to any research in the field.

3.1 In-service impact events

The lack of a common impact testing method in the marine industry is highlighted by Hildebrand [84] where all eight referenced experimental marine impact studies each use a different test method, and he notes that, 'As the comparison of test results obtained with different methods is nearly impossible, it is obvious that the general knowledge and thereby also the predictability of sandwich impact strength will remain poor as long as no common method is in use.' Muscat-Fenech et al. [88,89] conduct a review of the current state of sandwich impact damage testing of both BS EN ISO and ASTM standards and present the, 'various shortcomings in the standards'. They note that for quasi-static low-velocity indentation impact (QSLVII) the standards do not fully describe sandwich indentation impact (being directed at monolithic laminates) and prescription for marine sandwich panels is non-existent, and hence they extended the procedure for use on sandwich panels.

It is imperative that any impact testing replicates as well as possible the expected in-service impact event(s). According to Echtermeyer et al. [90], 'The critical point is to evaluate the impact resistance in a meaningful way. The impact event should model the collision with floating debris fairly accurately, i.e. loads have to be close to reality.' Hence, it is clear that the first step should be to identify the most pertinent impact event(s) before developing an appropriate impact test set-up. However, there are worryingly extremely few mentions, let alone studies, of the fundamental link between in-service requirements and impact research. This is perhaps not surprising given the 'inherently limited information of the details of accidental impacts' [34]. However, there are a few studies within the marine industry that do consider this most important of aspects, as outlined in the following paragraphs.

An application that requires an especially durable design is that of assault craft. Razola et al. [91] discuss differences between material systems (aluminium and composite) in relation to local assault loads and give a valuable background in relation to rule requirements, concluding that, '… specification of requirements and validation of robustness is today practically non-existent.' Through interviews they also gather information from the shipbuilding industry and operators, stating that, '… there are preconceived opinions on what type of materials that are robust and what robustness actually means.'

Ping et al. [92] discuss 'attempts to establish impact criteria', noting that high-speed vessels may encounter several types of local impact loadings including:

- Collision with a floating or submerged object,
- Objects dropped onto a deck, and
- low-speed berthing impacts

They also note that there were no agreed rules or standards defining such loads or the required impact resistance. They observe that research into impact resistance was divided into two main areas; (i) development of suitable tests and criteria, and (ii) of studying the impact resistance of available materials. This was true during the 1990's period that this paper reviews; at this time (i) was still being researched in the marine industry, mostly in Scandinavia where fast composite ferries were being introduced, and is discussed in the following paragraphs.

However, since then, this area seems to have been largely forgotten in favour of (ii) - materials impact work, despite the fact that the problem of impact test development was by no means already solved. This is in all probability because of the very large number of impact parameters and hence almost limitless number of possible impact events. Tellingly, McGeorge et al. [93] considered the problems of developing requirements for local impact strength, and then considered the more feasible approach of developing tests for comparing new designs to proven ones. Hayman and co-workers develop an approach where the structure is monitored via NDT methods to verify that no critical impact damage is present, thereby elegantly sidestepping the problem of characterising the impact event, [94,95,20,23]. The work of Cripps et al. [96] is also of interest in this context.

Classification societies try to ensure adequate resistance to impact loads such as collision with floating and deck-drop objects by specifying minimum plate thickness requirements. Echtermeyer et al. [90] describe in detail the DNV minimum thickness for impact resistance approach, which is mainly related to the vessel length and is to prevent damage to floating objects 'e.g. logs, fish boxes etc.', and also provides protection against drifting into jetties. They state that this thickness is largely based on experience; despite not knowing the impact loads, vessels with plates of these thicknesses have not suffered serious impact damage. In order to replicate a floating object hitting a moving vessel in the bow area, drop tests are performed on single skin GRP panels at an oblique angle of 24°, which they consider representative, noting that previous tests showed this to give significantly different results to those at 90°. They conclude that thinner laminates that satisfy global and slamming criteria but not those of minimum thickness are not equivalent to traditional thicker laminates in terms of impact, but that they could be improved in this respect.

In a continuation of the work by McGeorge and Echtermeyer, Aamlid [97,98] compares the impact strength of aluminium and GRP single skin and sandwich panels impacted at an oblique angle of 35°, and relate the results to DNV's Rules for minimum thickness. Their main conclusions are listed below:

- Based on equivalent thickness or weight, aluminium has much better impact resistance than does single skin GRP, especially for thicker panels,
- The thinner outer skin of sandwich laminates are more easily perforated than an equivalent single skin laminate,
- The outer skin of a sandwich structure is less easily perforated compared to a single skin laminate *of the same thickness*,
- Sandwich laminates resist full perforation (of both skins) better than aluminium plates of the same thickness as each of the sandwich skins.

With respect to minimum thickness requirements, they note that an overall safety assessment to determine an adequate level of impact resistance is still lacking. Also, since comparing single skin and sandwich plates is not straightforward, especially given the number of laminate and material permutations possible, '… a proper strategy for this comparison should be decided upon.' They also reflect that the DNV minimum thickness is independent of vessel speed and that a speed dependent value should be assessed.

Further details of this work at DNV may be found in [99–101,8].

Pedersen and Zhang [102,40] use analytical methods to describe impact events on aluminium and GRP plates, and propose performance requirements to supplant minimum plate thickness requirements. They conclude that impact strength is determined by plate thickness, size and aspect ratio, impact location and angle, plate material yield stress and critical strain. Also, perpendicular impacts are found to be a worst case for falling objects, but for impacts with floating (slender) objects, plate rupture is more probable when the object is aligned with the sailing direction. Comparisons of results with DNV test results 'show an acceptable agreement'.

With respect to the use of test methods developed for the aerospace industry, Hildebrand [3] notes that, 'Bearing in mind the probable objects which can lead to heavy impacts on actual ship sandwich structures, it seems obvious that objects with a constant projected contact area, such as cylinders, are particularly rare. There are various potential impactor objects with edges, an impactor shape to which the used test method corresponds well.' The test method to which he refers, developed by VTT Technical Research Centre of Finland, used a pyramidal impactor (see [63] for more details) and was developed because of two main drawbacks of the existing standards with respect to marine cases; (i) The impactor is too small compared both with sandwich thickness and probable in-service impacts, and (ii) the desired failure modes (i.e. those seen in service) are not produced [84]. The fact that test results obtained using different test methods led to different impact strength ratings for both outer and inner faces highlights the importance of the choice of test method. This does not have to mean that one test method is superior to another, just that they consider different aspects of impact strength, and that a good material solution is not necessarily the best one for all impact cases.

The, 'bewildering variety of [impact] situations which might be encountered' were discussed by Choqueuse et al. [4] at IFREMER (Institut français de recherche pour l'exploitation de la mer). They attribute this to both the wide range of types of marine structures ('from pleasure boats to frigates and fast ferries, and from marina jetties to offshore production platforms'), and the correspondingly wide range of loading conditions, for example, 'Pleasure boats need tolerance to accidental damage, while ocean-racing yachts require additional wave and floating object (ice) resistance - A fast passenger ferry might require resistance to accidental dropped object damage on the deck, floating object impact at 40 knots, repeated wave impact (slamming), and even to collision with port structures or other ships. A minesweeper would need all these in addition to its primary function of resisting underwater explosion. Offshore platform structures require different levels of impact resistance according to the utilization of the different zones, storage, accommodation, helidecks, production etc.' They also accept that in general, relevant test data either does not exist, or is not replicable due to incomplete published information. Davies [103] describes low energy drop tests to simulate the damage to boat decks or hulls induced by falling or floating objects, and the accidental dropping of a 4 ton container onto full scale (4 x 5 m) deck panels for an offshore platform.

Davies and Chauchot [104] address yet more marine applications - those underwater for oceanographic, submarine and offshore, where filament-wound cylindrical structures are prevalent. Impact conditions '… reasonably close to those that might be expected in service' were considered, namely tubes supported over spans up to 3.2 metres and impact energies ranging from 55 to 275 Joules. Further work [105,106] reasons that since 'the descent speed of immerged objects is often around 1 m/s, the falling weight impact setup is the most appropriate apparatus to reproduce the low energy impacts that may occur in underwater applications in service or during handling.'

Although slamming is not covered in any detail here, it is worth noting the work at IFREMER [107–109] to develop a soft 'medicine ball' drop weight test to directly simulate wave impact / slamming on sandwich racing yacht composites. Similarly, The Royal National Lifeboat Institution (RNLI) has decades of practical experience of impact events in the most demanding of conditions and Cripps [110] notes that, 'the major structural load for small fast craft is slamming loads on the hull structure' and describes an in-house developed design procedure for determining maximum design bottom pressures for their lifeboats based on this service experience. A recent review of the state of the art is also given by Kim et al. [111].

Foreign body impact is also of interest to the RNLI and Trask et al. [112] show photographic examples of operational damage experienced by marine rescue craft, which is then characterized into five increasing levels of damage from the erosion of a portion of the laminate by minor impacts to complete failure of the skin.

Vosper Thorneycroft [113] performed impact tests on full scale 500 cm square panels with a 170 kg swinging pendulum with an impact head that replicated a corner of a steel box or pontoon. The panels were restrained on two edges only to simulate a long panel as found in a vessel, and impact was perpendicular to the panel at its centre. This work was to investigate if higher technology laminates could replace the traditional GRP materials, and is further discussed in part II of this paper [63].

The work at the United States Naval Academy (USNA) [45,114,115], was inherently application focused since it was part of the design process for new ‘Mk 2’ models of the existing ‘Navy 44’ Sail Training Craft, and because it was led by Prof Paul Miller, who is also an accomplished commercial marine composites designer. In fact, the driving design criteria was impact toughness, ‘Whether as novices or hot-dogs, the midshipmen manage to hit docks, rocks and each other with the NA44’s, and they have to resist such punishment much more successfully than boats built for the consumer or charter markets.’ Hence, a test setup was designed to directly simulate the collision of two Navy 44’s. Having realised that the published literature did not consider suitably applicable impact events, ‘a steel replica of the first eight inches of the current Navy 44’s bow was fabricated and attached to a six-foot swing arm assembly.’ An impact speed of 8.5 knots was considered appropriate, and the impactor was allowed to continue striking the panel until all energy was transferred to simulate the common repeated impacts due to waves continuing to drive the hulls together after the initial impact.

Further, they were ‘lucky’ enough to be able to record an in-service validation of the final laminate selection in terms of impact resistance, ‘… when Integrity (Mk 2) was hit by Flirt (Mk 1) each boat was broad reaching on starboard at 6-8 knots when Flirt decided to duck behind Integrity. They hit at an impact angle of approximately 30 degrees from perpendicular. After the initial impact Flirt continued to turn toward Integrity sweeping along the side until leaving in opposite directions. In addition to sweeping off the lifeline stanchions on Integrity and the destruction of the bow pulpit on Flirt, the impact just forward of the rub rail on Integrity resulted in a damage to the laminate approximately 5” wide and two feet long. The damage did not penetrate the hull however and was easily repaired.’

Miller [116] also considered the potentially large impact loads between a crew member aloft, their equipment and the mast of an America’s cup yacht due to the vessel’s rolling. Consultation with the crew provided information on the equipment and the likely operating conditions which would give ‘worst case’ impact loads which was used to set energy values and to design a representative impactor.

Muscat–Fenech and co-workers at the University of Malta [88,89,117] also evaluated impact on genuinely designed marine laminates through the use of seven realistic marine panels engineered following small craft standards and the maritime rules (BS EN ISO 12215-5 [118]) to which boat builders must conform to obtain the required CE certification. They again note that marine impacts are more likely to involve sharper edged impactors than the hemispherical ones ubiquitous in the literature.

In testing within the literature the impact almost exclusively occurs at the centre of the target, which is obviously unlikely to always happen in-service. It may be thought that this would be a worst case, but this may not always be true – the fact that a window should be broken with a safety hammer at the edge in an emergency giving an illustrative example.

Suvorov and Dvorak [17] surmise that previous research has only considered an impact point either in the centre or above the supports (stiffeners). An FEA simulation considering impacts over the entire span of a sandwich laminate indicated that for an impact within approximately two to three times the total sandwich plate thickness from a support, local face sheet deflections and core interface indentations (as potential sources of damage, causing core crushing, and face sheet delamination and/or penetration) were found to be high, with significantly lower values at greater distances.

Although also impacting targets at the centre, the author's work [119,52,120] proposes that the thickness to panel span or diameter ratio may also be interpreted in terms of the distance between impact and stiffener. The behaviour of thick laminates would correspond not only to that of thicker panels, but also to that of thinner panels where the impact occurred near to a stiffener. Hence, two types of test are advocated; on 'thin' specimens to induce a bending/membrane controlled event such as would occur at the centre of a panel, and on 'thick' specimens to induce a shear/indentation controlled event such as would occur near to a stiffener.

Yet another common, and very different, marine scenario is that of impact with ice. Recent studies [58,62] have started to address this problem but the fact that the impactor itself is not only very deformable but also extremely variable in size, shape and consistency further exacerbates the problems involved in selecting suitable impact events to try to simulate in testing.

Surfboards, as a simple example of sandwich panel construction, are made to minimum weight and thickness and are hence particularly prone to impact damage [121]. The impact resistance was improved considerably when E-glass was substituted by S-glass, and further improved with the use of epoxy instead of polyester resin. Mines [41] used as case studies a surf board and also a sailing dinghy to illustrate the relevance of three point bending to foreign object impact cases and of four point bending to cases where global deformation dominates in providing straightforward configurations to be studied and optimized for various material combinations in terms of impact behaviour.

Finally, defining the impact event is of course not fully dependent upon the materials used and hence there may well be further relevant work in this respect which considers impact on structures in other materials. However, where impact with foreign objects is of most interest, i.e. for HSLC, the requirement for light weight means that such craft are only constructed from composites or aluminium, and hence work considering the impact on aluminium craft, such as that of Boon and Weijs [122], would be of most interest.

3.2 Comparisons with other material systems

Despite their many advantages, the uptake of composite materials by boat builders is often hindered by concerns over their 'robustness' to impact. Razola et al. [91], after researching the views of various designers, yards and operators describe a large degree of contradiction and subjectivity in attitudes to the relative performance of aluminium and composite construction in terms of impact. An example is given of a Swedish combat boat built in both aluminium and composite sandwich and both having similar structural performance concerning assault loads, where despite this there was still a ‘conception’ that the composite version was less robust. They note the difference between the mainly plastic and simpler impact failure modes of isotropic aluminium and the manifold impact failure modes of composites which make the subject of impact damage to composites ‘extremely complex’. Practically, they conclude that, ‘dealing with localised assault loads and robustness in relation to composite craft is a matter of addressing the general perception that ships should manage almost any type of rough handling, even when striving to optimise performance with respect to weight. It is also a matter of addressing conservatism and reluctance to using composites in for example naval applications.’ Hence, comparisons with the other, more ‘traditional’ material systems such as steel, aluminium and wood are considered below.

Chalmers [7] notes that, ‘it is dangerous to use mild steel in any large structure which may be subject to relatively high rates of loading (minor impact) in cold conditions’ and that plywood structures will also have poor resistance to impact loads. Due to their relatively high strength and low elastic modulus GRP should, under ideal conditions, have the capability to absorb elastically up to 10 or 15 times as much impact energy as ‘equivalent’ steel or aluminium plates. However, in reality this is much reduced due to the weaknesses induced by low interlaminar tensile and shear strength, lack of ductility and the weakness of joints of GRP structures. In fact he states that, ‘the strength of a complex GRP structure under impact loads is likely to depend more critically on the performance of bonded connections than on the strength of the parent laminate.’

Aamlid [97,98] compares graphically the critical impact energy for perforation of aluminium, monolithic GRP and sandwich panels (for the latter to perforation of the outer skin only) in terms of plate thickness, mass per unit area, bending stiffness per unit width and bending strength per unit width. Summarising the data, an attempt to approximately compare the impact strengths of panels designed to the minimum thickness of the DNV HSLC rules as a function of vessel length is presented, concluding that (although ‘very rough’ estimates) aluminium impact strength is only dependant on vessel length to a low degree whereas GRP impact strength rises with vessel length. For smaller vessels single skin GRP will be weaker in impact than aluminium until at 80 m the two systems are very similar in this respect. Although only perforation of the outer sandwich skin is considered, and hence this construction method actually has a significantly increased reserve impact strength in practice, the plot shows that for smaller vessels sandwich is comparable to aluminium whilst larger sandwich vessels will have a higher impact strength. These comparisons are then extended to include aramid plies and different fibre architectures [123] (see [63]).

Materials typical in boat-building; plywood, GRP, ABS (acrylonitrile/butadiene/styrene), PE (polyethylene), PC (polycarbonate) and aluminium were tested and compared in terms of impact by Hildebrand [124]. Since vessel weight is usually critical, specific impact strength was compared, resulting in the following ranking (% of the strongest material):

1. PC (100%)
2. Aluminium (40-62%)
3. ABS (36-40%)

4. PE (29-31%)
5. GRP (6-16%)
6. GRP reinforced Plywood (6-14%)
7. Plywood (2-3%)

The strongest materials (aluminium and the thermoplastics) all exhibited a high degree of plastic deformation with maximum force occurring at displacements of 2.5 to 5 times the thickness. Plywood and GRP were more brittle, with maximum forces occurring at displacements similar to thickness.

Large scale tests in which a 4 ton container is dropped from 3 meters onto steel and composite floors [4,103] demonstrated the feasibility of composite materials for floor structures on offshore installations. The test was passed by both steel and composite (pultruded sections) systems; despite significant damage for both it was still possible to walk across the floors after impact. Notably, replacement of the damaged composite elements would have been much easier than replacement of the damaged steel structure.

Findon and Lee [113] compared the impact resistance of aluminium (5mm - 'typical of a 7m powerboat hull'), 'traditional' thick single skin GRP and various candidate replacement 'higher technology' composite laminates using a large scale swinging pendulum test rig. Panels were graphically ranked in terms of damage with increasing incident energy, and fell into two distinct groups; total failure (i.e. potential vessel loss) and manageable damage. As expected, the aluminium and thick single skin GRP panels performed well, but Monolithic higher technology laminates gave similar impact resistance and some thin skin cored laminates had better impact resistance, all with significant weight savings.

The author [52] presented comparative experimental data of small scale impact tests on GRP, aluminium 5083 and steel plates. The impact resistance to perforation of the metal plates was much higher than that of the GRP ones, but the behaviour up to perforation was more complex. Both composite and metal plates suffered damage at very low incident energies, but in practice this would be much harder to detect on gel-coated GRP panels. It was stressed that care must be taken to ensure that the relevant comparisons are made; flexural stiffness equivalence was used in this case, but if strength, thickness, or weight equivalence would have been considered the results would have differed (quantitatively and in all probability qualitatively) in each case.

The impact strengths of standard yacht construction PVC foam sandwiches and Aluminium Foam Sandwich panels were compared by Crupi et al. [53], as further discussed in part II [63].

In terms of relative ice impact resistance, representative CFRP sandwich and aluminium hull panels from equivalent vessels designed to DNV-GL HSLC based on the same operational profile and design code were tested by Burman and Niclasen [58]. Although the CFRP suffered only very local damages whereas for the aluminium panel both local and global permanent deformation occurred, the damage to the aluminium was not thought to be critical whilst reinforcement of the CFRP panels was recommended.

4. Conclusions

A concise number of review papers which categorise and discuss over 1500 references concerning impact on composite materials up to 2007 has been provided. This has been augmented by a bibliography consisting of nearly 200 more studies undertaken in the decade after this.

Although there may be relevant information in these many studies, a discussion of the complexity of the problem and the importance of the many material and impact event parameters (and the interactions between them) has made it clear why there is a strong need for a collation of specific data and information on 'impact on marine composites'. This is because both the materials and the impacts encountered in the marine industry are distinct and very different from those found in the aerospace industry, which has been the driver of a great majority of the research and standards development in the area.

The relevant marine impact scenarios and how these are crucial to the planning of relevant impact tests has been discussed, and comparisons between the impact performance of composite and other more traditional construction methods made.

Together with parts II and III of this review, this paper has identified, characterised and discussed 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.

Given the dependence upon many impact and materials parameters, and the huge number of possible combinations of these parameters, it would be dangerous to try to make conclusions on general trends when considering 'marine impact on marine composites'. The safest approach is still one of a testing programme specifically tailored to the specific case considered, in terms of both materials and impact event.

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