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Review

Impact fatigue, multiple and repeated low-velocity impacts on FRP composites: A review

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ABSTRACT

A review of experimental evidence from the literature in relation to “impact fatigue”, “multiple impacts”, and “repeated impacts” on FRP composites, along with articles discussing theoretical and numerical simulations, is provided. A new terminology and definition is presented to clear the meanings of these types of loadings. Experimental investigations about the impact fatigue, have been categorized in terms of the impact energy and the number of impacts. Also, many parameters are considered to illuminate their effects during the repeated impacts on FRP laminates. Discussion of the reported results will be presented along with a recommendation for future explorations and research paths to fill in the knowledge gaps.

1. Introduction

Fibre reinforced polymer (FRP) composites have seen an increase in demand over the past few decades due to their exceptional mechanical properties, particularly due to their best strength-to-weight and stiffness-to-weight ratios. The problem with composite materials, however, is that they are highly susceptible to out-of-plane mechanical loading particularly impact loading [1–12]. In service, components experience a wide range of loading conditions, which can result in a complex state of stress that promotes the development of several damage mechanisms and the coupling between them [13–15]. Low-velocity impacts, which cause internal damage within structures without causing visible damage on the surface, may be the most critical type of loading [16,17]. For example, delaminations happen at specific interfaces within laminates, in particular resulting from low-velocity impacts, that are caused by subsurface cracks, and that reduce structural stiffness and cause damage to grow until fracture [18–20]. Particularly, when performing routine visual inspections, inspectors often overlook low-velocity impacts, which may cause structural failure [21]. Due to the heterogeneity of composite materials, this problem is further complicated, since the characterization of fracture behavior and morphology is more difficult for polymer composites than for conventional materials. As a result, low-velocity impact damage is usually complex and involves several damage mechanisms, such as local permanent deformations, matrix cracks, delaminations, fiber fractures, and interface debonding [22,23].

Research over the past two decades has been focused on how composite structures perform after being subjected to various impact loads (single, repeated, and multiple impacts). Concerning single impacts, there are two general types of impact damage to FRP composite structures: those that penetrate completely (as with a high-speed impact) and those that do not (such as low- velocity impact) [23]. Most realistically, however, are events consisting of multiple or repeated impacts rather than of a single impact. When composite structures are placed in service conditions, they may be repeatedly struck by low energy impacts, resulting in progressive matrix cracking, delamination, and fibre fractures [23]. Here, a single impact on a composite component may not result in any damage, but the accumulation of damage caused by multiple or repeated impacts may substantially increase the probability of reducing the FRP’s load bearing capacity and, therefore, the likelihood of unexpected failures [24].

Despite this, only a limited amount of studies have been conducted about impact fatigue, repeated impacts or multiple impacts on composite structures relative to the extensive amount of studies that deal with single low-velocity impacts. Of these studies in literature dealing with repeated impacts, most are devoted only to testing the impact fatigue of FRP composites, and determining the corresponding damage progression [17,25–38].

While this research on impact fatigue and repeated impacts on composite structures has provided valuable insights in particular

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Table 1
Terminology for impact, consistent with mechanical fatigue.

Mechanical	Description	Impact
Mechanical fatigue	Phenomenon of damage induced by repetitive nature of events at levels below failure strength resulting in permanent structural changes, loss of load bearing capability and/or potential failure	Impact fatigue
Load cycle	Complete sequence of single event, where load is applied mechanically or through impact until that load is (fully) relieved	Impact
Cyclic loading	Repetitive occurrence of (loading) events	Repeated impacts
Multiple load cycles	Occurrences of (un)connected (loading) events	Multiple impacts
Fatigue damage	State of damage induced by cyclic loading or repeating impacts	Impact damage
Fatigue life	Number of loading or impact events that lead to failure	Impact fatigue life
Fatigue limit	Largest load cycle or impact energy that can be infinitely repeated without resulting in failure	Impact fatigue limit
Low-cycle fatigue	Phenomenon where limited number of events induce significant damage	High impact energy fatigue
High-cycle fatigue	Phenomenon where large number of events induce limited damage	Low impact energy fatigue
Proportional loading	Multiple loading or impact contribute together consistently to the development of damage	Concentrated impacts
Non-proportional loading	Multiple loading or impacts each contribute to (potentially) unconnected damage development	Distributed impacts

through experimental characterization, further study is required. Not only, because additional numerical simulation can give a better understanding of this behavior under repeated impacts being an affordable alternative to highly time-consuming and costly experimental efforts [24], but particularly because the field is yet incomplete. While the research area regarding single and repeated impact resistance of composite components seems sufficiently complete, a theme like distributed impact is still at a very early stage.

Although many review articles and even books have been written on impact properties of composites [19,20,39–51], a comprehensive evaluation of the field of impact fatigue is non-existent. The authors believe that a review article covering this scenario of impact response has significant value to the composite community, both scientists in academia and the engineers in industry, as it highlights gaps in knowledge and research paths forward. It should be noted that the list of main papers reviewd in this article are listed and compared in Tables 2–4 in the Appendix section.

Therefore, this paper first defines a consistent terminology to structure and categorize the research area to put it into a broader context of fatigue and damage tolerance. Subsequently, pertinent literature on impact fatigue, repeated impact, and multiple impact properties of FRP composite structures is reviewed, enabling the identification of the key technical problems to be solved in the future.

2. Terminology, definitions and categories

To develop understanding of how damage develops under repeated impacts, also known as impact fatigue, a terminology is proposed in Table 1, consistent with what is known as mechanical fatigue. Where in mechanical fatigue the repetitive or cyclic nature of mechanical loading is considered, here the repetitive nature of impacting should be considered.

In addition to the above consistent terminology, the investigations on repeated impacts can be categorized into distinct cases, illustrated in Fig. 1:

- Case I: Repeated impacts at a single point of the target essentially considers impact fatigue, a material characteristic (as geometry effects are excluded) usually referred to as "impact fatigue".
- Case II: Repeated impacts at various locations of the target builds on case I, introducing target plate geometry effects
- Case III: Repeated impacts at two locations addresses interaction phenomena between these locations, viewed from the material fatigue perspective of case I (no geometry considered)
- Case IV: Extends case III to multiple impacts at any point of the target plate (combining material, interaction and geometry) representing 'multiple' impacts at multiple locations

Following the logic of the four cases in Fig. 1, the present article reviews all literature on repeated impacts in an attempt to better highlight research gaps.

3. Case I : "Impact fatigue" considered as material characteristics

Degradation of mechanical properties of a material or a component

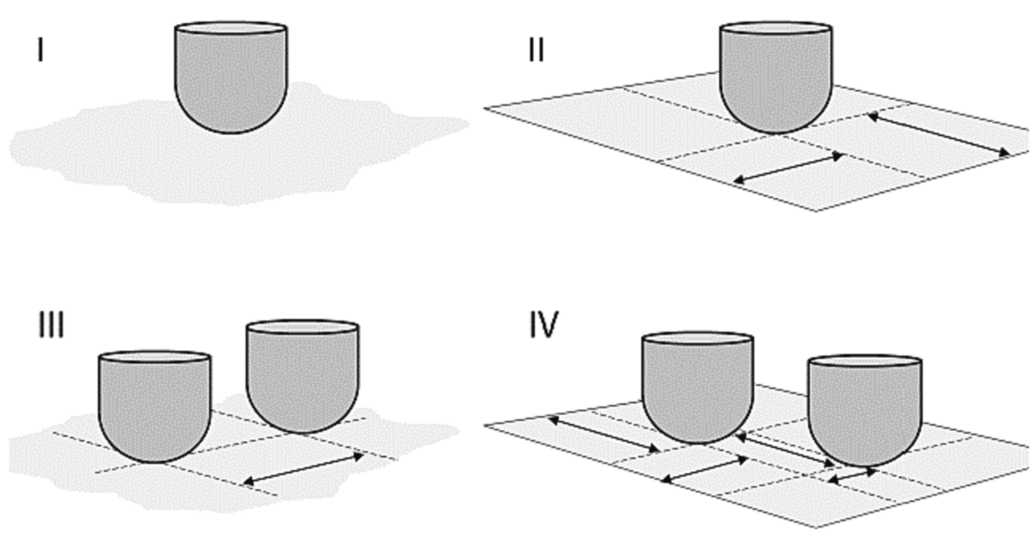

Fig. 1. Categorization of repeated impact: Cases I and II evaluate single location impacts as material characteristic and geometry induced, respectively, while Cases III and IV evaluate the interaction between multiple impacts as material characteristic and geometry induced, respectively.

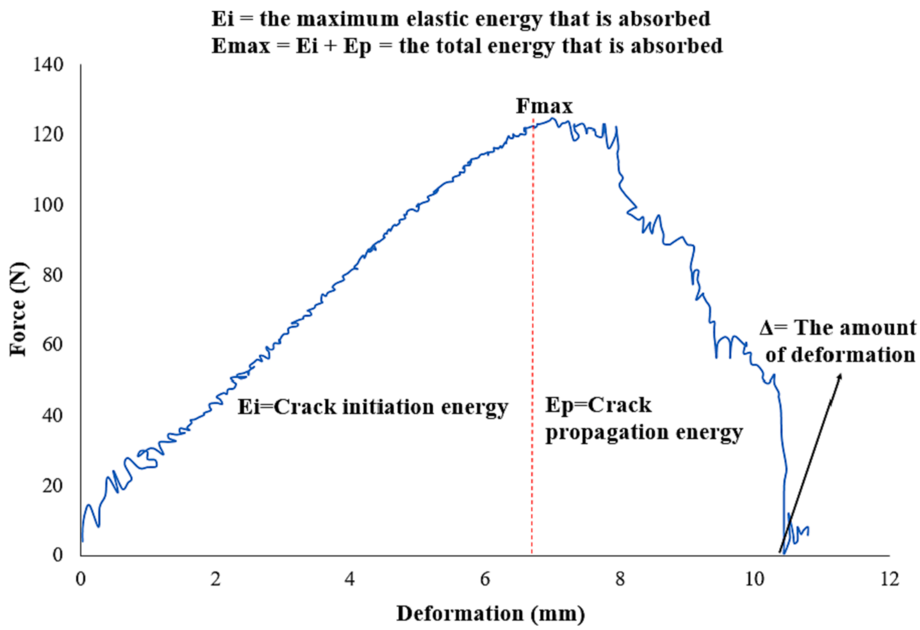

Fig. 2. Instrumented impact test parameters related to force-deflection (UD carbon fibre reinforced PEI) [60].

under cyclic loading is generally called "fatigue" [52]. Similarly, repetition of low-energy impacts, with each impact being insufficient to cause the total failure of a structure or component, is known as "impact fatigue" [53]. When a specimen or component is subjected to repeated impacts it may develop one or more cracks and eventually break into pieces. It is then said to have failed by impact fatigue [54]. The strain-rate involved in impact fatigue is about $10^3 s^{-1}$ which is substantially higher than the strain-rate usually used in a conventional mechanical fatigue or tensile tests [54].

Research into impact fatigue started around the same time as standard, non-impact fatigue research, in the middle of the nineteenth century [53]. Over a century ago, "shock fatigue" tests, characterized by a large number of small blows, were used to compare steels' responses to this type of loading with static tests and single-blow tests [55]. It became apparent during that time that impact fatigue differed from both single-impact loading and standard fatigue, and that durability limits (known as 'limiting resistance') did not exist [53]. Since then, the impact fatigue field has received significantly less attention than that of the standard, non-impact fatigue. Further, the concept has not been seriously incorporated into design standards. There are probably a number of reasons for this. Uncertainty in the choice of loading parameters is one. Standard fatigue testing uses the stress amplitude, which is related to Wöhler's S-N diagrams (i.e. stress versus number of cycles) in stress-controlled fatigue testing [55]. A maximum stress magnitude is rarely the only parameter to be considered when performing impact fatigue tests since, depending on the loading conditions, and particularly the impact velocity, this parameter may correspond to different levels of applied energy. Therefore, different authors have used various loading parameters in their studies.

The specific way impact fatigue manifests itself in different types of materials is another reason for this. It is a result of the interaction of impact energy levels, contact durations, and damping properties, resulting in a specific type of spatial localization of stresses and their decay with distance from the contact zone. The linkage can vary depending on the specimen geometry, the fixture, and the impact-induced deformation kinematics [53].

Laminated composites fail due to the sequential accumulation of damage during static and fatigue loading. The standard impact fatigue experiment involves repeatedly striking the sample with a hammer until it fractures [54]. All strikes are recorded during the experiment to determine deformations, energy absorption mechanisms, and impact forces. It is still not understood how composites fatigue under dynamic loading despite ongoing research.

It is especially important to determine the potential accumulated damage on airplane bodies that are subjected to many small impacts during their service lives. Have the damages reached the point where they can be considered as a catastrophic failure risk? The current airworthiness certification process does not consider impact-fatigue in order to predict composite material lifespan; neither is there an adequate model to predict impact-fatigue for composite materials [56]. On the other hand, the mechanical fatigue loading can be modeled in different ways. In the early studies of composite fatigue behavior, fatigue life and stiffness loss were primarily measured under mechanical fatigue loading [35,57,58]. It is common to use the fatigue ratio (the ratio of strain at fatigue limit to static fracture strain) to quantify the fatigue degradation of composite materials. Low energy levels are less likely to damage the laminate, but internal damage may well occur when the laminate is repeatedly loaded. The result has been a setting of "zero growth" requirements, under which no damage to the material is possible if impacts upon the material are below a certain strain level [12,59].

The investigations of impact fatigue properties of composite materials are first discussed with respect to the following typical impact sequence aspects: Force-time/force-deflection, impact energy, damage (delamination and crater), residual properties and impactor geometry and mass effects. Afterwards, the effects specifically related to the target material properties will be discussed.

3.1. Force-Time or Force-Deflection

In determining the impact characteristics of materials, it is critical to analyze force-time or force-deflection curves. A sample of the latter is shown in Fig. 2. As the hammer impacts the sample, the contact force between the sample and the hammer rises sharply up to a maximum value and then decreases gradually. Dropping the contact force down to zero in F-d diagram means that catastrophic failure (fracture) has occurred. Under the force-deflection curve, the total area represents the maximum impact energy absorbed by the target. Generally, there are two dominant regions in such curves. The first region characterizes crack initiation, while the second region describes crack propagation.

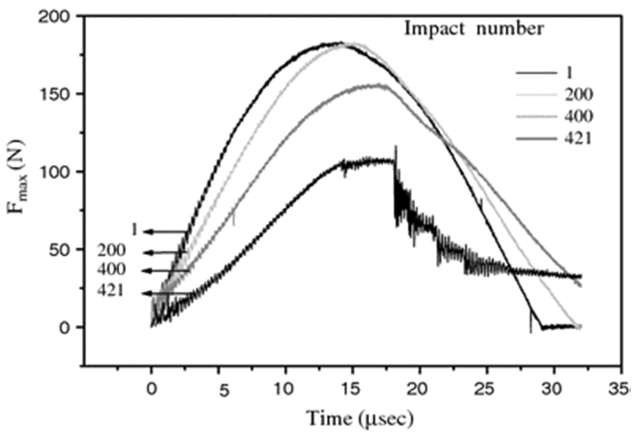

Fig. 3. Impact response of samples subjected to repeated impact loading with an impact energy of 0.35 J (UD carbon fibre reinforced PEI) [61].

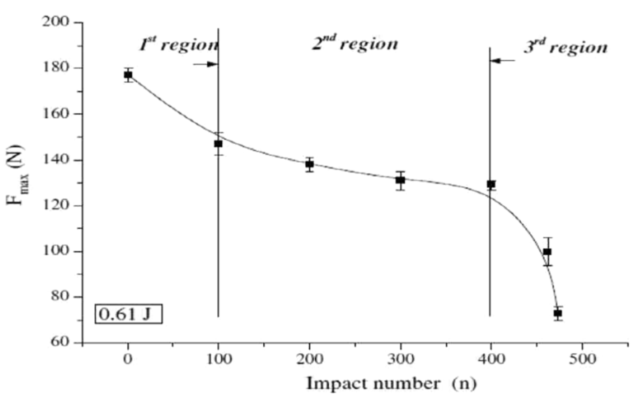

Fig. 4. Variations of F_{max} values during the impact-fatigue experiments (UD carbon fibre reinforced PEI) [62]

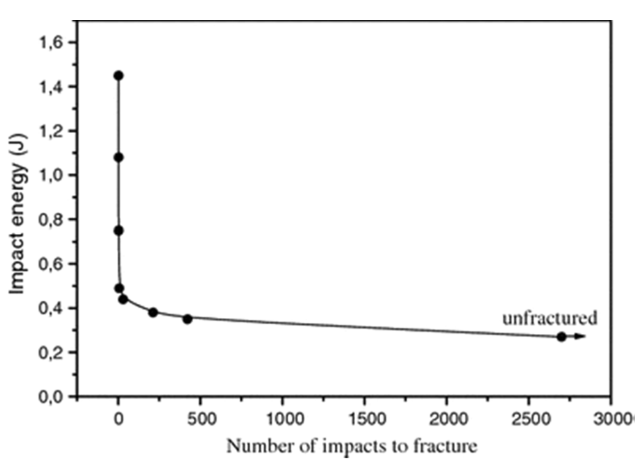

Fig. 5. The impact energy of hammer and number of impacts to fracture relationship(UD carbon fibre reinforced PEI) [61].

Under each region, the areas quantify the absorbed energy for crack initiation and crack propagation processes, which are defined as Ei and Ep, respectively. A sample's inertial oscillations are responsible for the spikes in the first region. In Fig. 2, Δ values represent the amount of the deformation at each impact.

3.2. Impact energy

The first important parameter in investigation of impact fatigue is the level of impact energy which is allied with another principal factor the impact number. Damage to composite materials due to repeated impacts is substantially affected by both of these factors.

A systematic study of impact fatigue behaviour of the composite laminates implies to start with the single impacts on the targets at various impact energies [61]. The lowest impact energies do not create any damage within the samples and the symmetrical F-t or F-d curves are appeared which represent the typical elastic deformations. In this range of impact energies, achieved maximum forces (F_{max}) are increased by increasing in impact energies. At higher impact energies, the symmetry of the F-t curves disappears and some sudden drops appear due to damage phenomena within the laminate [60]. The energies which cause fracture in the target leads to minimum contact time compared to those without failure in the samples [61].

Repeated impacts are then used to subject the specimens to impact fatigue. During impact fatigue experiments, the maximum number of impacts to fracture is obtained at minimum impact energy levels [62]. A sample of force time curves in this stage is shown in Fig. 3. which was obtained from impact–fatigue experiments, where the impact energy was 0.35 J [61]. With increasing impact number, the maximum contact force and slope of curves decrease [17,60,61]. Fracture occurs at 422nd impact on this sample. It is noteworthy that no crack initiation was observed at 0.35 J at first impact. Despite not having a crack initiation, the sample fractured following a typical impact-fatigue failure.

Most curves representing various impact fatigue results in the literature were observed to have three regions. The curves exhibiting these three regions are:

- Displacement after each impact in terms of impact number [60].
- Maximum impact force against number of impacts [62].
- Maximum impact force against impact energy [61].
- Impact duration in terms of number of impacts [63].
- A measure of damage based on impact number [25].
- Crater diameter in terms of impact number [21].
- Crater depth in terms of impact number [21].
- Delamination area in terms of impact number [21].
- Normalized (crater & delamination) surfaces in terms of life fraction [21].
- A measure of bending stiffness based on the number of impacts [64].

As a typical result, these 3 regions in the curve of F_{max} in terms of impact number is reintroduced in Fig. 4 [62]. At a given impact energy level, the maximum force F_{max} reduces over successive impacts, illustrating three regions. Initially, F_{max} values drop sharply due to fibre fracture in the compression zone. With the compressive strength of the carbon fibre reinforced polyetherimide composite lower than the tensile strength, composite material initially deforms in compression zone during repeated impacts (Fig. 4). In this zone, the carbon fibres exhibit micro buckling and shear deformations, illustrated by the many kinked fibres within the compression zone. These fractured fibres cause a sudden drop in F_{max} values during the impact-fatigue experiments, in what is labelled as 1st region in Fig. 4. The 2nd region in Fig. 4 can be called the "plateau region" where the F_{max} values remain approximately constant. In this region, initiation and propagation of matrix deformations and multiplication of delaminations occurs, as reported by Azouaoui et al. [25]. In this region after a certain number of impacts under the same impact energy, the phenomena of delamination saturation happens. No remarkable fibre cracking occurs. In the 3rd region, the F_{max} values decrease sharply again, because of fibre fractures in the tensile zone. Finally, the samples fully fracture at the end of this region with a minimum F_{max} value.

An impact above a certain critical incident energy E_c usually produces a significant delamination in a material. This damage increases

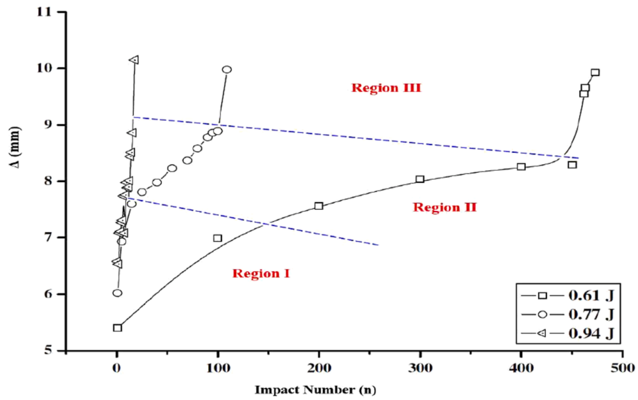

Fig. 6. Variation of deformations during impact fatigue experiments at different energy levels (modified) (UD carbon fibre reinforced PEI) [60].

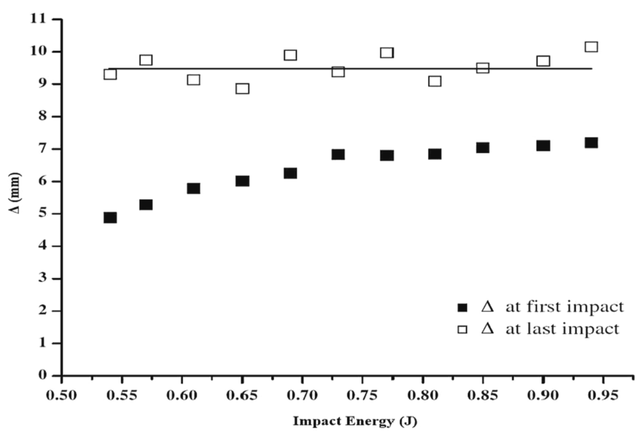

Fig. 7. Effect of impact energy values on initial and final deformations (UD carbon fibre reinforced PEI) [60].

with successive impacts. When the impact energy is higher than E_c, the first impact causes the first and biggest damage, while subsequent impacts cause less damage through incrementing the existing damage [65]. This process develops with each impact until the plate is perforated. The number of impacts required to perforate the plate decreases with increasing impact energy, as illustrated in Fig. 5 [61]. It is more likely for a perforation to be caused by multiple impacts than if only one is made. For a higher impact energy, the damage is also distributed over a larger area, and the perforation seems cleaner as well [65].

Fig. 5 essentially shows a S-N type of fatigue curve for the composite material, where the endurance limit is reached with an asymptote at an impact energy of 0.27 J, where no crack initiation was observed after 2801 impacts [61].

The level of impact energy influence the maximum deformation obtained, described by Δ in Fig. 2. This is illustrated in Fig. 6 [60] where at high impact energies the first, second and third regions converge to a narrower band (a limited number of impacts) compared to low impact energies. The transition from one region to the next occurs very rapid at high energies (0.8 and 0.9 J) while at lower impact energies (0.61 J) a significantly wider 2nd region is observed. While final fracture in 3rd region remains abrupt due to progressive fibre breaking, reducing the impact energy increases both 1st and 2nd region.

This similarity abrupt failure in region 3, corresponds to a similar maximum deformation at failure, as illustrated in Fig. 7 [60]. While final impacts (at fracture) show approximately the same deformations, the deformations are remarkably lower at low impact energies. Hence, at lower impact energies, there are greater differences between the initial and final deformations, resulting in greater 1st and 2nd regions [60].

3.3. Delamination area

A rather important feature in impact fatigue investigations is the evolution of the delamination area. This delamination appears in glass-epoxy composites as a white circular surface in the center of both faces of the plate, because the material is translucent, and it becomes opaque during delamination [66]. Delamination area can be depicted in terms of impact energy, impact number and cumulative impact energy (Fig. 8) [66]. At low energy level, it is observed that delamination propagates slowly even with the increasing of impact number (Fig. 8a). The delamination area varies significantly more when the energy level is higher. Also, delaminated surfaces are much more obvious when the number of impacts is large. According to Fig. 8b, the variation of delamination surface grows in a quasi-linear manner with low impact number, while when the energy level is greater, its slope is more apparent [66].

A projected area of delamination is depicted in Fig. 8c as cumulative impact energy increases [66].Multiplying the impact number by the incident impact energy yields the cumulative impact energy added to the specimen. Similar to the results discussed according to Fig. 6, here again three distinct zones can be observed for low impact energies. i.e. a rapid increase at first, followed by a slower growth of delaminated area and finally an acceleration of damage until the total failure of the sample. In other words delamination is thought to absorb a large portion of cumulative impact energy in phases I and III, whereas deceleration noted in the intermediate phase II indicates that the delamination energy is less significant. That is due to during the second phase, other types of damage (mainly, punching of impacts surfaces, crater expansion, matrix cracking at opposite faces, etc.) as well as the bending elastic strain of the plate absorb the energy "lost" through delamination. Despite the relatively low impact number, delamination propagates rapidly at higher impact energies (Fig. 8c)

3.4. Crater expansion

Another parameter reported in impact fatigue literature is the evolution of crater expansion. Usually, crater is defined as a semi-hole damage due to punching the impacted face. Essentially, people identify two factors: crater diameter and crater depth. Azouaoui et al. [66] reported that by cyclically punching the impacted face, crater diameter seems to experience a linear evolution, while for crater depth, exponential growth was observed. However, the variation of depth-to-diameter ratio relative to the number of impacts offers a better understanding of how crater dimensions evolve relative to each other (Fig. 9) [66]. The following two phases are discernible:

- First, the ratio of crater depth-to-diameter grows linearly according to a shallow slope, which is lower for lower impact energies. Consequently, the diameter of craters increases much faster than their depth.
- Secondly, the significantly steeper linear evolution of depth-to-diameter ratio indicates that depth increases faster than diameter, which explains the imminent perforation of the plate. This phenomena occurs earlier for higher impact energies.

3.5. Residual properties

Researchers are interested in investigating the residual tensile and compressive strengths of specimens after repeated impact [67]. Multiple impacts progressively increase the material's damage and decrease its residual strength. In addition, impacts with higher energies, which do not puncture the specimen in an impact, cause more degradation than several lighter impacts.

Further, the surrounding area is less damaged by a plate perforated at a high energy than by a plate perforated in a series of impacts with less energy.

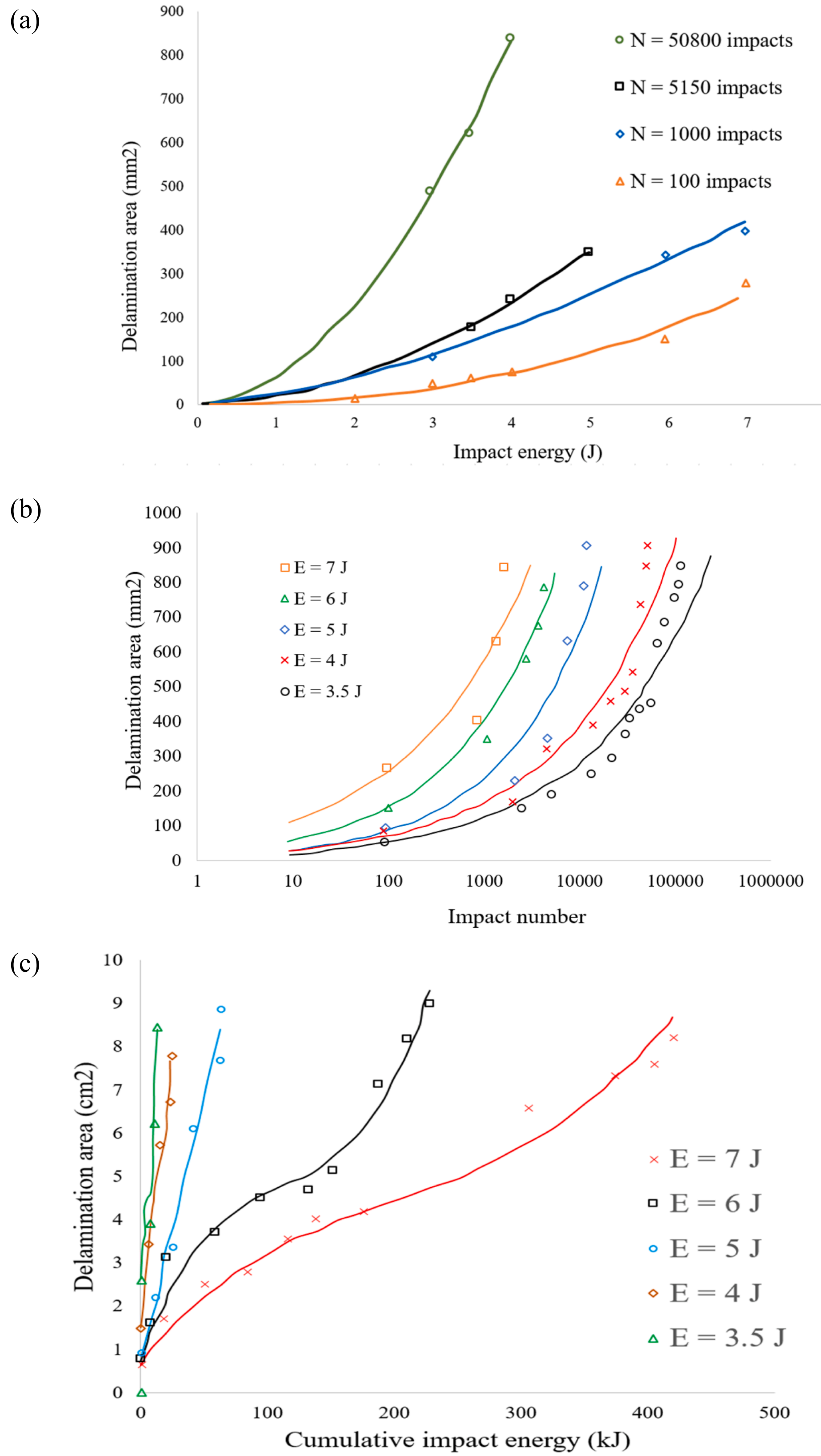

Fig. 8. Evolution of delamination area according to a) energy level, b) impact number, c) cumulative impact energy(UD glass fibre reinforced polyester) [66].

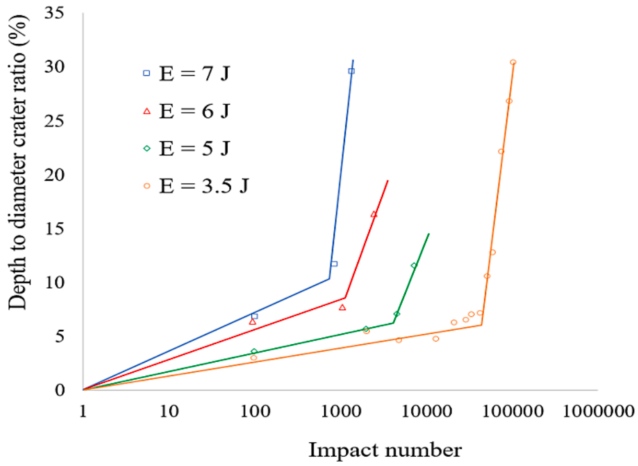

Fig. 9. Evolution of crater depth to diameter ratio according to impact number (UD glass fibre reinforced polyester) [66]

When the damaged zone is present in the test specimen, the residual tensile strength of the composite is degraded. However, damage resulting from a few very light impacts does not affect the residual tensile strength.

An apparent threshold energy exists below which the tensile strength will not degrade during a single impact [67].

As the number of impacts increases, the tensile strength degrades as well. In spite of low impact energies, below the single impact threshold energy, residual tensile strength degradation may begin after several impacts. A few impacts can achieve perforation at intermediate impact energies, resulting in an extreme loss of tensile strength. Once the impact energy reaches a certain level, a single impact will perforate the specimen and severely reduce its tensile strength.

Upon perforation of a plate, the residual tensile strength appears to be essentially the same, regardless of whether the perforation results from several impacts or a single impact.

As opposed to tensile strength, compressive strength is almost completely unaffected by damage, no matter how light [67].

The compressive strength decreases with increasing impact energy, and this drop is significant for even very light impacts.

The compressive strength of the material decreases with increasing impact number, with the initial impact causing the greatest degradation. The incremental degradation in compressive strength decreases as the number of impacts increases. In a similar manner to the observed behavior of tensile strength, a single impact at a high energy yields greater strength loss than many smaller impacts.

It appears that the number of impacts on a perforated plate affects the compressive strength much more than the tensile strength.

It is common to report the residual strength, modulus, and toughness properties in literature. In terms of residual strength, 3 regions can be observed in Fig. 10 (a). Lower numbers of impacts do not affect residual strength, but as the number of impacts increases, there is a gradual decline, followed by an abrupt decline.

For residual modulus and residual toughness (Fig. 10 (b) & (c)) there is a shallow but continuous drop when the number of impacts increases, without initial plateau. If the residual properties continue to decline even after reaching the endurance limit, this indicates that there are a

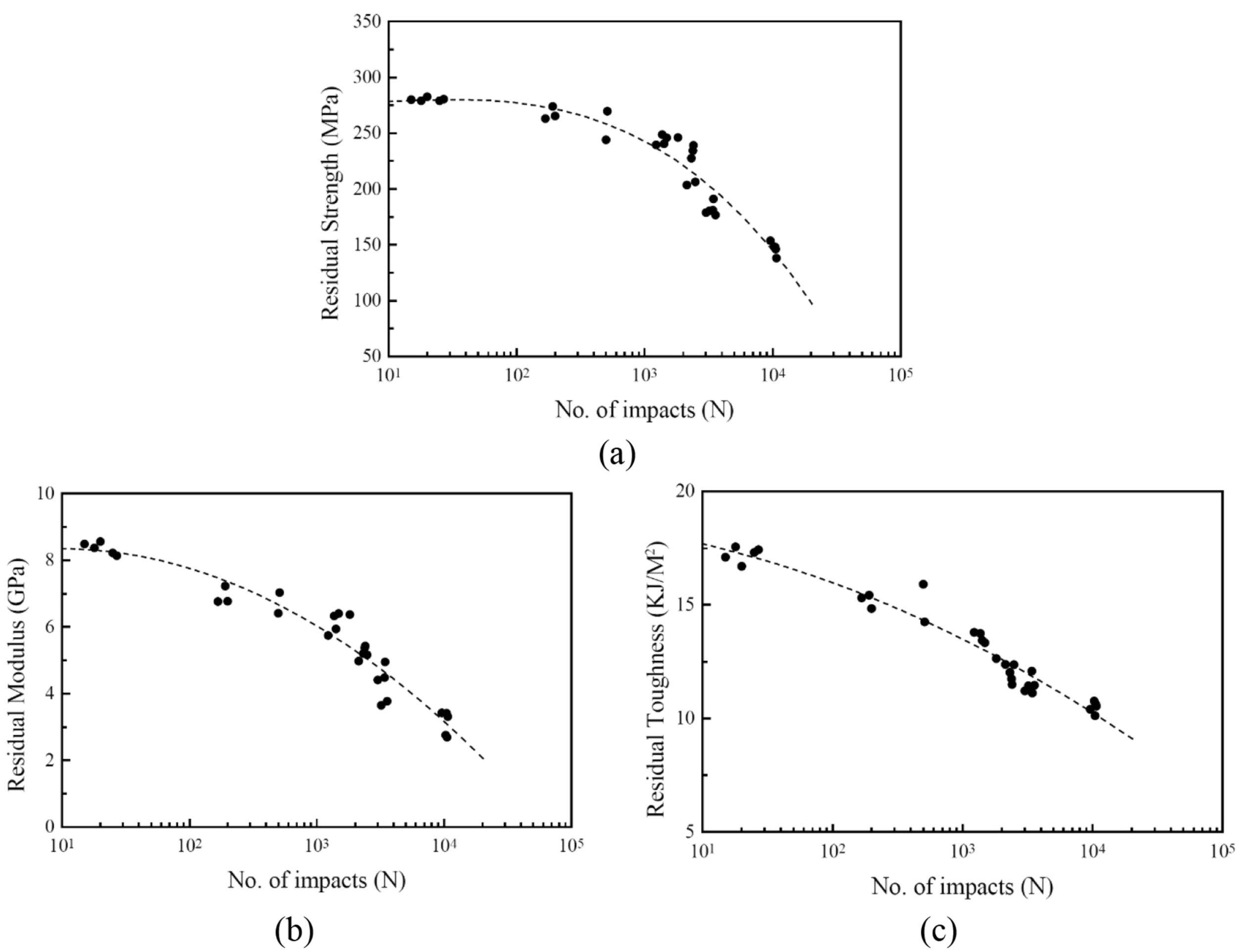

Fig. 10. Residual strength (a), residual stiffness (b) and residual toughness (c) of GFRP (glass fibre reinforced vinylester) –12 composite after impact fatigued [35].

large number of microcracks and weakened fibres that influence the residual properties by damage accumulation.[35].

An investigation of residual impact strength of carbon/epoxy laminates after flexure loading [68] demonstrates that the degree of initial damage has a significant effect on the impact parameter values, i.e. the impact strength of laminates subjected to repeated low velocity impact loads depends strongly on the damage caused by different bending loads.

3.6. Impactor geometry and mass effects

Impact response of the specimen depends on many factors, including the size, mass, shape, material, and angle of incidence of the impactor [5].

A few results have been published on the impactor's effect on repeated impacts. The number of drops to failure of laminates reduces with heavier impactors at low impact energies. Further, the effect of impactor mass was observed to diminish as the incident impact energy increased [69].

In force-time and central displacement-time, the same three regions may be observed, namely the delamination damage threshold at first impact, the constant impact force plateau and the large drop in impact force, regardless of impactor diameter [64]. It has been shown that regardless of impactor diameter, the first impact reduces bending stiffness due to matrix cracking and delamination, however, for impactors with larger diameters, a constant plateau of bending stiffness can be observed for impacts by impactors with larger diameters. Upon fiber breakage, the bending stiffness significantly decreases. When absorbing energy gradually decreases to its lowest value, a steady plateau is also reached for larger impactors due to less damage per impact. The following is increased energy absorption due to fiber breakage. Peak impact force shows opposite characteristics to energy absorption. Fiber breakage causes the duration time and maximum central displacement to increase significantly for larger impactor diameter.

For impacting tips with hemi-spherical impactors with a large tip diameter and relatively low impact energy, the twin ellipse damage shape is evident while for other shapes the damage started to appear with the cross-like shape delamination. [23]. In addition to the impact energy, the shape of the impactor tip plays an important role in determining structural residual life. Reduced diameter hemispherical impactors cause higher local stress concentrations, which in turn leads to a decrease in the residual life of the impacted composite structures. An interesting fact to note is that the number of impacts to failure for hemispherical impactors with the smallest diameters is comparable with that obtained for structures subjected to impact loads with impactors with sharp tips. As a result, although varying the sharpness of the impactor enhances the penetration of a GFRP structure, it does not have a major effect on damage propagation.

4. Parameters studied in literature for Case 1

Concerning the properties of target plate materials, first the constituent properties are evaluated (i.e. reinforcement material and resin material), after which the aspects related to material architecture are discussed (stacking sequence, stitching concepts, laminate thickness and laminate hybridization). This section continues with addressing the influence of manufacturing methods, and ambient temperature and ends with impact energy division effect.

4.1. Influence of material properties

Impact dynamics and residual strength of laminates can be significantly influenced by the properties of composite materials. A matrix's properties, reinforcements, and interface all contribute to impact resistance. As examples, fibers with high strain-to-failure values, tougher resin systems, compliant layers between some plies, or woven or stitched laminates enhance impact resistance [5].

4.1.1. Reinforcement material

From literature, it is clear that fibers with higher failure strains provide better impact resistance of the composites to high impact energy levels [39,70].

Reinforcement type's effect was demonstrated for repeated low-velocity impacts with the three most common types of reinforcements used (glass, carbon and kevlar) [71]. The slope of curves of peak load versus number of impacts (N_f) and total energy versus N_f are increasing with the reinforcement's stiffness. Similarly, as a result of damage propagation (delamination followed by fiber breakage), energy absorption increases continuously during subsequent drops. However, the N_f at which total energy drops inversely relates to the fibre's stiffness. For example, under repeated impacts, Kevlar composites showed greater delamination than glass composites with the same incident energy [71], and carbon fibre laminates have a lower resistance to repeated impacts than glass fibre laminates [72]. Evidence of this is reported in the response curves of laminated structures to impacts, the greater damage area and the tendency for repeated impacts to damage the laminate structure. Propagation of damage resulting from repeated impacts is caused primarily by damage that occurs during the initial impact. Furthermore, in comparison with aramid and carbon fibers, glass fabric composites performed better due to the finer fibers, resulting in a higher area coverage [73]. For the reason it is relevant to consider the anisotropic character of carbon fibers and aramid fibers compared to the isotropic properties of glass fibre.

4.1.2. UD, 2D and 3D reinforcements

Continuous fiber reinforcement can be categorized into three basic types: unidirectional reinforcement, 2D fabrics, and 3D fabrics [26]. Most commonly, these basic architectures are stacked and consolidated to form composite laminates. There has been extensive research on laminates that contain unidirectional reinforced layers [74–77]. 2D fabrics come in many shapes (plain weave, satin weave, twill, 2D braid), but they all feature fiber interlacing and undulation. Several studies reported examining these materials [57,78–80]. Delocalized energy absorption can also be achieved by means of other reinforcement geometries. Three-dimensional textiles include stitched laminates, 3D orthogonal weaves, 3D braids, and angle-interlock weaves [81]. Research on the mechanisms of damage and energy transfer between these materials, as well as their dependence on striking velocity and energy, is in its primary stages illustrated by the limited amount of literature [26].

There are distinct modes of failure for 2D and 3D fibre architectures composite systems under repeated drop-weight impact loading [26,82]. Unlike 2D laminates, the 3D systems display a greater radial spread of damage; this result is related to fiber straightness [38]. Compared to a 2D plain-woven fabric with undulating interlaced rovings, straight fibers are quickly placed in tension when they are under a transverse load. When the 3D systems starts to perforate, debonding extends to the test panel's edges. In comparison to 2D laminated systems, 3D laminates survived more strikes before perforating, and they absorbed more energy in total due to the straining and fracturing of the z-tows damage mechanisms. According to the areal density normalization, 3D systems are more damage tolerant than 2D systems because of the 3D reinforcement geometry's unique damage mechanisms. Three-dimensional orthogonal weaves are found to be strained significantly on the z-axis. There are often fractures in these tows, and surface weft tows are often pulled through unbroken crimps of the z-tows. Z-crimps fail under tension and the surface weft slides across them under friction, which are new, significant sources of energy loss.

Totally, 3D architectures can be both energy dissipative and provide better perforation strength than conventional 2D laminate [82].

4.1.3. Resin effects

The threshold kinetic energy is strongly dependent on the matrix properties, and largely independent of the fibers, the layup, and whether the layers are woven or unwoven [5]. Incipient damage is dominated by matrix and interface [83], when a matrix crack reaches an interface between layers with different orientations, delamination initiates [5].

Both types of polymeric matrices, i.e. thermoset and thermoplastic, are used extensively in composite industry. Similar to single impact loading, the resin type plays a critical role in repeated impact responses. A study comparing thermoplastic and thermoset matrix composites [84] revealed that the impact perforation energies are similar for both systems. In thermoplastic matrix composites, the contact force is less than half that of thermoset composites, but due to its low bending stiffness and deformability, it absorbs energy equally. Deformability as a result of delamination increases the absorbed energy. The vitreous structure of thermoset can cause fiber damage in connection with early deformation, making that fibers cannot transmit stress through their body, resulting in damage propagating in the impact direction. Thermoplastic matrix composites can be a good candidate to resist repeated impact conditions, such as wave impacts.

Self-reinforced laminates made of polypropylene (PP) has attracted more attention in repeated impact investigations [78–79]. Polypropylene self-reinforced tapes exhibit strain hardened failure mechanisms, where elongation at break is relatively high (>20%) at impact strain rates, therefore, plastic deformation is predominant during penetration impacts, with localized “star”-shaped holes as result [85]. In higher impact energies, transition from plastic deformation to fibre fracture reduces fatigue life of the specimen. Furthermore, the main factor contributing to the increase in peak load and decrease of deformation induced by each impact is strain-hardening.

When plastic deformation is caused by successive impacts, absorbed energy decreases, but when tape breaking begins, absorbed energy increases. This result is contrary to what was previously observed by researchers using thermosetting composites [85,86].

4.2. Stacking sequence

It is known that composites with configuration $[0/90/+45/-45]_s$ exhibit greater number of impacts to failure (N_f) and more substantial final failure area than corresponding cross-ply composites $[0/90/0/90]_s$[87]. This is attributed to the difference between angles of layers and presence of 45° layers. Stacking sequence affects the CAI strength greatly. Also, composites repeatedly hit with low energy have lower CAI strength as a result of the greater delamination area. The preference of symmetric laminates have also been reported in other articles [63,88].

Based on their findings, the fibre orientation of the top laminates dictates the surface crack pattern, indicating matrix cracking and fiber-matrix interface rupture. In contrast to the symmetric laminates, large surface indentations on cross-ply and non-symmetric laminates are easily visible by naked eye, well before failure occurs. The safety of these two configurations can therefore be inspected with respect to the impact scenarios analyzed.

4.3. Stitching of laminates

Stitching of GRP laminates under single-impact loading causes a slight reduction in flexural strength but a large reduction in interlaminar shear strength [89].Upon repeated impacts, laminates developed a significant decrease in flexural strength due to fracture of glass fibres. Stitched laminates are somewhat more likely to be damaged by single or repeated impacts. In contrast to other impact studies on stitched composites, a research [90] reported that stitching did not improve impact damage resistance, post-impact flexural strength, or interlaminar shear strength of GRP. This conclusion can, of course, change depending on the stitching density.

However, usually, stitching limits the damage size. For example 40 repeated impact at energies up to 30 J was sustained by all laminates (stitched and unstitched), whereas stitched laminates sustained more repeated impacts at 40 and 50 J in comparison to unstitched laminates [90]. In terms of stitching density of laminates coarser densities are able to withstand more impacts.

Multi-axial stitched fabrics that are thick and high-performance reinforcements are used for large-scale composite structures. A 3D impact damage model for multi-axial stitched CFRP was presented by Saito and Kimpara [91].

4.4. Laminate thickness

The flexural stiffness of a laminate is affected by many factors, such as the material properties, the laminate thickness, the lamination process, the laminate’s size, and the boundary conditions [5]. Accordingly, the thickness affects the maximum contact force and, therefore, the extent of damage induced [5].

Thicker samples require more impacts in order to penetrate [92]. The flexural stiffness is defined both by thickness and panel dimensions, smaller sized impact samples can be combined with interlaminar shear strength determination tests to assess the post-impact strength retention properties [86].

Under a certain level of energy, however, it appears that the laminate cross section comes into play as the most significant variable that affects impact resistance [73]. Regardless of the fiber used to reinforce the laminate, all experimental points below this certain energy level fall on a single curve in this case. The increase in resistance to repeated impacts is also influenced by the fibers and the distribution of the fibers used for the analysis at the higher energy level. As the thickness increased in the perforation case, single impacts under higher energies resulted in greater damage areas than repeated impacts due to localized fiber fracture rather than delaminations [93].

4.5. Hybridization

An efficient method to improve composite properties is to hybridize the layup of the laminate. There are two main ways to hybridize: one is to combine different fibre types, and the second is to combine metal and composite layers in one laminate; called as Fiber Metal Laminate (FML).

a. Different fibres

Hybridization of glass and graphite layers was observed to be effective in reducing accumulation of damage[94]. Additionally, the manner in which a hybrid composite is laid up influences how much damage accumulates. When compared to a hybrid specimen with graphite-epoxy skins, a hybrid specimen with glass-epoxy skins will survive the double amount of successive impacts [94].

b. Fibre metal laminates

Despite the fact that considerable effort has been devoted to analyzing the low-velocity impact behavior of FMLs [41], there are only a few articles discussing the repeated impacts’ response. The aluminum layer plays an important role in these hybrid laminates. FML failure in glass fibers was never observed at low velocity impact before cracking of the outer aluminium was observed. Hence the aluminum plate acts as a sacrificing layer [95]. The metal layer’s strain hardening effect also improves the laminate’s behavior.

Due to the degradation of FML, peak loads, impact energies, and failure strain decrease with increasing number of impacts [95–97].

A comparison of CFRP/AL and GFRP/AL performances with monolithic aluminum plates of the same thickness shows that monolithic aluminium plates provide higher load bearing capacity, however the Al plates also exhibit a greater capacity for energy absorption due to spreading the damage throughout the plate [96]. In fibre metal laminates, the damage is concentrated, resulting in a lower capacity for absorbing energy. Impact damage zones become larger as the number of impacts rises, irrespective of the specimen system, however, different shapes are observed around the point of impact, such as ring, round, or diamond shape petalling in the FML specimens.

Under repeated impacts, damage occurs as follows: plasticity of matrix with delamination and yielding of aluminum; disbonding at the interface between composite and aluminium; fracture of composite layers followed by thinning, shear fracture and cracking of aluminium; penetration of laminate and petalling of aluminum [98]. The high elastic tensile strength of the glass–epoxy plies enabled them to resist several impacts before they were perforated, despite delamination growth in the vicinity of the impacted area. Aluminum layers that are damage tolerant prevent a projectile from penetrating the plate and prevent delamination from expanding. In this way, the structural integrity of GLARE is preserved until the aluminium at the non-impacted side begin to crack.

Two repetition sequences in a unique investigation have been tested on Glare laminates [99]. First, there were successive impacts with the same energy, but lower than the first one. During the second sequence of impacts, follow-up impacts were based on the rebound energy of the preceding impact. Such impacts would reflect drop weight impacts. 'Threshold energy' describes the amount of energy required to produce no further damage after the first impact. With repeated impacts between the threshold energy and the first impact, damage propagation was observed. Structural integrity was not affected by successive impacts with impact energies below the threshold. Dropped tool sequences showed that rebound energies are not a significant factor and damage propagation caused by rebound energies is negligible.

In terms of the effect of impact angle on Glare limited results in the literature [100] reveals that impact angle significantly influences GLARE's dynamic performance. Impact processes slow down as the angle of impact decreases. Alternatively, as the impact angle increases, the aluminum layers' plastic deformation, maximum impact force, energy absorption, and composites' damage increase. Therefore, perpendicular impacts (i.e.,90° impacts) are the most dangerous.

4.6. Manufacturing methods

A single study by Belingardi et al. [101] studied the repeated impact response of glass reinforced laminates when two manufacturing processes were used: hand lay-up (HL) and vacuum infusion (VI). Although both laminates react similarly before perforation, the HL specimens survive more impacts before perforating, absorbing more energy when the impact energy is sufficient to perforate the laminate.. Also, the delamination area grew most in the first impact in both test series and for all impact velocities being considered. Delamination areas are saturated from the first impact for VI specimens, and follow closely the behavior of bending stiffness against impact number. Also, the rate of accumulating stable damage is not significantly different for HL and VI specimens at the same impact energy.VI specimens, however, sustain fewer impacts before developing unstable growth.

4.7. Temperature effects

The temperature effects' researches can be divided into low and high temperature conditions and their comparison with the behaviour at room temperature.

There have been relatively few reports of composite material experiences of repeated transverse impacts under low and high temperatures [102]. Variations in impact characteristics, such as maximum deflection, contact duration, and absorbed energy values, result as the temperature changes[103].With decreasing temperature, the perforation threshold, contact force and total failure area increase. However, both room and low temperatures produce similar total failure areas at low impact energies. In terms of high temperature and multiple low-velocity impacts there has been reported [104] that absorbed energy is higher for laminates impacting at ambient temperature than those impacting at 65° C. At 85 °C, laminates are reported to absorb more energy than at 65° C, but still far less energy than measured at ambient conditions. In UD specimens, this is the result of the brittle to ductile transition. Delamination failure mode, regardless of temperature, increases with an increased number of impacts at 65° C. Damage accumulation may also decrease at 85° C due to the increased number of impact events.

4.7.1. Postcuring

In addition to many investigation of influencing of curing agents in the impact properties of FRP composites (e.g. [105], the postcuring effect has been assessed only in one reference in terms of two parameters: (N_f) (number of impacts) and dA (delamination area growth) [106]. An optimal postcure schedule can be found for increasing the (N_f) and dA values. Through these investigations, a relationship can be established between impact damage tolerance and the chemical cure status of the composite.

4.7.2. Aging

There is a dearth of literature addressing the age-related impact response of composite materials [107]. The degradation of material properties may significantly deteriorate polymeric composites' damage resistance after aging. Also, damage resistance is significantly affected by the aging environment [108], hygrothermal ageing causes more target deformation and a longer contact duration during low velocity impact test [109].The correlation between increasing damage area and increasing aging duration has been found in repeated impact response of composite laminates exposed to thermal aging, especially for smaller impact energies [107]. In unaged samples, the total absorbed energy is approximately three times the absorbed energy in samples exposed to temperature and humidity. When thermal aging is applied, there is a substantial variation in the impact characteristics like energy absorbed, peak contact force, maximum deflection, and contact time for successive impacts until the sample is perforated.

4.8. Electric current effect

Quantifying the effect of the electric current on composite laminates subjected to multi-impacts was performed in [110]. As a result, it is possible to conclude that unidirectional laminates are much more sensitive than cross-ply composites when exposed to an electric current. After being exposed to electric current, an overall decrease in maximum load and elastic recovery can be observed, regardless of the lay-up. However, displacement shows an opposite trend. Due to the higher pre-damages caused by the thermal stresses in unidirectional laminates, the exposure time also played a role. A higher ply number leads to lower temperatures, and, therefore, thicker samples are less sensitive to the effects of the electric current as compared to cross-ply composites. In addition, it is also possible to conclude that an electric current exposure decreases the life of the impact fatigue as a result of the severity of the pre-damage induced.

4.9. Impact energy division effects

There is an idea about how a single impact compares to multiple impacts involving the same total energy. This idea has been followed

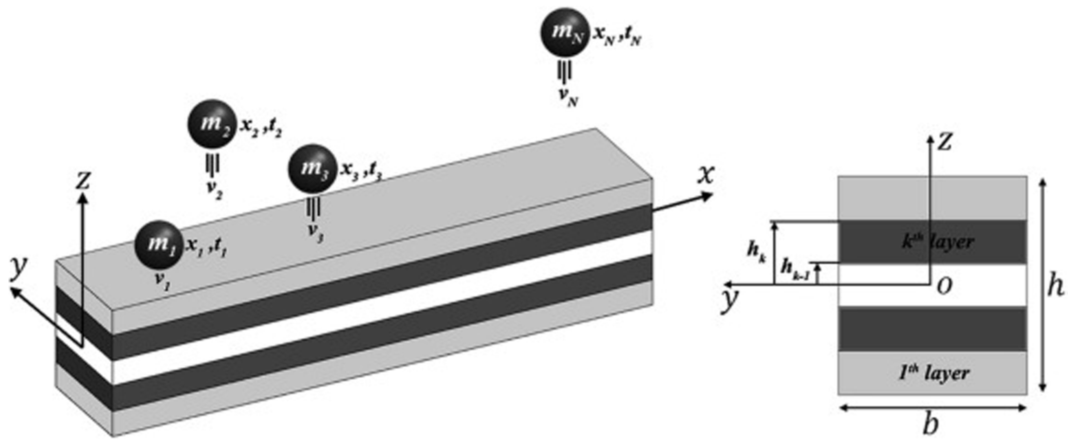

Fig. 11. Geometry and coordinate system of laminated uniform beam and multiple impactors [126].

when the targets are FML or FRP.

After the impact energy is divided into two quantities, the FML target responds stiffer in the second impact due to the elastic-plastic characteristic of the layers of metal, resulting in strain hardening and the creation of the dent, thus increasing both the area of contact and the stiffness of contact [111]. Thus, the contact time in the second impact is shorter regardless of the level of energy in each impact. In contrast, the maximum force is highly dependent on the impact's energy level. If the energy level of the first and second impact is equal, the stiffer behavior of the second impact will lead to an increase in peak load. Energy is absorbed more when the primary energy is split into two lower energies. Neither impact energy division nor its sequence affect debonding between the aluminum layer at the bottom and the composite layer above it. Specifically, this type of failure only occurs in repeated impact arrangements where there is a pre-debonding region between the aluminum bottom layer and the composite layer. First impact energy determines whether a crack is created in the aluminum layer underneath. Moreover, the energy of the second impact must be sufficient to separate the upper aluminum layer from the composite layer [111].

Similarly, dividing of 3 J impact energy to three 1 J or to 1 J + 2 J in [112] depicted that the only impact of 3 J is more damaging than the cumulative damages caused by division cases. The numerical results revealed that for three impacts of 1 J, damage generally remains constant. In contrast, the cumulative damage resulting from the 1 + 2 J series of impacts is inferior to that caused by a unique 3 J impact event.

5. Case II (Repeated impacts at various locations of the target builds on that addressing target plate geometry effects)

In literature only a few studies address impact locations other than the plate centre, while that may create more severe damage. This seems peculiar as many types of impacts can occur during manufacture and use of composite structures near the edge (transverse) or on the edge (in-plane) [113].

A study tried to provide a summary of the effects arising from the impact at various locations of laminates to see how damage results [113]. Different damage mechanisms were found depending on where the impact occurred. Impacts on the edges of composite laminates (in-plane) are less damaged, but they suffer a higher rate of fibre failure. Maximum forces are almost identical for near-edge impacts (transverse) and central impacts. There is a higher energy absorption for the central impact and a lower energy absorption for the on-edge (in-plane) impacts, likely due to the wider deformation area around the central impact. Indeed in this part, the lack of investigations on repeated impacts is obvious.

6. Case III (Repeated impacts addresses interaction phenomena between two impact locations, from a material fatigue perspective (no geometry considered))

There are some investigations on the effect of double impact positions in low velocity impact on composite laminates [114–118].Here, the main research questions are the effects of impact spacing and the impact energy on the damage response of the laminate. Impact distance and energy level affect the impact behavior and damage mechanisms of FRP laminates in different ways. Both impacts have a strong correlation with the impact distance [118], with a greater distance, the mechanical response curve had weaker correlation and higher coincidence. Furthermore, the relation between the two impacts could be explained directly by the separation degree between the two damaged areas. Peak impact force and total energy dissipation are diametrically opposed for different impact energies, which can be explained by the effect of the first impact on laminate stiffness and the main type of damage in the laminate after the two impacts. After the two impacts, there is an overlapping state in the damaging region associated with the distance between the impacts, and the damage modes are dependent on the energy of the impacts in the overlapping region.

Due to the fact that the two impacts are interacting, the second impact's delamination initiation threshold is lower than the one in the first impact and even none appears, since the initial delamination damage caused by the first impact allows delamination propagation to be more stable in the second impact [114]. Due to the reduction in bending stiffness caused by the first impact, the second impact caused the maximum displacement to be larger than that of the first for two interfering impacts. When the impact distance is 0 mm, the energy dissipation for the second impact is less than that for the first impact at low impact energy with dominant delamination damage, while it is the opposite effect at high impact energy due to fiber damage caused by impact. In addition, the values of the peak energy moment for the second impact are greater than those for the first impact, as the two impacts interfered [114].

As a result of the experiments [115], the Z-Pinning method is unable to limit the initiation of delamination at low impact energies, resulting in similar delamination conditions at double impacts as those at which laminates are not pinned. On the other hand, Z*pinning suppresses delamination damage and internal defects at high impact energies, thereby reducing damage interferences. For Z*pinned laminates with high impact energy, the critical impact distance as critical interference state was less than it was for unpinned laminates.

During repeated impacts on fibre metal laminate (GLARE), the metal layer plays a key role, and its importance is apparent when considering the distance between impact locations. Before cracks appear, a decrease in impact location distance increases plate stiffness. Due to cracks, however, the reduction in impact distance leads to a loss of plate stiffness. In order to predict damage, repeating impact at the same location can provide a good estimate for perforation and first cracks. A single intermediate location is sufficient for constructing the relation between these parameters and the distance. The intermediate location, however, is critical to the degree to which damage is linked up. At zero and infinite separation distances, damage link-up does not occur [117].

When a plate is subjected to multiple impacts, the fiber architecture and z-binding yarns play a significant role in determining the severity of the damage and how it propagates [116]. A non-crimp fabric within a laminate that is repeatedly struck at different locations is more susceptible to growing and connecting the damaged areas than a 2D plain weave fabric due to the waviness of the individual plies. As a result of the Z-binding yarns in 3D woven composites, the damaged area is localized and the impact regions do not interconnect. Additionally, non-crimp fabrics exhibit the deepest dents in comparison to 2D plain weave and 3D woven composites.

Also, the multi-impact response of glass-epoxy composite laminates with open holes was studied [119]. To evaluate the effect of holes on damage development, plates without any holes and those containing one or two holes were tested under low velocity multi-impact loading. Based on experiments, it was demonstrated that the maximum load and dissipated energy decrease with the number of impacts, while displacement increases for all cases. Moreover, holes were found to have a significant influence on those parameters.

7. Case IV (multiple impacts at any point of the target plate (combining material, interaction and geometry) representing as ‘multiple’ impacts at multiple locations)

In applications where multiple impact sequences are expected, repetition of impact does have its relevance. In aviation, examples include the primary structures that are subject to hail impacts and the cargo floors that are subject to luggage impact. In the case of subsequent impacts, the observed damage progression may result in perforation below the energy determined for single impacts. A multiple impact situation at a single site could exaggerate the issue, since impacts would most likely not occur at exactly the same location [117].

However, all of the above mentioned studies in “cases 1 and 2” of this paper concentrated on the low velocity impact at a single point of composite laminate. These studies focused on single-position impacts and ignored the damage interference that occurs from multiple impacts. By focusing only on single-position impacts, real problems may be exaggerated. For example, in reality, the area delaminated by two consecutive hailstone impacts at the same location is much smaller than that delaminated by two hailstone impacts at two independent locations [120]. Multi-impacts take place at different places and at a certain distance from each other. Multiple low velocity impacts on different locations have not yet been examined in depth for their mechanical characteristics, such as impact force, peak energy and maximum central displacement. Thus, it would be more relevant to study the mechanical responses and damage mechanisms of low velocity impacts at different impact positions, which are not extensively explored in the current research.

8. Analytical investigations

Analytical modelling of multiple and repeated impacts on composites beams and plates is based on the extension of the analysis of single impact on a target [121]. The analytical solutions of single impact on simply supported, specially orthotropic rectangular laminated plates, that were originally developed by Dobyns [122] and Christoforou and Swanson [123] may be extended for multiple impacts [121]. In Christoforou and Swanson’s work, they developed an equilibrium equation between the plate and the impactor and then by using Laplace transform techniques the equation was solved to find the contact forces. The response of the plate was calculated using Equation (1):

$$w(x,y,t) = \frac{ab}{uvm_1}\sum_m\sum_n \frac{P_{mn}}{\omega_{mn}} Sin\frac{m\pi x}{a} Sin\frac{n\pi y}{b} \times \int_0^t F(\tau) Sin\omega_{mn}(t-\tau)d\tau \quad (1)$$

In this equation, m_1, is the mass of the plate, ω_{mn} are its natural frequencies, and P_{mn} depend on the size and position of the loading area [123]. When multiple impacts are applied after the first impact, the laminate response can be obtained from equation (l) by substituting time t_{1e}(when the first contact is lost) in place of the upper limit of the integral. The contact force in the convolution integral is then known, and Equation (1) can be solved in closed form. Up to the beginning of the second contact, this solution is valid. As in the previous contact, a solution can be provided during the second contact. A new time coordinate is calculated from the beginning of the second impact in order to simplify the solution. It is then necessary to add the laminate response from the first contact into the equation for the equilibrium between impactor and laminate. Following the operations in Refs [123,124], the solution can be obtained. Subsequent contacts can be handled in a similar manner.

In terms of multiple impacts with multiple masses, the theory should allow impactors of different masses to strike the beam at arbitrary locations on its top surface with different velocities at different distances from the origin [125]. As a key feature of the theory, the laminated beam and impactors are treated as one system. Using this concept, the contact forces are regarded as internal forces of the system. Higher-order shear deformation theory representing the displacement field of laminated beam may be applied. In order to satisfy the boundary conditions, simple polynomials are used as the shape functions. By means of a modified contact law, the interactions between the beam and the masses of the impactors are described. The Lagrangian equation of motion is used to obtain the governing equations for the system.

The theory developed for multiple simultaneous impacts can be extended for the analysis of low velocity asynchronous/repeated impacts as was followed by Sisi et al [126]. Locations, times, masses, and velocities of impacts are arbitrary (Fig. 11).

According to their results, positive and negative superpositions of induced waves propagating in a beam will impact the structure by their time of impact due to non-simultaneous impacts. As the time interval between impacts is increased, the first impact will have constant results. So, for a critical time interval between impacts, the second impact is not able to affect the first.

The same procedure discussed above was followed to evaluate the response of carbon nano tube-reinforced composite plate (NTRC) under simultaneous multiple impacts [127]. Comparing the CNT’s profile distributions, the one that CNT is connected in the top and bottom planes shows the shortest contact duration, the highest maximum contact force and the lowest maximum lateral deflection.

9. Numerical modelling

To understand the dynamic behavior, stress–strain response, and degradation mechanisms in composites subjected to repeated impacts, numerical simulations are needed in addition to experimental studies. In addition to the high time and cost of experimental campaigns, the exact numerical simulation allows for design purposes that cannot be answered by the trial-and-test approach [24]. Despite that numerical simulations can save time, most of the numerical studies tend to focus on modeling composite laminates for a single impact, rather than repeated impact. To numerically model multiple or repeated impacts, the literature presents two approaches. The first approach involves developing a 3D finite element algorithm along with suitable delamination initiation criteria and the second category has been followed by using FEM software and integrating certain subroutines. In both approaches, similar to the theoretical attempts, the numerical models developed for the repeated impacts are the extension of works related to the single impact on the targets. Multiple simultaneous impacts and sequential repeated impacts can be included in this extension.

Following the first approach, a transient dynamic FE analysis using the Newmark-β method and Hertzian contact law, as well as an algorithm to determine the response of laminated plates under multiple impacts have been developed.[128]. This research utilized the Choi's et al.[129,130] impact induced delamination criterion for assessing delamination initiation at the interface of the laminate.

In the second approach of numerical investigations of repeated or multiple impacts LS-Dyna 3D and Abaqus/explicit are the most applied softwares.

LS-Dyna 3D software maybe used to simulate impacts and to gain into failure modes, energy absorption and damage prediction [131,132]. One of the main extension in applying LsDyna 3D software to simulate repeated impacts is to select the distances of the projectiles apart from the target when they are fired simultaneously or sequentially to minimize computational time and interaction between stress waves.[131].

For the analysis of single and multiple impacts on (GLARE) using LS-Dyna it is necessary to write a user subroutine for material performance gradual degradation method using a failure-judgment method[132]. Using the Johnson Cook Plasticity Model (J-C)[133], the stress-strain relationship in the aluminum alloy sheet of GLARE is analyzed during impact, whereas, for composite layers, there is considered many kinds of failure modes by applying Hou's strength failure criterion [134]. A Kermanidis' proposed material-property degrading mode also should be applied [135].

Numerical investigations maybe conducted using ABAQUS/Explicit as well [24,100,136,137]. In applying ABAQUS Explicit a user-defined subroutine (VUMAT) is developed to construct a progressive damage model for laminates based on a continuum damage model, the 3D Hashin failure criterion and the damage evaluation model based on equivalent displacement..

As two parts of the impact damage prediction, "Progressive Damage Model (PDM)" for a lamina (intralaminar) and "Cohesive Zone Model (CZM)" for interfaces (interlaminar) are used in applying ABAQUS Explicit. Among three commonly used models: failure-criterion-based model, fracture mechanics model, and cohesive zone model [138], the last one which uses strength-based criteria and fracture energy criteria to describe damage initiation and evolution is used in recent studies. The PDM consisting of a CDM, 3D Hashin failure criterion (or the Puck failure criterion[139]) and the damage evolution model based on equivalent displacement is coded in the user-defined subroutine (VUMAT). CZM (usually bilinear traction-separation relationship) is applied to simulate the delamination in the laminates[24,136]. In ABAQUS/Explicit, a general contact algorithm is applied to simulate the contact events in the model. Multiple single impacts can be assumed as a repeated low-velocity event. After the analysis step is reached the predefined time period, the simulation of a single impact process has been completed, and all results are stored in a file. The restart technology in ABAQUS then imports the result of the previous impact into the next single impact as the initial condition.

For FML composites, max stress, 2D Hashin, and 3D Hashin failure criteria have been compared for accuracy and efficiency in predicting damage behavior [100,140]. It was concluded that 2D/3D Hashin criteria are more accurate than max stress criteria for low-velocity impact simulations. Despite its superior accuracy, the 3D Hashin criterion has the lowest efficiency.

Further, repeated impacts on patch-repaired laminates analyzed using ABAQUS/Explicit has shown that the accumulation of damage under repeated impacts was found to be closely related to the dissipation of interlaminar energy[137]. Under repeated impacts, the degree of damage accumulation of patch-repaired laminates can be reflected by the degree of delamination damage. Patch-repaired laminates accumulate damage in relation to the evolution of interlaminar damage.

As a useful technique a multi-step concept may be used to simulate the repeated impacts [24]. The striker hits the plate, causing it to undergo a loading–unloading process. The next step is to introduce artificial damping to the model to mitigate the oscillations and residual elastic vibrations. The plate is then subjected to the next impact load and the sequence is repeated.

As a closure to this section, let's refer to [121] which provides an estimation of the accuracy of composite shell elements that require less computer resources compared to three-dimensional elements. The limitations of shell elements include the inability to represent wave propagation in thickness direction, which results in very inaccurate responses in the contact region. A very short wave can also not be transmitted by the element. Although deficiencies were observed [141], composite shell elements may achieve accurate results in transient analysis involving flexural and shear wave propagation for specially orthotropic laminates. It is accurate in problems with a limited number of natural frequencies, as well as in impact problems with relatively low contact stiffness. Despite a high number of natural frequencies being excited in the impulse loading problem, it was reported that the elements can achieve pretty good results. When multiple impacts occur, accuracy begins to deteriorate. Additionally to the number of natural frequencies and the size of the smallest wavelength, the accuracy can be affected by composite parameters. As previously reported in [141,142], they observed some errors in amplitude of the $[45/-45]_n$ laminate.

10. Conclusions

In the past 25 years, many attempts have been made to illustrate and answer questions about the effects of repeated impacts on composites. Most studies essentially considered impact fatigue a material characteristics, because geometry effects are excluded in the single impact location. Although the results have accumulated a wealth of knowledge and data, the other 3 cases have not received much attention and no consensus has been reached on best practices. What has become clear is that:

- Similar to fatigue in general, repeated impacts on a material eventually degrade the material to the level of failure at energy levels that are considered insignificant in single impact events. The lower the impact energy, the more impacts are required to cause failure, while below a certain energy threshold, infinite life may be achieved.

Similarly, dividing single impact energy over two successive impacts, the cumulative damage is inferior to the single impact event, because the absorbed energy is higher in multiple impacts.

- Similar to mechanical fatigue in composites, three regions can be identified in the impact fatigue scenario: first impacts create obvious damage in matrix cracking, delaminations and/or fibre fracture, followed by a plateau in which damage increments marginally under successive impacts, with a third region rapidly developing damage and fibre fracture towards failure. An initial gradual decrease in residual strength, stiffness, and toughness will be followed by a sharp decline as the impact number increases.
- The composite lay-up has a considerable effect on the impact fatigue performance; symmetric lay-ups perform better than asymmetric or unidirectional lay-ups, while hybridizing the lay-up with metal layers, substantially improves the impact fatigue life.
- 3D material architectures generally improves the impact fatigue performance, introducing additional ways of energy absorption while suppression of particularly delamination growth. While stitching usually limits the damage development, the performance depends on many factors, including stitch density.
- Ambient temperature influences the impact fatigue performance; the perforation threshold, the contact force, and the extent of damage increase as temperature decreases. At elevated temperature, less energy is absorbed compared to room temperature. Similarly, the total energy absorbed in unexposed plates is substantially higher than in thermally exposed plates.

However, impact fatigue is not only a material characteristic, in which one impacts on a single spot on the plate repeatedly; in reality multiple impacts may occur within each other's vicinity, or in vicinity of stiffening elements, imposing more significant damage growth compared to single spot impact fatigue. This implies for the research on impact fatigue that

- When plate flexure is suppressed by stiffeners, less energy is absorbed than in a plate's centre, imposing more damage,
- The distance between two impacts influences the damage formation, a damage link-up, and plate's stiffness as consequence. This influence strongly correlates to the impact energies of respective impacts. In the analysis of impact fatigue, the first impact can be considered as a single impact on the plate, where the laminate's response can be recorded as the initial conditions for the second impact. It is then possible to predict the onset and propagation of damage by applying appropriate failure criteria. However, full analytical assessment of multiple simultaneous or asynchronous impacts towards damage growth is still in its infancy.

11. Recommendations for future works

- Depending on whether impact fatigue can be considered a single- or multi-spot problem, analysis of repeated impacts should consider the interaction of damage initiation events, rather than only damage increment. Also geometrical aspects comprising effects of flexural stiffening by clamping or reinforcing structural elements should be studied more explicitly. In case of distributed impacts, one should consider damage link-up between two adjacent impact damages and its influence on plate response.
- In the theoretical evaluation of impact fatigue, numerical evaluation should be considered more cost-effective to unravel the influence of the multiple parameters involved in randomly distributed impact fatigue. However, experiments are expected to remain necessary to demonstrate validity of theories.
- While the division of impact energies between subdivisions has received more attention. Despite this, the sequence of these divisions, particularly when they are impacted on different locations, needs further investigation. It may be necessary to design tests and perhaps some statistical models to combine variables like energy divisions, impact points, and other impactor and target configurations.
- In spite of the fact that repeated oblique impacts may not cause more damage than normal impacts, it is necessary to check the level of damage if the horizontal component of impact force is combined with pre-tension in the sample. The pre-tension should also be studied independently.
- Finally, extending investigations of low velocity repeated impacts to high velocity impacts can be a new area of research. The penetrated or unpenetrated samples in the first impact and its residual strength can be different inputs for subsequent impacts.

CRediT authorship contribution statement

Mojtaba Sadighi: Conceptualization, Writing – original draft, Supervision, Writing – review & editing. **René Alderliesten:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

See Tables 2–4.

Table 2
General Features of Case I (Repeated impacts at a single point of the target essentially considers impact fatigue, a material characteristic).

Refs.	Force-Time/Force-Deflection	Impact Energy	Delamination Area	Crater Expansion	Residual Properties	Impactor Geometry & Mass Effects
[60,61]	✓	✓				
[62,63]		✓				
[64]		✓				✓
[21]		✓	✓	✓		
[25]		✓				
[65]		✓				
[66]			✓	✓		
[35,67,68]					✓	
[23,69]						✓

Table 3
Parameters studied in literature for Case 1.

Refs.	Material Properties			Stacking Sequence	Stitching	Laminate Thickness	Hybridization		Manufacturing Methods	Temperature (102–104)		Electric current Effect	Impact Energy Divisions
	Reinforcement material	UD,2D&3D Reinforcements	Resin Effects				Different Fibres	Fibre Metal Laminates		Post Curing	Aging		
[70–72]	✓												
[73]	✓					✓							
[26,82,83]		✓											
[83–86]			✓										
[63,87,88]				✓									
[89]					✓								✓
[90,91]					✓								
[92,93]						✓							
[94]							✓						
[95–100]								✓					
[101]									✓				
[105,106]										✓			
[107–109]											✓		
[110]												✓	
[111,112]													✓

Table 4
Cases 2, 3, 4, analytical and numerical References.

Refs.	Case II	Case III	Case IV	Analytical	Numerical
[113]	✓				
[114–116]		✓			
[117]		✓	✓		
[118,119]		✓			
[120]			✓		
[121–127]				✓	
[24,109,128–140]					✓

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