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Low Velocity and High Velocity Impact Test on Composite Materials – A review

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ABSTRACT

A question that is naturally raised is how to improve the survivability of aircraft structures regarding low and high velocity impacts. Since structural failure is caused primarily by fracture, a fundamental understanding of the mechanisms and mechanics of the material is one of the most important steps needed to solve the problem. In a high velocity impact, fracture often occurs in an impacted zone where compression is dominant. For a low velocity impact, invisible cracks often occur, but they cannot be seen using the naked eye. It is important to understand the deformation and damage mechanisms involved in the impact of targets, for the effective design of composite structures.

Keywords: *Composite Materials ,High Velocity Impact (HVI), Impact Damage, Low velocity Impact (LVI), Non-destructive Testing (NDT).*

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I. INTRODUCTION

In the last few decades, the use of composite materials in different structures has become increasingly popular since composites are well known for their excellent weight/strength and weight/stiffness properties and this makes them the material of choice for lightweight structures. Laminated fibre-reinforced composite materials are also known for their good environmental resistance and fatigue resistance. Previously, light alloys were widely used in aircraft. However, composites have now replaced light alloys in aircraft structures since they have a lower maintenance control surface (1). Aircraft structures need to be constructed using material that possesses high durability, high hardness and light weight.

Aircraft structures are at risk of experiencing structural failure and damages. Voids in the microstructure of the material, design errors such as the existence of notches, holes, and tight fillet radii, and corrosion of the material are several reasons for failures to take place when a component or structure cannot resist the stress applied to it (2). The most essential features of fibre-reinforced composites in an aircraft or structural application are damage tolerance and damage resistance under impact loading, because they are exposed to unplanned impact loading of numerous kinds during the manufacturing process and in service (3). There are several categories of impact loading, and specifically these are: low velocity (large mass), intermediate velocity, high/ballistic velocity (small mass), and hyper velocity impact. These categories of impact loading are important because there are extreme changes in energy transfer between the projectile and target, energy dissipation and damage propagation mechanisms as the velocity of the projectile varies (4). Low velocity impacts occur at a velocity below 10 m/s, intermediate impacts occur between 10 m/s and 50 m/s, high velocity (ballistic) impacts have a range of velocity from 50 m/s to 1000 m/s, and hyper velocity impacts have the range of 2 km/s to 5 km/s (5).

II. COMPOSITE MATERIALS

A composite material is a combination of two or more materials and it creates a new material with a unique combination of properties. Normally, composite material is formed by reinforcing fibres in a matrix resin as shown in Figure 1. The strength and stiffness of the composites is provided by the reinforcing fibre or fabric, while the rigidity and environmental resistance of the composite is provided by the matrix.

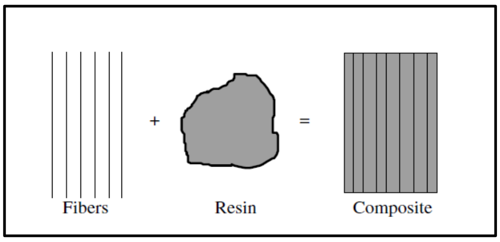

Figure 1: Formation of composite material using fibres and resin (6).

Composites made with a polymer matrix have become more common and are widely used in various industries. In the mid-1960s and early-1970s, composites started to be developed in the aircraft industry. The military were the initial inventors and users of composites where the high performance composites were applied on the empennages of the F-14 and F-15 fighter aircraft. The F-15 fighter aircraft used Boron/epoxy for the horizontal stabilisers, rudders and vertical fins. In the mid-1970s, the fighter aircraft F-15 used carbon/epoxy for the speed brake (7).In the past few decades, the use of composites in structural applications, especially in the aerospace industry has been increasing as shown in Figure 2.

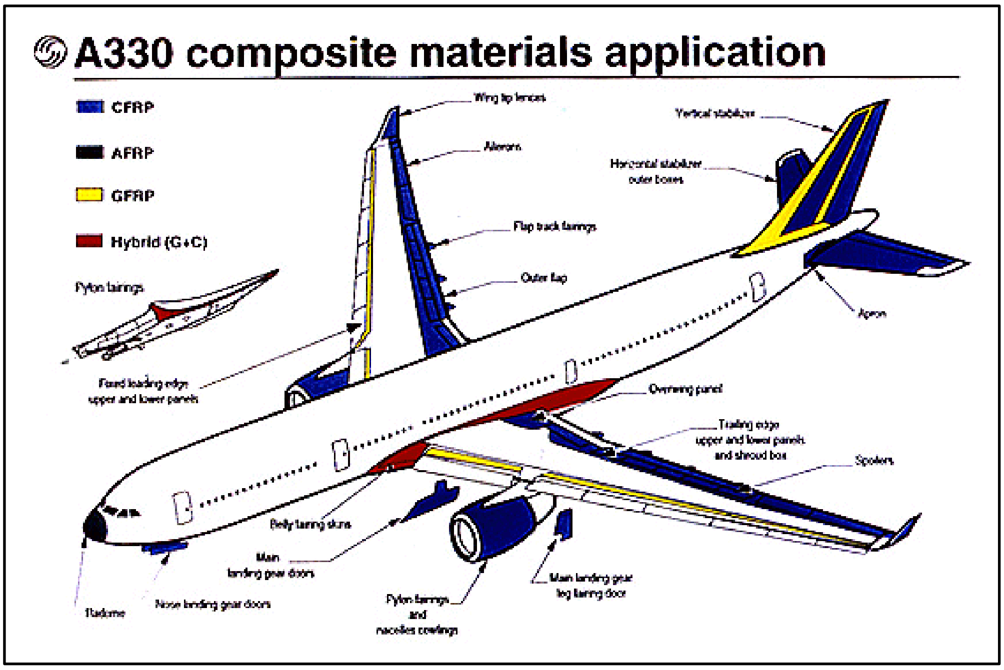

Figure 2: Typical composite structures used in A330 commercial aircraft (8).

A composite material is composed of at least two elements to produce a structural material with improved mechanical and physical properties compared to the mechanical and physical properties of the components separately (9). There are three major classes of composites based on their matrix phase as shown in Table 1:

Table 1: Classes of composites(9)

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.

PMC is commonly used in a high performance structural application. PMC has excellent mechanical properties; high specific strength, high specific stiffness, high fracture toughness, increased fatigue life and high corrosion and puncture resistance (10). Some of the common applications of PMCs are aerospace structures, automotive parts, radio controlled vehicles, bullet-proof vests and armour parts. Hybridisation is one of the effective ways of improving the energy absorption capability of PMCs. The behavior of hybrid composites under ballistic impact loading conditions should be well understood. Composite material is commonly used in aircraft. An aircraft usually contains one or a combination of the following composite materials as shown in Table 2.

Table 2: Fibre composites and their use in aircraft (2)

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

Table 2 shows the fibre composites and their application in an aircraft. The Boeing 787 as shown in Figure 3 and the Airbus A350 are typical examples of composites being used in aircraft structural applications. Comparing Table 2 and Figure 3, it can be stated that Carbon Fibre Reinforced Polymer (CFRP) is mainly used in aircraft structures compared to Glass Fibre Reinforced Polymer (GFRP). Glass Fibre Reinforced Polymer (GFRP) is normally chosen in impact sensitive applications, even though it has a lower elastic modulus and resistance to fatigue compared to carbon fibres. In fighter aircraft, the percentage of composite material is in the range of 20–30%.

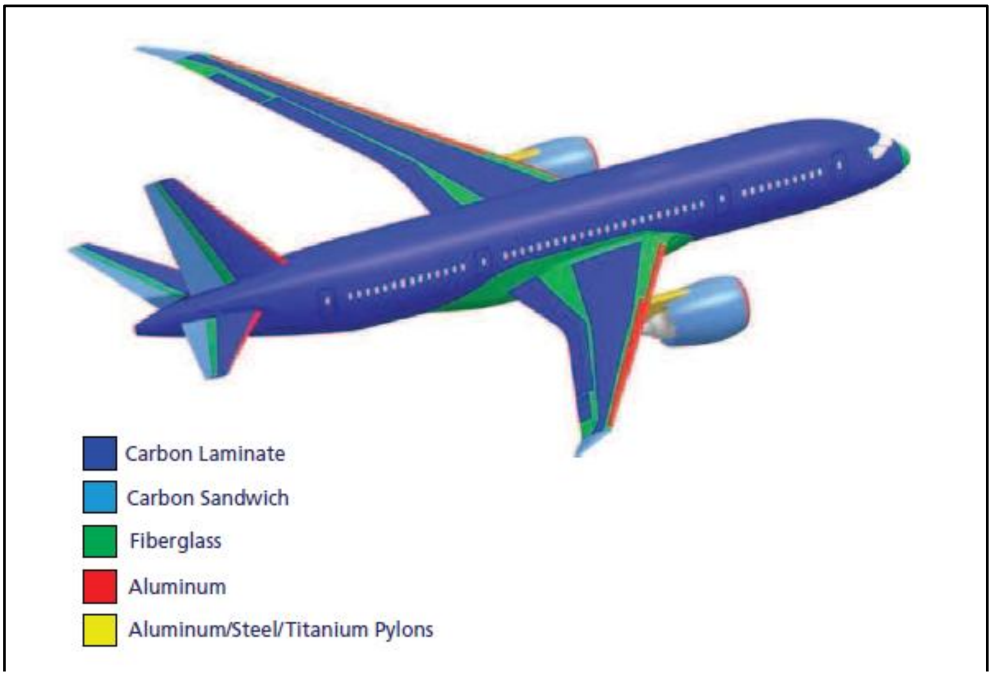

Figure 3: Boeing 787 Material Distribution (7)

Usually, for structural application, unidirectional (UD) layers are used to laminate a composite. Laminates which are unidirectional 0º have higher strength and stiffness. However, in the 90º direction, they are very weak, because the load is being carried by much weaker polymer. They are also highly exposed to impact damage because of their lower transverse tensile strength. Therefore, woven-fabric layers are chosen to replace the unidirectional layers and refine the impact performance of polymer-matrix composites(11). The manufacturers have used various techniques to improve the impact resistance and damage tolerance characteristics of fibre composites. The advantages of composite materials are that they can have the best qualities of their original material and often some qualities that neither element possesses. Some of the properties that can be improved by forming a composite material are as shown in Figure 4.

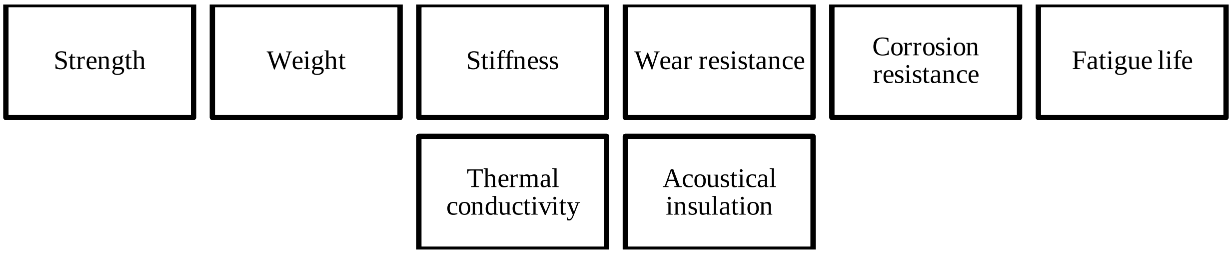

Figure 4: Properties that can be improved after producing a composite(12)

Composites are used not only for their mechanical properties, which are best for the applications that need good weight to strength ratio, but also for electrical, thermal, tribological and environmental applications (13). Lately composites have been used in beam-type structures under high loading rates, such as the drive shafts in vehicles, the rotor blades of helicopters, the intake fan blades of jet engines and the entire composite wing of a spacecraft (14).

III. LOW VELOCITY IMPACT TEST

Low velocity impacts can be defined as events which can occur in the range 1–10 m/s depending on the target stiffness, material properties and the projectile mass and stiffness (15). A low velocity impact event can occur in-service or during maintenance activities and can be considered one of the most dangerous loads on composite laminates. It is an unsafe type of load since it affects the performance of composites.For low velocity impact events, the usage of pendulums like the ones present in the Charpy test, the Izod test and drop towers or drop weights have become standard. A drop weight impact testing unit enables the simulation of a wide variety of real-world impact conditions and collects detailed performance data (16). One of the advantages of this test with respect to the Charpy and Izod tests is that a wider range of test geometries can be examined, thereby enabling more complex components to be tested (17).There are several different techniques for testing composites using low velocity impact testing. Table 3 shows the types of low velocity impact tester that are commonly used in research studies.

Table 3: Types of Low Velocity Impact Tester (18)

Methodology	Main Function
Izod 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, impacting the specimen.	To test the impact behaviour of composite plates.

The Charpy and Izod impact tests are commonly used to compare the impact response of isotropic materials that are different in composition or manufacturing condition (19). Both impact tests use a pendulum, but the difference is that in the Charpy impact test the specimen is supported as a simple beam, and in the Izod impact test the specimen is supported as a cantilever. Izod and Charpy impact testing can provide a large amount of data since they are easy to set up and can collect a large amount of data quickly. However, the results obtained from these tests are not in depth such that they will show more of the characteristics of the material. Nevertheless, researchers have advanced the usage of Charpy impact tests to obtain results that show crack propagation and measure force more accurately using high speed photography (20).

Fibre composites are subject to delamination due to their low intralaminar strength. Interlaminar stresses occur in the boundary layer of laminates under transverse loading. The polymeric matrix in the material allocates the energy inside it and makes it capable of absorbing impact energy. A low velocity impact state does not produce perforation, but creates delaminations between the layers with no visible damage on surfaces (21). During the industrial process, delamination can also occur in the material because of contaminated reinforcing fibres, insufficient wetting of fibres, machining and mechanical loading and the lack of reinforcement in the thickness direction (22).

There are a few parameters that affect failure modes in composites due to low velocity impact loading conditions; type of fibre, resin, lay-up, specimen thickness, velocity and type of projectile (23). Metals absorb energy in elastic and in plastic regions, whereas composite laminates mostly absorb energy in elastic deformation. Since most composites are brittle in nature they can absorb energy in elastic deformation and damage mechanisms and not due to plastic deformation.

IV. HIGH VELOCITY IMPACT TEST

During flight, take-off and landing, aircraft structures and equipment, such as radome, radar antenna, landing lights, canopy, windshield, lateral section or intake of the engine nacelle, turbine blades, wing or tail empennage leading edges, are open to high velocity impact loading. One of the major causes is bird strikes, because of their high probability of occurrence and their consequences (24). When a bird strikes an aircraft, the relative velocities between the two objects are so high that the material of the airplane could suffer instant damage and failure. This situation can be simulated by high velocity impact testing. High velocity impact testing provides more severe damages which could lead to the immediate failure of the material (16). Various applications require structural survivability against impact by high speed projectiles. In aircraft and land-based vehicles, composites are used and designed to survive high speed impact from wrecking engine parts, turbine blades and other debris (25). It is important for these materials to be highly resistant against penetration by high velocity projectiles. First, it is important to understand the terms related to high velocity impact testing. Impact in high velocity impact testing means the collision between two or more bodies. Projectile is a term for any item being launched. Target is the term for any stationary or moving item that can be struck by the projectile.

There are two types of single-stage gun, which are powder guns and gas guns. A powder gun uses normal gunpowder as the propellant, with a maximum velocity of about 2.0–2.2 km/s for the projectile. A single-stage light-gas gun uses compressed helium or hydrogen gas as the propellant (26).During the early 1950s, light-gas gun technology had not yet achieved velocities of interest, but the theoretical potential of gas guns and their position as the fastest launchers available assured their detailed consideration by government laboratories in the United States and Europe and by a few commercial firms involved in defence activities (27). Previous research has investigated the penetration and perforation of Fibre Reinforced Polymer (FRP) laminates using flat-faced, hemispherical ended, conical-tip and truncated-cone-nose projectiles in high velocity impact (28). Based on previous studies, most of the impact tests have been on thin laminates, usually no thicker than 2 or 3 mm. Aslan et al.(29) and Raju et al.(30) study high velocity impact tests on thick laminates.

V. FACTORS INFLUENCING IMPACT CHARACTERISTICS

This section will discuss the parameters that affect the performance of composite materials under low velocity impact and high velocity impact testing. The most important parameters affecting the ballistic capacity of a target plate seem to be the projectile (size, shape, density and hardness), the target plate (hardness/strength, ductility, microstructure and thickness) and the actual impact conditions (such as impact velocity, angle of attack and projectile attitude). Several parameters, such as the ratio of target thickness to projectile diameter, the projectile nose shape and the materials involved, are known to affect the penetration mechanisms.

5.1 Effect of fibre properties

Naik et al. (4) investigated the ballistic impact behaviour of two-dimensional woven fabric of plain weave E-glass/epoxy and twill weave T300 carbon/epoxy composite. From the results, the ballistic limit is higher for E-glass/epoxy than for T300 carbon/epoxy.

5.2 Effect of Specimen Thickness

Most of the research studies have been on the effect of thickness on low velocity and high velocity impact testing of a composite structure, since it is well known as an important factor in obtaining the impact response. Under the high velocity impact scenario, thick composites perform differently compared to thin composites (31). In the early 1980s, Cantwell et al.(32) performed a study on the impact testing of CFRP laminates with different thicknesses and found that changes in the thicknesses affect the laminate fracture mode. For thick targets, the damage initiated was due to the high contact stresses generated by the projectile. Gellert et al. (33) found that the energy absorption in thin GRP targets is largely independent of projectile nose geometry while studying the thickness dependence of the perforation of GRP composites for three projectile nose shapes. Shaktivesh et al.(34) studied the effect of thickness and found that the sum of the energy absorbed by different mechanisms leads to an increasing, nearly constant and then an increasing trend for the ballistic limit velocity as the target thickness increases.

5.3 Effect of Projectile Shape and mass

Under a high velocity impact scenario, the projectile shapes normally used are blunt, conical, hemispherical, conical and ogive. For the low velocity impact test, the impactor/striker shapes normally used are, blunt, conical and hemispherical. Studies in the literature show that the effect of projectile nose on the target plates varies with various parameters such as the thickness of the target plate, the impact velocity of the projectile, the target thickness to projectile diameter ratio and the nose angle or nose radius of the projectiles. Different investigators have varied different parameters to study the effect of projectile nose shape on the target plates. However, there still remains a need for a systematic study of the influence of projectile nose shape, the thickness of the target plate and the projectile impact velocity on deformation behaviour of the aluminum plates. Corran et al. (35) showed that the critical impact energy depends on the projectile nose radius.

. Blunt projectiles cause failure by shear plugging, conical projectiles cause petaling in thin plates and ductile hole enlargement in thicker plates, and hemispherical projectiles cause tensile stretching after severe indentation and thinning of the target plate (36). Othe et al.(37) found that the conical projectiles required less perforation energy compared to blunt and hemispherical projectiles. Wen et al.(28) and Wen et al.(38) created an analytical model to calculate the penetration and perforation of monolithic composite laminates impacted transversely using projectiles with different nose shapes. Mitrevski et al. (39) and Mitrevski et al. (40) studied the effect of impactor shape on the drop-weight impact performance of thin woven carbon/epoxy composites. They concluded that the specimen absorbed more energy when impacted by a conical impactor. Impacting specimens using hemispherical impactors produced the highest contact force and lowest contact time. Mitrevski et al. (41) studied the effect of impactor shape on the low velocity impact response of preloaded carbon/epoxy composites. It was found that the impactor shape had little effect under preloaded conditions. Zhou et al. (42) conducted low-velocity impact testing on glass-reinforced woven fabric laminates using a flat-ended impactor. It was reported that the structural characteristics of these impact damage mechanisms are affected by geometry.

5.4 Effect of Projectile Velocity

For high velocity impact testing, the velocities of the projectiles depend on the pressure exerted by the gas gun. However, for low velocity impact testing, the velocity of the drop mass depends on the height of the drop mass as explained in section 2.5.3.Lesard et al. (43) studied the effect of impact energies on four different fibre reinforced composite plates. It was found that carbon fibre reinforced polymer plates show the best structural performance under low velocity impacts, and for high velocity impacts, a hybrid composite that contained carbon/glass fibre shows the best structural performance.

For low velocity impact loading, the magnitude of the impact velocity influences the contact force and deflection of the sandwich structure. Lee et al.(44) showed that the peak force increased with increasing impact velocity. In ballistic impacts (short contact between impactor and target) the damage is localised and clearly visible by external inspection, while a low velocity impact involves a long contact time between the impactor and target, which produces global structure deformation with undetected internal damage at points far from the contact region (45).

VI. FAILURE MODES IN IMPACT TEST

Impact behaviours and impact damage depend on many parameters such as the projectile/impactor shape, impact velocity and energy, boundary conditions and lay-up sequence (46). Furthermore, laminated fibre reinforced composite materials have various damage modes such as fibre breakage, matrix cracking, and delamination. These various damage modes appear together under the impact loading (47).The polymer matrix composites' response to impact laminates is important. In an impact event, internal damage was formed in the composite laminates and expanded around the impact area (48), reducing the composite stiffness and strength. Most of the kinetic energy of the projectile was expended in the plastic deformation of the target material before perforation due to the better bending stiffness of the target plate. Possible failure modes in composites subjected to impact loading according to their stages are shown in Figure 5:

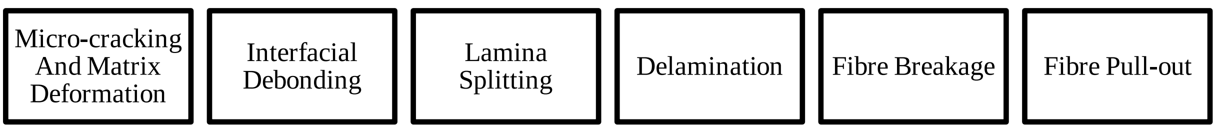

Figure 5: Possible Failure Modes in composites (11)

6.1 Matrix cracking

Matrix cracking is the first type of failure, usually caused by low-velocity impact and occurs parallel to the fibres due to tension, compression and shearing. Shear cracking (inclination of 45º) and bending cracking (vertical inclination) are examples of matrix cracking. It is the first damage that affects the structure but cannot be seen by naked eye. The impact response of the structure is not affected by matrix cracking (49). It can decrease the interlaminar shear and compression strength properties on the resin or the fibre/resin interface. Micro-cracking can have a very negative effect on a high temperature resin's properties (50).

6.2 Delamination

In a low velocity impact, the most critical damage mechanism in composites is delamination. Delaminations form between the layers in the laminate. It may be initiated by matrix cracks when the threshold energy has been reached or from low energy impact. Delamination can dramatically reduce the post-impact compressive strength of the laminate (51). Bending cracks and shear cracks are also responsible for delaminations. Delaminations are frequently generated in composite laminates due to out-of-plane impacts, and many experiments and analytical studies on low-velocity impact damage [(52) and (53)] have been conducted assuming tool drops.

6.3 Fibre Failure

Fibre pull out and fibre breakage are the most common failures under low velocity impact testing (54). Fibre failure occurs because of the high stress field and indentation effects. The projectile induces a shear force and high bending stresses in the non-impacted side of the specimen.

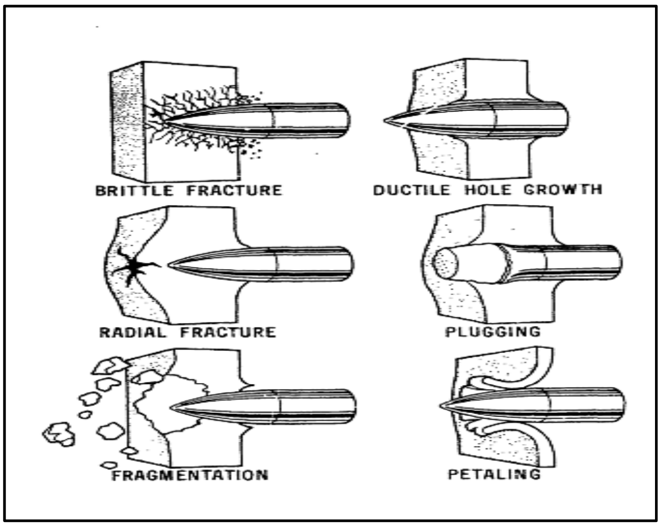

Figure 6: Failure Modes in impacted plate (55)

Figure 6and

Table 4show the most common failure modes experienced by the impacted specimen in high velocity impact testing. According to Zukas(55), failure modes depend on parameters such as the material's properties, the impact velocity, the projectile nose shape, the target geometry, the support conditions, the relative mass of the projectile and the target.

Table 4: Failure Modes in an impacted plate(55)

Brittle Fracture	It is initiated when the maximum normal stress surpasses a tensile threshold.
Ductile Hole Growth	It is initiated when the average stress exceeds a tensile pressure criterion.
Radial Fracture	It is common in materials such as ceramics where the tensile strength is lower than the compressive strength.
Plugging	It occurs when the projectile pushes a plug out of the target approximately equal in diameter to that of the projectile. This type of failure usually occurs when blunt projectiles are used.

Petaling	It occurs when the tensile strength is exceeded at the rear side of the target, and it develops a star-shaped crack around the tip of the projectile. Petals are formed when the sectors are pushed back by the motion of the projectiles.

VII. STRUCTURAL HEALTH MONITORING (SHM)

An aircraft needs to operate in extreme conditions such as undergoing high loads, high fatigue cycles and extreme temperature differences. Hence, it is important to inspect the structural condition to make sure the aircraft will operate safely and efficiently. Damages are tolerable in aircraft throughout operation as long as they are within safe limits in order to achieve lighter aircraft structure (56). In the last few decades, non-destructive testing and valuation techniques have been employed to measure the health of aircraft structures.Damages in aircraft can be in several categories such as corrosion, fatigue, accidental (impact) damage, and associated repairs. Vlot (57) reported that at least 13% of 688 repairs to 71 Boeing 747 fuselages were related to impact damage. Vlot(58) also reported that impact damage is usually located around the doors, on the nose of the aircraft, in the cargo compartments and at the tail (due to tail scrape over the runway).

Impact damage on aircraft is affected by runway debris (in the order of 60 m/s), hail (on the ground 25 cm and 60 m/s and in flight in the order of hundreds of metres per second), maintenance damage or dropped tools (less than 10 m/s), collisions between service cars or cargo and the structure (the velocity is low), bird strikes (high velocities), ice from propellers striking the fuselage, engine debris, and ballistic impact (for military aircraft) (58). According to a composite aircraft design handbook (59), damage criteria are grouped into five categories subject to the severity of the damage. The first category is barely visible impact damage (BVID), and the second category is visible impact damage (VID). Barely visible impact damage (BVID) is damage that can rarely be seen using the naked eye. Visible impact damage (VID) is damage to the specimen that can be easily seen using the naked eye. Both types of damage can be evaluated using post impact testing. There are two types of structural health monitoring methods (SHM); Passive SHM methods and Active SHM methods. More details on both types are as shown in Figure 7.

Passive SHM	Active SHM
• As example: acoustic emission, impact detection, strain measurement. • This method is needed for continuous monitoring.	• Able to perform on-demand interrogation of a structure even when the structure is still in service.

Figure 7: Types of Structural Health Monitoring Method (60)

The main NDT techniques for composite materials are: Visual Inspection; Optical methods; Eddy-current (electro-magnetic testing); Ultrasonic Inspection; Laser Ultrasonic; Acoustic Emission; Vibration analysis; Radiography; Thermography; Lamb waves (61). Previous research studies have used various methods to detect impact damage such as by using X-rays (62), C-scans (63), Scanning Electron Microscopes (SEM) (64), and (65) optical microscopes. It is essential to determine the existence and location of the damage..

VIII. CONCLUSION

Most importantly, material properties and the thickness of the laminates influence the impact dynamics. The characteristics of the projectile – including its weight, shape, elastic properties and incident angles are other parameters to be considered. These review areas include: an introduction and classification of composites, low-velocity impact testing, high velocity impact testing and modes of failure in composites. The application of composite materials has become increasingly popular, especially in aerospace structures.The advantages of using composites in aircraft structures are; weight reduction, high corrosion resistance and high resistance to damage from fatigue. These factors play a role in reducing the operating costs of the aircraft in the long term, further improving its efficiency.

IX. ACKNOWLEDGEMENTS

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Biographies

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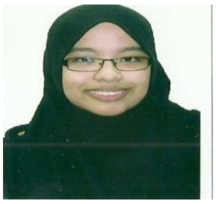

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