A REVIEW OF IMPACT BEHAVIOUR IN COMPOSITE MATERIALS

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Abstract - The damage of composite structure caused by impact events is one of the most critical damages that have been caused several design problems. Understanding damage and failure of composite materials is critical in order to produce a reliable and cost-effective design. Generally, the character of impact response influences the extent of structural degradation and type of damage. Therefore, it is important to identify the properties and physical parameters that determine the nature of impact response. We need to detect, characterise, size and localise the impact damage. This study presents types of damages in composite materials, impact damage and its classification in composite materials.

Keywords - Impact, Damage in composite materials, Acoustic Emission, Composites, Failure,

I. INTRODUCTION

In the last decade, researchers have studied the effects of impact damage on the damage tolerance of composite structures that has been revealed several design problems. Composites are more effective in their performance compared to metals because of its fundamental characteristics. Several distinct features of composite materials make them to be essential materials in aerospace and automotive such as; excellent damping characteristics, light weight, resistant to corrosion destruction and stress-free attainment of complex forms. Understanding damage and failure of composite materials is critical in order to produce a reliable and cost- effective design. Damages in composites can be manifested as matrix cracking, fiber fracture fiber debonding/ fiber pull-out, and delamination. It is important to understand the damage mechanism in order to improve composite design structure and also choose method that minimizes costs of all operations. One of the most critical behaviour in composite structure is damage caused by impact events.

There is several published work that considers about different type of impact on the edge and near the edge of composite structure [1-4] which might produce some severe damage in the center of composite structure [5-8]. Damage refers to the collection of all irreversible changes in the materials brought by a set of energy scattered chemical or physical processes, resulting from the application of thermomechanical loadings. Generally, damage mechanics deals with condition from initiation to distributed changes as well as the consequences of those changes on the response of the material to external loading [9-12]. Generally, the character of impact response influences the extent of structural degradation and type of damage. Therefore, it is important to identify the properties and physical parameters that determine the nature of impact response.

II. COMPOSITE MATERIALS APPLICATION IN AIRCRAFT

A composite material is a combination of two or more constituent materials which produces properties and characteristics and retains their individual characteristics as they act together. One of these constituents is called matrix and the other major components are reinforcement in the form of fibres or particulates to improve the matrix properties. The matrix of a composite can be a polymer, a metal, or a ceramic, and fibre categorised to Fibreglass, carbon, Kevlar, Natural fibre and etc. Composite structures are designed for a purpose; for example if the structure is supposed to work over a period of time, then the design must meet its functionality without losing integrity over that period; or if it expected to carry loads, then the structure must has sufficient load-suffering capacity. Based on the composite materials, designers enable to use optimum combination of resin and fibre reinforcement to develop a material designed for a particular application (Fig.1).
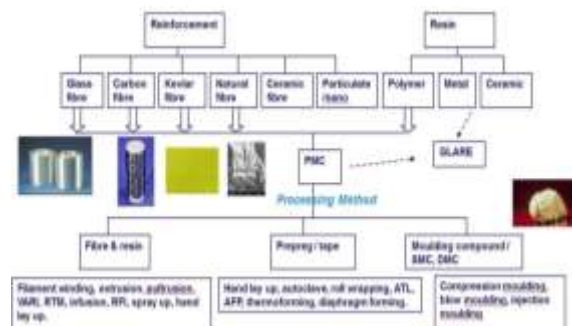

Fig.1. A wealth of design option [13]

Composite offers distinct features such as stiffness and strength characteristics, the absence of corrosion which leads to reduce the cost of the maintenance, low weight, simple design and lower energy consumption. These superior specific features make the composite materials distinctive compared with metals. As the composite structures are combination

of the high strength and low weight, and since in aircraft and space product applications, one of the critical parameters in determining performance is the weight of structures, in the past few decades, the use of composites in structural applications has been increasingly used in aerospace and advanced transportation industries (Fig.2) [14-18].
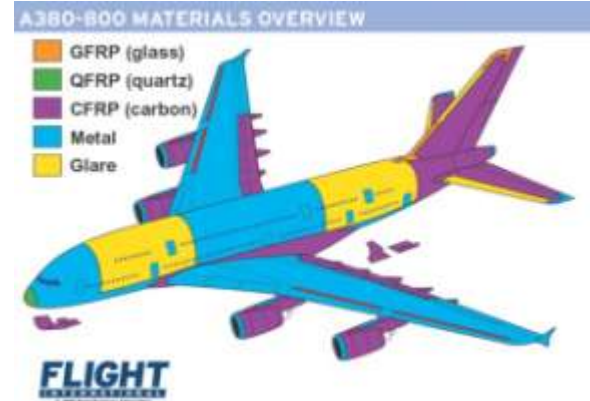

Fig.2. Typical composite structures used in A380-800 commercial aircraft [19]

The early use of composite materials in the aircraft industry dates back to the late 1950s and started with aircraft like the 707 and later DC-9 [20]. In the mid-1960s and early-1970s, due to high performance and high safety standards, composites were developed and applied in the aircraft on the empennages of the F-14 and F-15 fighter aircraft [21]. Carbon replaced fiberglass in the 1970s, although fiberglass was retained for many interior parts and fairings [20]. Carbon/epoxy was used for the speed brake in the fighter aircraft F-15 [22]. In the 1980s, one of the first high-performance composite materials was introduced on the 737 horizontal stabilizers and underwent extensive testing and in-flight evaluations [20]. In the mid-1990s, composite vertical and horizontal stabilizers for the 777 were developed, designed, and implemented into production, gathering the benefits of lightweight structures and improved aircraft performance [20]. In the early 2000 to 2013, composite materials were used in wings, stabilizers and fuselage barrels. Fig.3 shows the percentage of composite materials in airframe since 1940 and Fing.4 depicts evolution of composites application in aerospace since 1970.
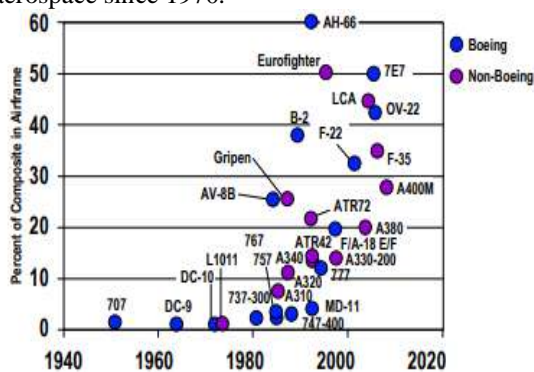

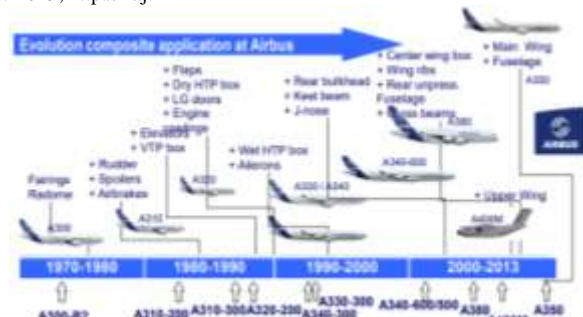Fig.3. The percentage of composite materials in airframe

Fig.4. Growth of the use of composite structure in aerospace [13, 20]

III. DAMAGE IN COMPOSITE MATERIALS

Damage refers to the collection of all irreversible changes in the materials brought by a set of energy scattered chemical or physical processes, resulting from the application of thermomechanical loadings. Generally, damage mechanics deals with condition from initiation to distributed changes as well as the consequences of those changes on the response of the material to external loading [9-12].

Material flaws are the major sources of composite failures. Conventionally, fracture is known as a "breakage" of materials that can be manifest in the basic forms of matrix cracking, fiber-matrix interfacial debonding [23-26], fiber fracture [27-29], fiber pull-out and separation of bonded plies (delamination) [30-32]. Fig.5. shows a schematic description of damage development in composite materials, although five recognizable damage mechanisms are shown on the basis of fatigue experiments [9], it provides the basic details for quasi-static loading as well.
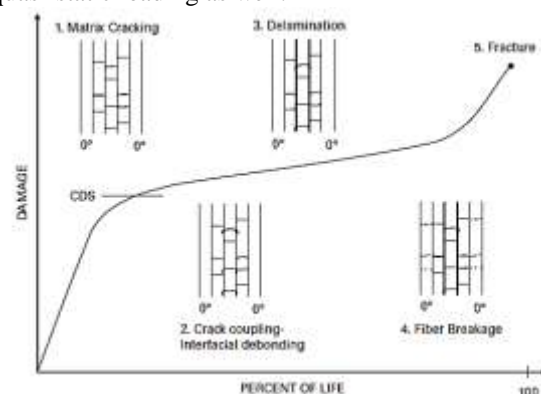

Fig.5. Development of damage in composite laminates [9, 33](characteristic damage state :CDS)

The field known as fracture mechanics deals with conditions for formation and enlargement of the surfaces of the material separation [9, 34-36]. The inability of the materials to perform its design function is knows as a failure. Fracture is one of the examples of possible failure. In reality, the failure event in a composite structure is influenced and ahead of the progressive incident and interaction of various damage mechanisms [9]. If the materials remains

intact and functional and retain adequate properties under loading, it means it contains the structural integrity and durability. Fig.6 presents a durability analysis of composite structure [9].
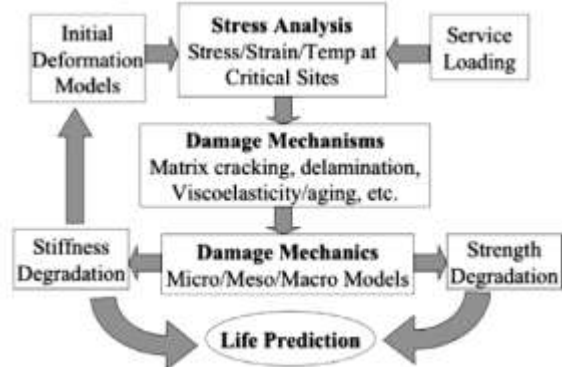

Fig.6. A durability analysis scheme for composite structural components [9]

As described above, damage mechanisms have different characteristics and also have different controlling length scale and evolving when loading is increased; depending on a variety of geometric and material parameters, therefore, in a given life period of a composite structure, which mechanisms is activated, depending on the properties of the base materials (e.g., matrix). The intralaminar damage is observed during the initial stages of the failure process in the form of matrix cracks. Matrix cracking is initiated long before the laminate loses its load-carrying capacity and gradually reduces strength of the laminate and the stiffness [37, 38]. In-service aircraft impact is considered as loads which may lead to an outsized internal damaged area of the laminate that is not detectable from visible observation. Fibres are able to absorb significant amount of energy in which the primary energy absorbing would be passing into failure of impacted composite laminates [39].

Since the structure of polymer matrix composites (PMC) is made of matrix and fibre and it is commonly used in a high performance structural application, and also as an impact responses in those materials, we should not neglect about them because some damages are occurring over time in certain phases [38].

IV. IMPACT ON COMPOSITE MATERIAL

Before discussing about impact behaviour on composite materials, the initial consider to the nature of the composite materials would be helpful. Modern polymer composites based on carbon, glass, ceramic, aramid or polymer fibre in a polymer matrix are anisotropic and heterogeneous materials. They have a high strength and stiffness and low density and therefore excellent specific properties. Generally, materials with matrix properties dependent are much lower than those which are governed by fibre,

however, matrix has an important role in composites behaviour; transferring stress, protecting fibre, and in some cases moderating brittle failure by providing alternative route for crack growth [40] .

The composite material's sensitivity to impact has been assessed widely in recent years. Based on the characteristics of the structure and impactor, the impact response can vary in nature, i.e dynamic, quasi-statics and half-space. Generally, the character of impact response influences the extent of structural degradation and type of damage. Therefore, it is important to identify the properties and physical parameters that determine the nature of impact response. Many studies concerned impact modelling [41-45], damage monitoring [8, 46-48]and the assessment of the post-impact residual properties [49-54].Mylsamy and Rajendran[55]founded the impact resistance value of 1.53 J in agave fibre epoxy composite with matrix crack growth. It has been concluded that good chemical bonding between fiber and an matrix led to improvement of the impact strength, flexural strength and flexural modulus of the composites. Sanjay et al. [56] evaluated the impact behaviour in hybrid composites by comparing laminates with different composition. The highest impact strength with 6J was founded in hybrid laminate. Abdul et al. [57] founded that the higher strength of glass fibers led to higher impact strength in glass/oil palm empty fruit bunches hybrid polyester composites. Hande and Omer [58]revealed that by adding high impact resistant fibres in outer layer, and placing high tensile strength fibres at the inner layer, higher impact values and tensile strength of composite materials can be attained respectively. Generally, we need to detect, characterise, size and localise the impact damage. Characterisation refers to the different types of damages that is induced by impact in the composite materials which is most frequently caused matrix cracking, fibre fracture and delamination (Fig.7) [59, 60].
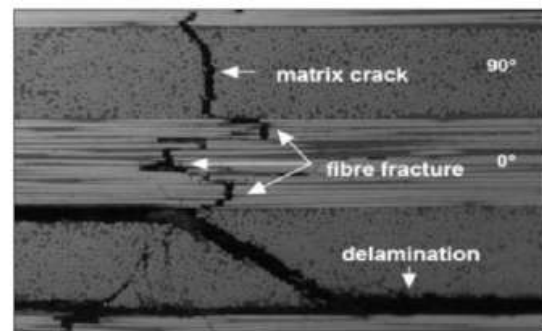

Fig.7. Types of impact damage in the fiber-reinforced laminates [60, 61]

Impact is a dynamic event which may involve a high contact load acting over a small area for a very period of short time [60]. During the operation of a composite structure impact is observing frequently. For instance in high-speed trains the front cab can suffer damage from objects such as birds or other

animals or boulders. Although impact damage is non-visible, it affects the mechanical properties of composite that has to be taken into account and the proper evaluation should be performed.

Determining the effects of impact damage may be divided into two areas:

1) impact damage resistance which is related to the response and damage caused by impact [62, 63] , and
2) impact damage tolerance, associated with the reduced stability and strength of the structure due to the damage [64, 65].

The impact process can be characterised by the velocity of the rocket or the kinetic energy. Composites are sensitive to impact load, as they absorb impact energy mainly through fracture mechanics, rather than elasticity and plasticity [60]. Impact is two or more bodies collision, where the interaction can be plastic, elastic, fluid or any combination of these [66]. One of the fundamental quantities in impact dynamic is impact velocity [67]. Generally, there are four types of velocity [68]:

- Low velocity
- High velocity
- Ballistic
- Hypervelocity

4.1. Low Velocity Impact (LVI)

Low velocity impacts does not always result in the puncturing of the composite and are expected to take place during life of the structure and manufacturing [59]. It can be occurred in the range 1-10 m/s depending on material properties, stiffness and projectile mass. When the time of impactor contacts is longer than the time for the lowest vibrational mode, low velocity impact happens [68]. It occurs with some frequency on composite applications such as airplane components. From ground operations to unavoidable birds, aircraft component may be subjected to unexpected impact loads. In the case of tool dropping, when the impactor has a relatively high mass but low velocity, damage produced is mostly in the form of delaminations, which is not easily visible [69]. Delamination and matrix damage area is proportional to the impact energy in LVI. Tougher materials have higher impact resistance than brittle; the higher toughness the lower delamination and matrix cracking. Typically, delamination occurs between plies of different orientation, and raises in size with thickness and mismatch angle of the plies (typically on 0°/90° or 45°/-45° interface) [70]. Rajesh Mathivan and J. Jerald [71] characterized the type and extent of the damage with different impact velocity in the laminate for a range of thickness. M. Parkesh et al.[72] analysed fiber metal laminate response based on the residual velocity of the impactor. Liu et al. [73] explored the effects of different failure criteria on the dynamic progressive failure properties of carbon fiber composite

laminates. The results showed the consistent energy dissipation and impact responses using three criteria, except some difference in damage features for matrix cracking and delamination [74, 75].

There are several different techniques for testing composites using low velocity impact testing. Table.1 depicts the types of low velocity impact tester that are commonly used in research studies.

Table.1 types of low velocity impact tester [21, 76]

Methodology	Main Function
Ized and Charpy Impact Test	
By placing a notched specimen into a large machine with a pendulum of a weight. The pendulum is raised up to a certain height and allowed to fall. As the pendulum strikes, it impacts and breaks the specimen, rising to a measured height.	i. To test the impact toughness of the material ii. To compare composites with different layups, including woven and unidirectional laminates.
Drop Weight Test	
A mass is raised to a certain height and released, imparting the specimen.	To test the impact behaviour of composite plates.

Both Charpy and Izod impact testing are popular methods to determine the impact strength, or toughness, of a material. The clearest difference between Charpy and Izod methods is the specimen positioning. In the Charpy test the specimen is upheld as a horizontal beam, while in the Izod specimen is placed in a clamp in which the pressure of the clamping is one of the most influential factors in Izod impact strength measurement [77]. Denise et al.[78]performed three point bend, tensile, and Izod impact tests on aligned and continuous piassava fiber reinforced epoxy matrix composites. Jean Igor et al. [79] studied the resistance to impacts of polyester matrix composites and analysed the Izod impact resistance improvement with the inclusion of malva fibers. Glória et al. [80] evaluated the Charpy impact energy of epoxy matrix composites reinforced with up to 30% of giant bamboo fibers. Glória et al. [80] evaluated the Charpy impact energy of epoxy matrix composites reinforced with up to 30% of giant bamboo fibres, and direct relation between incorporated fibre and exponential energy has been revealed. Rajbut et al. [81] used a drop-weight rig (DWR) for testing the impact response of laminated composite materials. González et al. [82, 83] presented finite element simulations of two performed tests in polymer–matrix composite laminates reinforced by unidirectional fibers: the drop-weight impact test and the compression after impact test.

4.2. High Velocity Impact

More severe damages is provided by high velocity impact which could lead to the immediate failure of the material and can be occurred in the range of 10-100 m/s [21]. A high velocity impact (>11 m/s) takes place through sources such as: debris from the runway hitting the fuselage during take-off or landing, ice from the propellers striking the fuselage, hail, and bird strikes [68]. Several applications demand structural survivability against impact by high-speed projectiles. Composites are used in

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aircraft and land-based vehicles as a high survivability materials against impact from turbine blades, wrecking engine parts and other debris [21]. The response of the structural component in high velocity impact is governed by the "local" behaviour of the material in the nearby of the impacted zone. If the duration of the impactor is much smaller than the time period of the lowest vibrational mode to reach the structural boundaries, high velocity impact occurs [68]. Under the low velocity impact and static test conditions damage extends over a wide area and is associated with shear-out damage, whereas under high-velocity impact conditions, damage is highly localised close to the impact zone and it is related to fibre tearing at the rear surface of the target sample and the pull out of material at the frontal surface. . Therefore, in LVI the boundary conditions play a significant role, depending on the projectile-target contact duration [84].

Impactor with velocity up to 2500 m/s, will result in fibre breakage and perforations in specimen, and impactor with speed between 5 m/s and 15 m/s (low velocity impact), or with impact energy in ranging from 0 J to 5 *1025 J, the laminate usually experiences matrix cracking and delamination which is invisible damage [85]. Moallemzadeh et al. [86] described the influence of tension, compression and hybrid preload on E-glass/polyester composite plates under high velocity impact loading in a velocity range of 185 to 235m/s. Delamination and fiber fracture founded as a major fracture modes followed by matrix fracture. On the other hand, Schueler et al. [87] founded no perforation in specimen under impact velocity of 70-105m/s by investigation of the effect of uniaxial compression and tension preloads, on damage behaviour of carbon/epoxy prepreg panels.

It has been determined that material properties affect the composite material performance for both categories; low velocity and high velocity impact [88]. Thus, four different stages based on the effect of the material properties during the impact damage process has been found by Dhakal et al. [89]. Stage 1 showed rapid load increase without visible damage, followed by matrix cracking in stage 2. The matrix cracking in stage 2 distributed rapidly and led to stage 3, which is interfacial de-bonding. In last stage, stage 4 the material experienced fibre breakage, delamination and perforation [90]. F.Chen et al. [91] presented a details of the impact behaviour of different fibre reinforced composites, namely laminates, three-dimensional (3D) woven fabric reinforced and non-crimp fabric (NCF) reinforced composites. In the test result, 3D woven composites showed the best damage resistance and tolerance in low-velocity impact (Fig.8.), while NCF composites had superior damage resistance in high-velocity

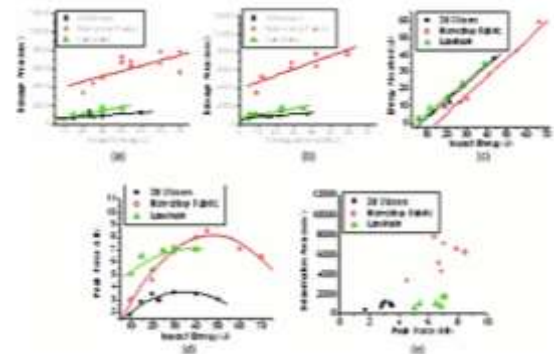impact. Laminate composites have the best in-plane mechanical properties (Fig.9.).

Fig.8. Comparison of three materials in low-velocity impact: (a) damage area versus impact energycurve; (b) energy absorbed versus damage area curve; (c) energy absorbed versus actualimpact energy curve; (d) peak force versus impact energy curve; and (e) delamination areaversus peak force curve[91]

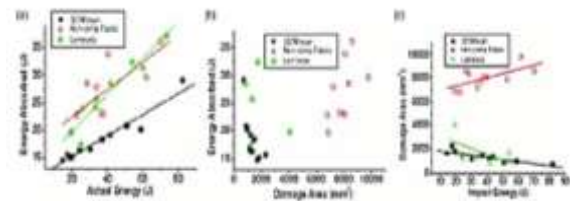**Fig.9.Comparison of the three materials in high-velocity tests: (a) energy absorbed versus actualimpact energy; (b) energy absorbed versus damage area; and (c) impact energy versusdamage area[91]**

Some studies investigated experimentally on low and high-velocity impact behaviour of composite materials which are important and provide essential information [92-95]; but since impact phenomenon depends on plenty of parameters, and an extensive knowledge of its influence on materials requires a broad test programme which is time-consuming and expensive, therefore other researchers used analytical models [96-98] and numerical [99-102], to analyse the perforation of composite structures which is critical to reduce cost and time in design processes. However, most recent investigations have been the combination of both numerical and experimental model [95, 103-105].

4.3. Ballistic Impact

A shorter time of applied load (the projectile-target interaction time) to the materials when compared with LVI load time is known as ballistic impact [84]. It can be occurred in the range 50-1000 m/s [21]. Damage caused by ballistic impact (>500 m/s) is normally concerned for military applications [68].
Ballistic impact culminates in two damage threats:
1)   damage to a target (e.g., helicopter skin); and damage to behind-target objects due to after perforation wreckage that can carry high kinetic energy [84]. Ballistic tests are executed in gas gun facilities on ballistic ranges. Law-Enforcement Applications [106, 107], and ballistic testing methodology [108, 109] are an example of a ballistic

range and layout. Earlier tests contained area of high explosive (HE) shells; Fragments size and weight information was recovered from the post-mortem analysis of witness plates or packs [84]. Recently, High explosive incendiary (HEI) rounds are designed to release a deadly combination of blast pressure upon explosion and metal segments [110, 111]. Studies [111-113] found stainless-steel composite metal foam (CMF) as a superior substance for shielding that is currently used by the military. Fig.10 portrays a comparison of stress distribution in CMF and aluminum panels.
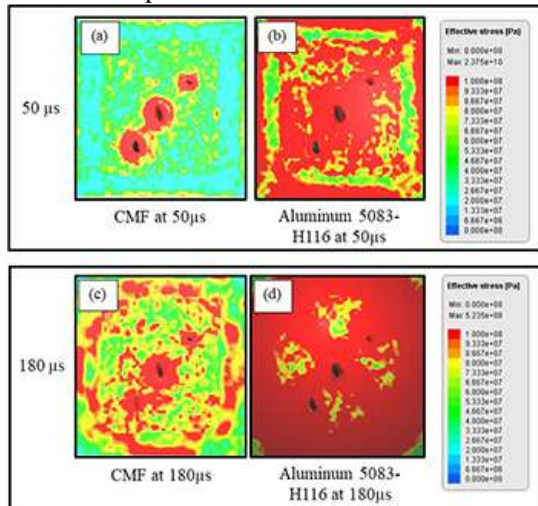

Fig.10. Comparison of the stress distribution in CMF (a,c) and aluminum 5083-H116 (b,d) panels upon interaction with blast wave and fragment impacts resulted from HEI round at 50 μs (a,b) and 180 μs (c,d). Note that the CMF and aluminum panels had the same thickness and mass [112]

Rasuo and Bosko[114] analysed the survivability of a heavy transport helicopter tail rotor blade made of composite laminated materials after ballistic damage made by the bullet of 7.9mm calibre shoulder weapons. Fig.11 shows the typical ballistic damages to the helicopter windshield [114, 115]. Fig.5 and Fig.6 present the characteristic damage after ballistic impact on the rotor blade and tail rotor drive shaft. Since helicopters are highly vulnerable and greatly exposed to the threats due to their low speed, their vertical take-off and landing , flight altitude, etc; they are given special attention and are characterised by high frequency under impact loads and damage [60, 114].

Fig.11. Ballistic damages of helicopter's windshield[114, 115]

Fig.12. Ballistic damage of the main rotor blade[114]

Fig.12. Ballistic damage of the main rotor blade[114]

There is a connection between the material mechanical properties and the ballistic performance. Some studies evaluated ballistic performances as a function of fibres mechanical properties in composite armors made up of Kevlar 29 fabrics impregnated by thermosetting resin [116], Kevlar fabrics with polypropylene (PP) matrix [117], woven fabric in an epoxy matrix which was enhanced by carbon nanotubes and milled fibres [118], and hybrid thermoplastic composite armors reinforced with Kevlar and basalt fabrics [119].Also, there are some attempts that is targeted some geometrical characteristics of the damage zones to relate damage properties and the ballistic resistance of composite. For example N.K.Naik and P.Shrirao[120] compared ballistic impact behaviour of plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composites. Different damage mechanisms and energy absorbing have been identified during ballistic impact. Paper by Nuneset al. [121]reported delamination in Fiber-reinforced composites by an automated digital analysis procedure developed in order to determine size and shape parameters that characterize the damaged areas.

4.4 Hypervelocity impact
In the hypervelocity impact, projectile energy is more dominant than its shape. Nevertheless, the impact energy concentration can be varied and some projectile shape influences can be found in this velocity range as well. For example, hypervelocity impact against Kevlar fabric was considered by Hayhurst[122]. It is necessary to understand both impactor and target materials behavior under hypervelocity impact, in order to understand the

damaged evolved, because each material has different reaction in different condition. Li [123] demonstrated a high resistance respond of porous materials to hypervelocity impact. Hypervelocity impacts are typically occurred in the range of 2km to 5km [21, 124]. Aerospace industry velocity of >2km/s are met in either pure hypersonic flight such as Space Shuttle orbit and re-entry or military applications such as proposed anti-ballistic missile (ABM) technology [124, 125]. The use of fibre reinforced polymer matrix composites in spacecraft structures and satellite components are extensive due to their high stiffness, high specific strength, and low coefficient of thermal expansion; namely in panels, antenna struts and low distortion frames [126, 127].Composite materials are combination of at least two or three elements to produce better mechanical and physical character and properties.

Three major classes of composites based on their matrix phase have been shown in Table.2.

Table.2Classes of composites [21]

Polymer Matrix Composites (PMCs)	PMCS, also known as fibre reinforced polymers (FRPs), or resin-based composites (RBCs). For the matrix, it uses a polymer-based resin and fibres as the reinforcement.
Metal Matrix Composites (MMCs)	MMCs are advanced materials because the material properties - such as corrosion resistance, high stiffness and high strength-to-density ratio, and sometimes special electrical and thermal properties - are combined. This material is progressively used in the automotive industry; it uses a metal matrix and reinforcement made of advanced ceramic fibres.
Ceramic Matrix Composites (CMCs)	CMCs are used when a material that can sustain both high temperature service and corrosion resistance to harsh environments is needed. It uses a ceramic as the matrix and short fibres or whiskers as the reinforcement.

Different studies considered the response of composite materials to hypervelocity impact [51, 128-130]. For example Xue et al. [131] considered hypervelocity impact behaviour on SiC coated C/C (SiC-C/C) composites under 2km/s to 3km/s impact velocity. Later the same authors [51] revealed the residual length of carbon fibre reinforced carbon (CC composite) under hypervelocity impact and the correlations between the impact direction, damage distribution, and the residual flexural strength of the composites has been detected. The most common techniques that are used in studies to achieve hypervelocity experimentally, can be categorised as Electrostatic dust accelerators, Plasma accelerators, Light gas guns, Shaped charges, Exploding wire/foil accelerators [124, 132, 133].

High-velocity impact usually causes more damage, larger transverse deflection, and even perforation. There are two criteria that are used to distinguish a low-velocity impact from a high-velocity one. One is based on the structural deformation and damage and the other on the structural response[134]. As mentioned before low velocity impact (LVI) deformation is localised around the contact area and high velocity impact leads to larger area of deformation or damage. Fig.13. shows solution methods for different category of impact.
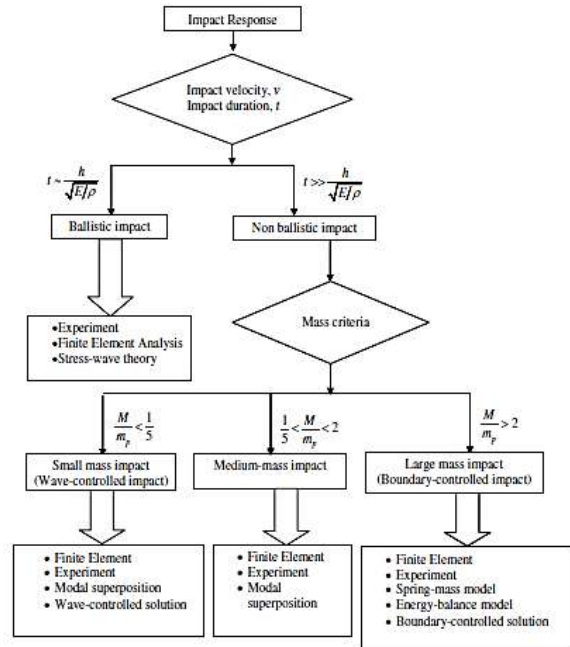

Fig.13. Solution methods for different category of impact[134]

V. THE INFLUENCE OF VARIOUS FACTORS ON IMPACT CHARACTERISTICS

5.1. Projectile shape and mass

The impact characterization involves many parameters related to both the impactor characteristics such as shape and mass and the target material [135, 136].Also material and consequent failure are sensitive to impact loading and response to loading rate [137]. Based on the materials and degree of deformation during impact loading, the projectiles is categorised into three parts; soft, semi-hard or hard. Soft projectiles endure significant deformation during impact, semi-hard projectiles experience some deformation, while hard projectiles undergo small or negligible deformations and the response is controlled by the target response [68]. C. Evci and I. Uyandıran[138] investigated the effect of temperature and impactor diameter on the impact behaviour and damage development in balanced and symmetrical CFRP. Both low and high temperatures affected the properties and impact behaviour of composite materials. The results showed direct relation between the increase of the delamination area, the threshold of penetration energy, main failure force, and impactor diameter at all temperature levels. No clear influence of temperature on the critical force thresholds has been derived. However, as the temperature was lowered, the penetration threshold energy decreased. Sheikh et al. [139] studied the projectile velocity variation on multiple glass fiber reinforced laminated panels during ballistic impact. While Zhu et al. [140] examined the projectile velocity, acceleration and damage in basalt/vinyl ester composite. The result showed that the residual velocity increases with occurrence velocity after ballistic limit.

The perforation behaviour of unidirectional glass fiber reinforced cross ply laminate experimentally and with finite element analyses with different projectiles nose shapes such as ogival, conical, spherical and blunt was examined by Ansari and Chakrabarti[141] , and concluded that the thick composite plate was targeted in more damage compared to the thinner target plate due to ballistic impact for all types of projectile shapes. As the projectile nose shape changes from conical to blunt followed by ogival and spherical, the damage in the target increases. Fibers on the back surface have eroded in case of impact by blunt projectile than the other nosed projectile. The ballistic limit of the projectiles increased with their nose shape changes from conical to blunt for all type of thickness. The amount of damage in the target plate increases with increases in the incidence angle of the projectile. Mohan and Sundareswaran[142] evaluated energy absorbed, the ballistic limit and the damage area caused by different projectile nose shapes on the composite plates made of glass fibre and vinyl ester resin with the orientation of (0/90)s, and it has been found that the truncated conical nose shaped projectile resulted in highest ballistic limit and largest damage area dominated by delamination.

5.2. Material properties

Both fiber and matrix properties influence the impact and damage tolerance of composite systems. Fibres provide the composite the majority of its strength and stiffness and play the main role in load-bearing constituent. Glass, carbon and Kevlar are known as the most common fibres. Carbon has the highest strength and stiffness values and is widely used in aircraft industry and many structural applications. However, it is also the most brittle with a strain to failure of 0.5 to 2.4% (Carbon's design ultimate allowable strain is only 0.4% currently). On the other hand, glass fibres have a higher strain to failure around 3.2% and also have a lower strength and stiffness and are less expensive than carbon fibres [143]. One or combination of the following composite materials is used in aircraft as shown in Table.3

Table.3composite materials [21]

Materials	Application
Carbon/epoxy	Used as primary structural and skin material
Kevlar/epoxy	Used as military applications, usually as primary structural and armour plating
Glass Fiber	Used as structural and skin material
Glass/phenolic	Used as interior fitting, fairadiag and structures
Boron/epoxy	Used as composite repair patches, older composite structures

Wang et al. [144] showed that graphite/PPS composites can be improved to the overall impact resistance of the material by addition of glass fiber plies. The maximum tolerated load and absorbed energy were found to increase with larger percentages of glass fibres. Epoxy resins uses in the majority of structural applications, as they meet the hot/wet compressive strength requirements. However, epoxy is brittle and has poor resistance to crack growth. In

an FRP the polymeric matrix (usually a thermoset) provides several key functions: it transfers the load to the fibres, protects the fibres from damaging themselves and aligns/stabilizes the fibres [143]. Morton et al. [145] compared the damage resistance of nine composite materials and showed that brittle systems have a higher damage area growth rate and lower threshold velocities than materials including a toughened matrix. Cantwell et al. [146] found that the damage in thin specimens is initiated in the bottom layers, whereas in thick specimens is begun on the top layers. They have shown that the critical force increases with the indenter diameter and is more significant in thinner laminates.

Mechanical properties of the matrix, fibers, and the fiber-matrix interface each have a particular effect on the residual compressive strength of impact-damaged composites. Chen et al. [147] showed that impact damage reduced the compressive strength of thin walled composite struts by a maximum of 45-55% when a graphite-epoxy material system was used. With a toughened epoxy matrix, the maximum strength reduction was approximately 10%. ChircorMihael et al. [148] investigated impact behaviour of composite materials with different types of measurement. It was shown in this study that in low velocity impact resistant, for all carbon fiber types, fiberglass canvas enclosed in a phenolic resin or to a Kevlar composite bar, the obtained deteriorations decrease as the resins' stiffness increases, though glass-epoxy bars have a high deformability before they break. In medium velocity impact resistance that has been obtained by C canner showed considerable changes in Kevlar and carbon fibre composite after compression pre-stressing while raw materials remained with no changes. Carbon fibre performance was depends on fibre resistance, it showed better behaviour with higher fibre resistance. The high speed tests depicted that the fiberglass multilayered materials experienced a much bigger delamination compare with carbon or Kevlar fibers but, in an impact with a 5,56 mm perforating bullets/missiles, they absorb twice the energy. Fig.14 illustrates delamination area of different type of fibre. A comparative impact resistance of some fiber reinforced multilayered composite that often used in the industry, presented in Fig.15.
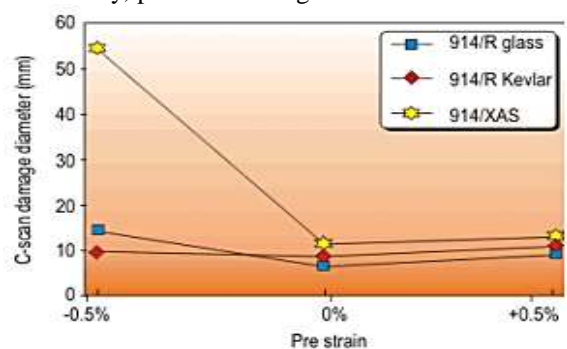

Fig.14. Delamination area depending on extension/compression pre-deformation
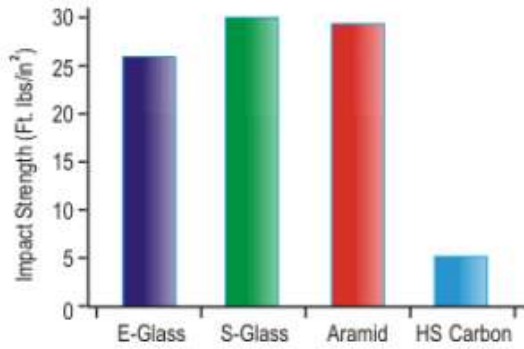
Fig.15. A few impact resistance

CONCLUSION

In this contribution, the application of composite materials and their efficiency in aircraft industry and other cases was considered.Several distinct features of composite materials make them to be essential materials in aerospace and automotive and make them more effective than metals. The materials classification based on their properties and characters was explained and the impact behaviour on different types of material has been investigated. The modes of impact damage derived range from matrix crackingand delamination through to fibre failure and penetration. Damage modes interaction, types of velocity, and influence of various factors on impact behaviour must be considered and understood to predict any failure in composite materials.

REFERENCES

[1] Malhotra, A., F. Guild, and M. Pavier, Edge impact to composite laminates: experiments and simulations. Journal of materials science, 2008. 43(20): p. 6661.

[2] Malhotra, A. and F. Guild, Impact damage to composite laminates: effect of impact location. Applied Composite Materials, 2014. 21(1): p. 165-177.

[3] Xiong, J., et al., Compression and impact testing of two-layer composite pyramidal-core sandwich panels. Composite Structures, 2012. 94(2): p. 793-801.

[4] Rhead, A.T., D. Marchant, and R. Butler, Compressive strength of composite laminates following free edge impact. Composites Part A: Applied Science and Manufacturing, 2010. 41(9): p. 1056-1065.

[5] Tiberkak, R., et al., Damage prediction in composite plates subjected to low velocity impact. Composite Structures, 2008. 83(1): p. 73-82.

[6] Khan, S.U. and J.-K. Kim, Impact and delamination failure of multiscale carbon nanotube-fiber reinforced polymer composites: a review. International Journal Aeronautical and Space Sciences, 2011. 12(2): p. 115-133.

[7] Baral, N., et al., Improved impact performance of marine sandwich panels using through-thickness reinforcement: experimental results. Composites Part B: Engineering, 2010. 41(2): p. 117-123.

[8] Saeedifar, M., et al., Barely visible impact damage assessment in laminated composites using acoustic emission. Composites Part B: Engineering, 2018. 152: p. 180-192.

[9] Talreja, R. and J. Varna, Modeling Damage, Fatigue and Failure of Composite Materials. 2015: Elsevier Science.

[10] Fakoor, M. and S. Mohammad Navid Ghoreishi, Experimental and numerical investigation of progressive damage in composite laminates based on continuum damage mechanics. Polymer Testing, 2018. 70: p. 533-543.

[11] Díaz-Álvarez, A., et al., Experimental analysis of drilling induced damage in aramid composites. Composite Structures, 2018.

[12] Nassir, N., et al., Damage initiation in composite materials under off-centre impact loading. Polymer Testing, 2018. 69: p. 456-461.

[13] Dr Faye Smith, the use of composites in aerospace: past, present and future challenges. 2013Avalon Consultancy Services Ltd.

[14] Holmes, M., Aerospace looks to composites for solutions. Reinforced Plastics, 2017. 61(4): p. 237-241.

[15] Balasubramanian, K., M.T.H. Sultan, and N. Rajeswari, 4 - Manufacturing techniques of composites for aerospace applications, in Sustainable Composites for Aerospace Applications, M. Jawaid and M. Thariq, Editors. 2018, Woodhead Publishing. p. 55-67.

[16] Howell, E., D. Neal, and D. Kieffer, Changing the paradigm of transportation: Lightweight composites used in solar car in intercollegiate competition. Reinforced Plastics, 2018. 62(4): p. 190-193.

[17] Misra, A., Composite materials for aerospace propulsion related to air and space transportation, in Lightweight Composite Structures in Transport, J. Njuguna, Editor. 2016, Woodhead Publishing. p. 305-327.

[18] S.Gholizadeh.; Leman, Z.B., B.T.H.T, A review of the application of acoustic emission technique in engineering. Structural Engineering and Mechanics, 2015. 54(6): p. 1075-1095.

[19] Fehrm, B. Filling the Middle Of the Market gap. 2017.

[20] William G. Roeseler, B.S., Max U. Kismarton COMPOSITE STRUCTURES: THE FIRST 100 YEARS in 16TH INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS 2007: Kyoto-Japan.

[21] Safri, S., et al., Low velocity and high velocity impact test on composite materials - A review. Vol. 3. 2014. 50-60.

[22] Campbell, F.C., Chapter 1 - Introduction, in Manufacturing Technology for Aerospace Structural Materials, F.C. Campbell, Editor. 2006, Elsevier Science: Oxford. p. 1-13.

[23] Ashouri Vajari, D., B.F. Sørensen, and B.N. Legarth, Effect of fiber positioning on mixed-mode fracture of interfacial debonding in composites. International Journal of Solids and Structures, 2015. 53: p. 58-69.

[24] Liu, X., et al., An acoustic emission study on interfacial debonding in composite restorations. Dental Materials, 2011. 27(9): p. 934-941.

[25] Paran, S.M.R., et al., Multiscale modeling of polymer systems comprising nanotube-like inclusions by considering interfacial debonding under plastic deformations. Composite Structures, 2018. 194: p. 302-315.

[26] Zeng, J.-J., W.-Y. Gao, and F. Liu, Interfacial behavior and debonding failures of full-scale CFRP-strengthened H-section steel beams. Composite Structures, 2018. 201: p. 540-552.

[27] Lassila, L., et al., Mechanical properties and fracture behavior of flowable fiber reinforced composite restorations. Dental Materials, 2018. 34(4): p. 598-606.

[28] Khan, Z., B.F. Yousif, and M. Islam, Fracture behaviour of bamboo fiber reinforced epoxy composites. Composites Part B: Engineering, 2017. 116: p. 186-199.

[29] Longbiao, L., Modeling first matrix cracking stress of fiber-reinforced ceramic-matrix composites considering fiber fracture. Theoretical and Applied Fracture Mechanics, 2017. 92: p. 24-32.

[30] Yao, L., et al., Thickness effects on fibre-bridged fatigue delamination growth in composites. Composites Part A: Applied Science and Manufacturing, 2018. 110: p. 21-28.

[31] Ladani, R.B., et al., Delamination toughening and healing performance of woven composites with hybrid z-fibre reinforcement. Composites Part A: Applied Science and Manufacturing, 2018. 110: p. 258-267.

[32] Teklal, F., et al., A review of analytical models to describe pull-out behavior – Fiber/matrix adhesion. Composite Structures, 2018. 201: p. 791-815.

[33] R.Talreja, Internal variable damage mechanics of composite materials. 1994, . P. Boehler. (London: Mechanical

Engineering): In Yielding, Damage, and Failure of Anisotropic Solids, ed. 509.

[34] Jia, H., et al., Fatigue and fracture behavior of bulk metallic glasses and their composites. Progress in Materials Science, 2018. 98: p. 168-248.

[35] Das, S., et al., Elucidating the influences of compliant microscale inclusions on the fracture behavior of cementitious composites. Cement and Concrete Composites, 2018.

[36] Leite, L.F.M., et al., Strain rate effects on the intralaminar fracture toughness of composite laminates subjected to tensile load. Composite Structures, 2018. 201: p. 455-467.

[37] Kashtalyan, M. and C. Soutis, STIFFNESS LOSS DUE TO TRANSVERSE CRACKING AND SPLITTING IN CROSS-PLY LAMINATES UNDER BIAXIAL LOADING. 2018.

[38] Dragan Kreculj and Boško Rašuo, REVIEW OF IMPACT DAMAGES MODELLING IN LAMINATED COMPOSITE AIRCRAFT STRUCTURES. 2013. 20(3): p. 485-495

[39] Othman, R., Finite Element Analysis Of Composite Ballistics Helmet Subjected To High Velocity Impact. 2009.

[40] Hancox, N.L., 1 - An overview of the impact behaviour of fibre-reinforced composites, in Impact Behaviour of Fibre-Reinforced Composite Materials and Structures, S.R. Reid and G. Zhou, Editors. 2000, Woodhead Publishing. p. 1-32.

[41] Thorsson, S.I., A.M. Waas, and M. Rassaian, Low-velocity impact predictions of composite laminates using a continuum shell based modeling approach Part b: BVID impact and compression after impact. International Journal of Solids and Structures, 2018.

[42] Chang, M., et al., A novel failure analysis of SMA reinforced composite plate based on a strain-rate-dependent model: low-high velocity impact. Journal of Materials Research and Technology, 2018.

[43] Chen, Y., et al., Low-velocity impact response of composite sandwich structures: Modelling and experiment. Composite Structures, 2017. 168: p. 322-334.

[44] Metoui, S., et al., A reduced model to simulate the damage in composite laminates under low velocity impact. Computers & Structures, 2018. 199: p. 34-45.

[45] Sun, W., et al., Modelling and simulating of the compressive behavior of T-stiffened composite panels subjected to stiffener impact. Composite Structures, 2018. 186: p. 221-232.

[46] Meola, C., et al., Impact damaging of composites through online monitoring and non-destructive evaluation with infrared thermography. NDT & E International, 2017. 85: p. 34-42.

[47] Malinowski, P.H., et al., Study of plant fibre composites with damage induced by laser and mechanical impacts. Composites Part B: Engineering, 2018. 152: p. 209-219.

[48] Liu, B., et al., Study on impact damage mechanisms and TAI capacity for the composite scarf repair of the primary load-bearing level. Composite Structures, 2017. 181: p. 183-193.

[49] Samal, S., et al., Impact and post impact behavior of fabric reinforced geopolymer composite. Construction and Building Materials, 2016. 127: p. 111-124.

[50] Zhao, W. and Q. Guo, Experimental study on impact and post-impact behavior of steel-concrete composite panels. Thin-Walled Structures, 2018. 130: p. 405-413.

[51] Xue, L.-Z., et al., Hypervelocity impact behavior and residual flexural strength of C/C composites. Vacuum, 2017. 144: p. 101-106.

[52] Liu, Q., et al., Crash responses under multiple impacts and residual properties of CFRP and aluminum tubes. Composite Structures, 2018. 194: p. 87-103.

[53] Guades, E. and T. Aravinthan, Residual properties of square FRP composite tubes subjected to repeated axial impact. Composite Structures, 2013. 95: p. 354-365.

[54] Aktaş, M., et al., Impact and post impact behavior of layer fabric composites. Composite Structures, 2012. 94(9): p. 2809-2818.

[55] Mylsamy, K. and I. Rajendran, The mechanical properties, deformation and thermomechanical properties of alkali treated and untreated Agave continuous fibre reinforced

epoxy composites. Materials & Design, 2011. 32(5): p. 3076-3084.

[56] M R, S. and B. Yogesha, Studies on Mechanical Properties of Jute/E-Glass Fiber Reinforced Epoxy Hybrid Composites. Vol. 04. 2016. 15-25.

[57] Aabdul Khalil, H.P.S., et al., The Effect of Different Laminations on Mechanical and Physical Properties of Hybrid Composites. Journal of Reinforced Plastics and Composites, 2008. 28(9): p. 1123-1137.

[58] Sezgin, H. and O.B. Berkalp, The effect of hybridization on significant characteristics of jute/glass and jute/carbon-reinforced composites. Journal of Industrial Textiles, 2016. 47(3): p. 283-296.

[59] SANTULLI, C., IMPACT DAMAGE EVALUATION IN WOVEN COMPOSITES USING ACOUSTIC AND THERMOELASTIC TECHNIQUES, in Department of Engineering Materials Science and Engineering. 2002, the University of Liverpool.

[60] Kreculj, D. and B. Rasuo, Impact damage modeling in laminated composite aircraft structures, in Sustainable Composites for Aerospace Applications, M. Jawaid and M. Thariq, Editors. 2018, Woodhead Publishing. p. 125-153.

[61] Davies, G.A.O. and R. Olsson, Impact on composite structures. The Aeronautical Journal (1968), 2004. 108(1089): p. 541-563.

[62] Katunin, A., K. Dragan, and M. Dziendzikowski, Damage identification in aircraft composite structures: A case study using various non-destructive testing techniques. Composite Structures, 2015. 127: p. 1-9.

[63] Sarasini, F., et al., Damage tolerance of carbon/flax hybrid composites subjected to low velocity impact. Composites Part B: Engineering, 2016. 91: p. 144-153.

[64] Koo, J.-M., J.-H. Choi, and C.-S. Seok, Prediction of residual strength after impact of CFRP composite structures. International Journal of Precision Engineering and Manufacturing, 2014. 15(7): p. 1323-1329.

[65] Li, B. and M.S. Hoo Fatt, Impact damage and residual strength predictions of 2D woven SiC/SiC composites. Finite Elements in Analysis and Design, 2016. 113: p. 30-42.

[66] Grytten, F., Low-Velocity Penetration of Aluminium Plates. 2008.

[67] Børvik, T., "An introduction to impact and penetration dynamics", in Department of Structural Engineering, . 2003, Norwegian University of Science and Technology

[68] N. Razali, et al., Impact Damage on Composite Structures – A Review. The International Journal Of Engineering And Science (IJES), 2014. 3(7): p. 08-20.

[69] Lopes, C.s., et al., Simulation of Low-Velocity Impact Damage on Composite Laminates. 2009.

[70] Rajbhandari, S.P., et al., AN APPROACH TO MODELLING AND PREDICTING IMPACT DAMAGE IN COMPOSITE STRUCTURES in ICAS CONGRESS 2002.

[71] Rajesh Mathivanan, N. and J. Jerald, Experimental investigation of low-velocity impact characteristics of woven glass fiber epoxy matrix composite laminates of EP3 grade. Materials & Design, 2010. 31(9): p. 4553-4560.

[72] Marimuthu, P., et al., Numerical Simulation of Low Velocity Impact Analysis of Fiber Metal Laminates. Vol. 20. 2016. 515-530.

[73] Liu, P.F., et al., Finite element analysis of dynamic progressive failure of carbon fiber composite laminates under low velocity impact. Composite Structures, 2016. 149: p. 408-422.

[74] Yu, G.-C., et al., Low velocity impact of carbon fiber aluminum laminates. Composite Structures, 2015. 119: p. 757-766.

[75] Bull, D.J., S.M. Spearing, and I. Sinclair, Investigation of the response to low velocity impact and quasi-static indentation loading of particle-toughened carbon-fibre composite materials. Composites Part A: Applied Science and Manufacturing, 2015. 74: p. 38-46.

[76] Duell, J.M., Impact Testing of Advanced Composites., in Advanced Topics in Characterization of Composites. 2004, Trafford Publishing. p. 97-112.

[77] Domínguez, C., M. Aroca, and J. Rodríguez, Izod impact tests of polypropylenes: The clamping pressure influence. Polymer Testing, 2006. 25(1): p. 49-55.

[78] Cristina O. Nascimento, D., et al., Studies on the characterization of piassava fibers and their epoxy composites. Vol. 43. 2012. 353–362.

[79] Margem, J.I., et al. Izod Impact Tests in Polyester Matrix Composites Reinforced with Malva Fibers. in TMS 2014: 143rd Annual Meeting & Exhibition. 2016. Cham: Springer International Publishing.

[80] Glória, G.O., et al., Charpy Impact Tests of Epoxy Composites Reinforced with Giant Bamboo Fibers %J Materials Research. 2015. 18: p. 178-184.

[81] Rajput, M.S., et al., Design and evaluation of a novel instrumented drop-weight rig for controlled impact testing of polymer composites. Polymer Testing, 2018. 68: p. 446-455.

[82] González, E.V., et al., Simulating drop-weight impact and compression after impact tests on composite laminates using conventional shell finite elements. International Journal of Solids and Structures, 2018. 144-145: p. 230-247.

[83] González, E.V., et al., Simulation of drop-weight impact and compression after impact tests on composite laminates. Composite Structures, 2012. 94(11): p. 3364-3378.

[84] Resnyansky, A.D., The Impact Response of Composite Materials Involved in Helicopter Vulnerability Assessment: Literature Review Part 2, in Department of Defence Science and Technology Organisation. 2006, Australian government-DSTO Defence Science and Technology Organisation: Australia.

[85] Gaudenzi, P., et al., On the evaluation of impact damage on composite materials by comparing different NDI techniques. Composite Structures, 2014. 118: p. 257-266.

[86] Moallemzadeh, A.R., S.A.R. Sabet, and H. Abedini, Preloaded composite panels under high velocity impact. International Journal of Impact Engineering, 2018. 114: p. 153-159.

[87] Schueler, D., N. Toso-Pentecôte, and H. Voggenreiter, Effects of static preloads on the high velocity impact response of composite plates. Composite Structures, 2016. 153: p. 549-556.

[88] Hodgkinson, J.M., Mechanical Testing of Advanced Fibre Composites. 2000: Elsevier Science.

[89] Dhakal, H.N., et al., The low velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites. Composite Structures, 2007. 81(4): p. 559-567.

[90] Safri, S.N.A., et al., Impact behaviour of hybrid composites for structural applications: A review. Composites Part B: Engineering, 2018. 133: p. 112-121.

[91] Chen, F. and J.M. Hodgkinson, Impact behaviour of composites with different fibre architecture. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2009. 223(7): p. 1009-1017.

[92] Tan, W., et al., Predicting low velocity impact damage and Compression-After-Impact (CAI) behaviour of composite laminates. Composites Part A: Applied Science and Manufacturing, 2015. 71: p. 212-226.

[93] Thorsson, S.I., et al., Experimental investigation of composite laminates subject to low-velocity edge-on impact and compression after impact. Composite Structures, 2018. 186: p. 335-346.

[94] Arslan, K. and R. Gunes, Experimental damage evaluation of honeycomb sandwich structures with Al/B4C FGM face plates under high velocity impact loads. Composite Structures, 2018.

[95] Arjangpay, A., et al., An experimental and numerical investigation on low velocity impact response of a composite structure inspired by dragonfly wing configuration. Composite Structures, 2018. 184: p. 327-336.

[96] Alonso, L., C. Navarro, and S.K. García-Castillo, Analytical models for the perforation of thick and thin thickness woven-laminates subjected to high-velocity impact. Composites Part B: Engineering, 2018. 143: p. 292-300.

[97] Mohamadipoor, R., M.H. Pol, and E. Zamani, Nonlinear analytical study of thin laminated composite plate reinforced by nanoparticles under high-velocity impact. Thin-Walled Structures, 2018. 127: p. 446-458.

[98] Salvetti, M., et al., Analytical model of the dynamic behaviour of CFRP plates subjected to low-velocity impacts. Composites Part B: Engineering, 2018. 142: p. 47-55.

[99] Pernas-Sánchez, J., et al., Numerical analysis of high velocity impacts on unidirectional laminates. Composite Structures, 2014. 107: p. 629-634.

[100] Jalón, E., et al., Analysis of low-velocity impact on flax/PLA composites using a strain rate sensitive model. Composite Structures, 2018.

[101] Menna, C., et al., Numerical simulation of impact tests on GFRP composite laminates. International Journal of Impact Engineering, 2011. 38(8): p. 677-685.

[102] Ivañez, I., et al., Numerical modelling of foam-cored sandwich plates under high-velocity impact. Composite Structures, 2011. 93(9): p. 2392-2399.

[103] Hassoon, O.H., et al., Mechanical behavior of composite structures subjected to constant slamming impact velocity: An experimental and numerical investigation. International Journal of Mechanical Sciences, 2018. 144: p. 618-627.

[104] Gliszczynski, A., Numerical and experimental investigations of the low velocity impact in GFRP plates. Composites Part B: Engineering, 2018. 138: p. 181-193.

[105] Mars, J., et al., Numerical and experimental investigations of low velocity impact on glass fiber-reinforced polyamide. Composites Part B: Engineering, 2018. 146: p. 116-123.

[106] Bhatnagar, A., Lightweight Ballistic Composites. Composites Science and Engineering. 2006: Woodhead

[107] Harel, H., Marom, G. & Kenig, S, Applied Composite Materials 2002. 9(33).

[108] Mascianica, F.S., Chapter 3 - Ballistic Testing Methodology, in Methods and Phenomena, R.C. Laible, Editor. 1980, Elsevier. p. 41-72.

[109] Crouch, I. and B. Eu, Ballistic testing methodologies. 2017. 639-673.

[110] LaneLong. Metal Foam Could Better Protect Soldiers Against Blast Pressure, Fragmentation. 2018 April 03].

[111] Marx, J., M. Portanova, and A. Rabiei, A study on blast and fragment resistance of composite metal foams through experimental and modeling approaches. Composite Structures, 2018. 194: p. 652-661.

[112] Afsaneh Rabiei and M. Shipman. Lightweight Metal Foam Blocks Blastwave, Debris From High-Explosive Rounds. 2018 26 March].

[113] Khan, B. Composite Metal Foam Stops Bullets and Shields Against Radiation. 2017 30 March].

[114] Rasuo, B., Experimental methodology for evaluating survivability of an aeronautical construction from composite materials: An overview. Vol. 12. 2007. 9-15.

[115] Wan, H., et al., Shielding performances of the designed hybrid laminates impacted by hypervelocity flyer. Materials & Design (1980-2015), 2013. 52: p. 422-428.

[116] Sorrentino, L., et al., Ballistic Performance Evaluation of Composite Laminates in Kevlar 29. Procedia Engineering, 2014. 88: p. 255-262.

[117] Bandaru, A.K., et al., Ballistic impact response of Kevlar® reinforced thermoplastic composite armors. International Journal of Impact Engineering, 2016. 89: p. 1-13.

[118] Gibson, J., et al., Enhancement in ballistic performance of composite hard armor through carbon nanotubes. International Journal of Smart and Nano Materials, 2013. 4(4): p. 212-228.

[119] Bandaru, A.K., S. Ahmad, and N. Bhatnagar, Ballistic performance of hybrid thermoplastic composite armors reinforced with Kevlar and basalt fabrics. Composites Part A: Applied Science and Manufacturing, 2017. 97: p. 151-165.

[120] Naik, N.K. and P. Shrirao, Composite structures under ballistic impact. Composite Structures, 2004. 66(1): p. 579-590.

[121] Nunes, L.M., S. Paciornik, and J.R.M. d'Almeida, Evaluation of the damaged area of glass-fiber-reinforced epoxy-matrix composite materials submitted to ballistic impacts. Composites Science and Technology, 2004. 64(7): p. 945-954.

[122] Hayhurst, C.J., et al., Ballistic limit evaluation of advanced shielding using numerical simulations. International Journal of Impact Engineering, 2001. 26(1): p. 309-320.

[123] Li, Y., J.B. Li, and R. Zhang, Energy-absorption performance of porous materials in sandwich composites under hypervelocity impact loading. Composite Structures, 2004. 64(1): p. 71-78.

[124] Appleby-Thomas, G.J. and P.J. Hazell, The impact of structural composite materials. Part 2: hypervelocity impact and shock. The Journal of Strain Analysis for Engineering Design, 2012. 47(7): p. 406-418.

[125] Bernhard, R.P., E.L. Christiansen, and J.H. Kerr, Space shuttle meteoroid and orbital debris impact damage. International Journal of Impact Engineering, 2001. 26(1): p. 33-38.

[126] Tennyson, R.C. and C. Lamontagne, Hypervelocity impact damage to composites. Composites Part A: Applied Science and Manufacturing, 2000. 31(8): p. 785-794.

[127] Soutis, C., Fibre reinforced composites in aircraft construction. Progress in Aerospace Sciences, 2005. 41(2): p. 143-151.

[128] Katz, S., et al., Response of composite materials to hypervelocity impact. International Journal of Impact Engineering, 2008. 35(12): p. 1606-1611.

[129] Cherniaev, A. and I. Telichev, Experimental and numerical study of hypervelocity impact damage in composite materials fabricated by filament winding. International Journal of Impact Engineering, 2016. 98: p. 19-33.

[130] Nam, Y.-W., et al., Multi-functional aramid/epoxy composite for stealth space hypervelocity impact shielding system. Composite Structures, 2018. 193: p. 113-120.

[131] Xue, L.-Z., et al., Effects of hypervelocity impact on ablation behavior of SiC coated C/C composites. Materials & Design, 2016. 108: p. 151-156.

[132] Schneider, E. and F. Schäfer, Hypervelocity impact research - acceleration technology and applications. Advances in Space Research, 2001. 28(9): p. 1417-1424.

[133] Field, J.E., et al., Review of experimental techniques for high rate deformation and shock studies. International Journal of Impact Engineering, 2004. 30(7): p. 725-775.

[134] Chai, G.B. and S. Zhu, A review of low-velocity impact on sandwich structures. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 2011. 225(4): p. 207-230.

[135] Mitrevski, T., I.H. Marshall, and R. Thomson, The influence of impactor shape on the damage to composite laminates. Composite Structures, 2006. 76(1): p. 116-122.

[136] Sutherland, L.S. and C. Guedes Soares, The effects of test parameters on the impact response of glass reinforced plastic using an experimental design approach. Composites Science and Technology, 2003. 63(1): p. 1-18.

[137] Evci, C. and M. Gülgeç, An experimental investigation on the impact response of composite materials. International Journal of Impact Engineering, 2012. 43: p. 40-51.

[138] Evci, C. and i. Uyandıran. The effect of the impactor diameter and temperature on low velocity impact behavior of CFRP laminates. in AIP Conference Proceedings 1809, 020014 2017.

[139] Sheikh, A.H., P.H. Bull, and J.A. Kepler, Behaviour of multiple composite plates subjected to ballistic impact. Composites Science and Technology, 2009. 69(6): p. 704-710.

[140] Zhu, L., et al., Ballistic impact damage of biaxial multilayer knitted composite. Journal of Composite Materials, 2012. 46(5): p. 527-547.

[141] Ansari, M.M. and A. Chakrabarti, Influence of projectile nose shape and incidence angle on the ballistic perforation of laminated glass fiber composite plate. Composites Science and Technology, 2017. 142: p. 107-116.

[142] Mohan, S. and V. Sundareswaran, Influence of projectile nose shape on ballistic limit and damage to glass/vinyl ester composite plates. Vol. 20. 2011. 126-133.

[143] Richardson, M.O.W. and M.J. Wisheart, Review of low-velocity impact properties of composite materials. Composites Part A: Applied Science and Manufacturing, 1996. 27(12): p. 1123-1131.

[144] Wang, C.J., et al., Impact Behavior of Hybrid-Fiber and Hybrid-Matrix Composites. Journal of Reinforced Plastics and Composites, 1991. 10(4): p. 356-378.

[145] Morton, J. and E.W. Godwin, Impact response of tough carbon fibre composites. Composite Structures, 1989. 13(1): p. 1-19.

[146] Cantwell, W.J. and J. Morton, Impact perforation of carbon fibre reinforced plastic. Composites Science and Technology, 1990. 38(2): p. 119-141.

[147] Chen, G.S., Bidinger, G. M., and Lou, M. C, IMPACT DEMAGE TOLERANCE OF THIN WALL COMPOSITE STRUTS, in Proceedings of the 34th AIAA Structures, Structural Dynamics and Materials Conference,. 1993. p. Part 2, 847-858.

[148] MIHAEL, C., D. RAMONA, and D.C. LAURENTIU, The Impact Behaviour of Composite Materials in Proceedings of the 3rd International Conference on Maritime and Naval Science and Engineering ISSN: 1792-4707 45 ISBN: 978-960-474-222-6. 2010.

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