The International Journal Of Engineering And Science (IJES)
|| Volume || 3 || Issue || 7 || Pages || 08-20 || 2014 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

Impact Damage on Composite Structures – A Review

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ABSTRACT

This paper is a study of impact damage for composite material. The damage of composite structures caused by impact events is one of the most critical behaviours that inhibits more widespread application of composite material. It is important to study and understand the damage mechanism in order to produce effective designs for composite structures. The aerospace industry is one of the industries that uses composite material widely in its structures. The failure caused by impact damage will contribute to unexpected scenarios. This paper discusses damage in composite material, impact in composite material, classification of impact, impact response, high velocity impact, energy absorption and impact force of composites, and modes of failure.

KEYWORDS: *Impact Damage, High Velocity Impact, Impact Force, Impact Energy, Modes of Failure*

Date of Submission: 25 June 2014 Date of Publication: 20 July 2014

I. INTRODUCTION

In recent years, impact damage induced in laminated composites used for primary load-bearing structures has been, and still remains, an area of great concern. This high level of concern stems from the fact that impact damage occurs in various forms such as matrix cracking, fibre/matrix debonding, surface microbuckling, delamination, and fibre breakage, and that the different forms of impact damage affect the various laminate properties to different degrees [1].Glass/polyester laminate structures are widely employed in the aeronautics as well as the naval and ground-transport industries owing to their good mechanical properties, low manufacturing costs, and permeability to electromagnetic waves. Although these kinds of structures are not designed as armour, they could be subjected to high-velocity impacts of low-mass fragments, and this requires deeper knowledge of their response to impacts of this type. Impact damage could significantly diminish their strength, although this may not be visually detectable [2]. This is one of the main reasons why the use of laminate-type composite materials is limited [3]. In this paper, reviews are based on the damage in composite materials, impacts on composite materials as well as failure modes in composite structures.

II. DAMAGE IN COMPOSITE MATERIAL

Composite is not atmospherically oxidised. Therefore maintenance can be reduced. Atmospheric oxidation is the main reason for the maintenance of metal parts. Composites are much more susceptible to damage caused by heat and ultraviolet light than metal. Both heat and ultraviolet light can degrade the resin composite by initiating chemical reactions such as oxidation. Oxidation of the epoxy resin due to heat damage can reduce the physical properties and mechanical strength of a composite [4]. Severe degradation of the resin component may reduce the overall strength of the composites often leading to premature failure. Thermal pressure caused by lightning, engine overheating or engine fire has been observed to cause loss of mechanical strength, enbrittlement and finally cracking.When composites were introduced into aircraft components, unexpected damage from in-service conditions occurred. Most of the damage was categorised as internal defects and generally consisted of matrix cracking which was not easily detected on the surface of the specimen. This may have been due to impacts during flight operations, such as runway debris impacting on composite airframes, bird-strikes during flight operations, or the dropping of hand tools during maintenance work. Under repeated or impact loads these materials were subjected to various forms of damage, mostly delamination and cracks [5].In the laminated composites usually used in aircraft applications, damage can appear in various forms: matrix cracking, fibre fracture, fibre pull-out and delamination. These are all possible damage mechanisms which can be faced by composite laminates in the event of impact. When these materials are subjected to impacts, the structural integrity, stiffness and toughness of the material are significantly reduced, resulting in catastrophic failure of the structure in extreme scenarios. Impact damage can cause a reduction in the performance of composite structures.

III. IMPACT ON COMPOSITE MATERIAL

In aviation, the collision of two or more bodies can range from dropped objects, the collision or grounding of vessels, the collision of vehicles or aircrafts to accidental impacts like bird strikes. Due to the increasing focus on the impact problem, it is important to understand the material's behaviour when subjected to impulsive loading. Impact is defined as the collision between two or more bodies, where the interaction between the bodies can be elastic, plastic, fluid or any combination of these. The impact velocity is one of the fundamental quantities in impact dynamics [6]. After the impact event, a series of physical phenomena takes place such as elastic, shock, and plastic wave propagation, fracture and fragmentation, perforation, and spallation [7]. Impact damage in aircraft can be caused by different sources [8]. In general, there are four types of velocity:-, low, high, ballistic and hypervelocity. A low velocity impact (<11 m/s) may occur through damage from, for example, service trucks, cargo containers, dropped tools during maintenance operations, etc. 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. Damage can also be caused by ballistic impact (>500 m/s) which is normally a concern for military applications. Finally, there is hypervelocity impact (>2000 m/s), e.g. the impact of space debris on a spacecraft. The impact problem can be simplified by dividing it into two separate conditions: low velocity impact by a large mass (dropped tool) and high velocity impact by a small mass (runway debris, small arms fire, etc.) [9]. The impact object may cause internal damage that is often hard to detect and this can result in a severe reduction in the strength and stability of the structure;-, thus the effect of foreign objects impacting on composite material is a major problem [10].

Composites have been widely used in aircraft, aerospace, marine, and automotive structures. However, composite materials have serious limitations. One of the most significant amongst these is their response to localised impact loading such as that imparted by a dropped tool or runway debris [11 – 15]. Internal damage can be formed in composite laminates extending well beyond the impacted area, and this will significantly reduce the strength and stiffness of the composite [16]. Composite materials' response to impact loading and also the dissipation of the incident kinetic energy of the projectile is very different when compared to metals. For low and intermediate incident energies, metals absorb energy through elastic and plastic deformation. Although these will result in permanent structural deformation, the consequences on the load carrying capability of the component are usually small compared to composites [17]. However, the ability of the composites to undergo plastic deformation is extremely limited as the resultant energy is frequently absorbed in creating large areas of fracture with ensuing reductions in both strength and stiffness [18].

The prediction of the post-impact load bearing capability of a damaged composite structure is more difficult than for metals. The damage zone of a composite is generally complex in nature and very difficult to characterise. The problem is further complicated by the lack of existing standards or established testing techniques for the impact damage of composite materials. Much of the work published in the literature has been conducted on purpose-built machines using convenient specimen geometries. As a result, direct comparisons between different material systems are often very difficult and immediate conclusions are sometimes hard to draw [19]. At high incident impact energies, target perforation may occur and the passage of the impactor will generally result in petalling, cracking and spalling. Although such damage will degrade the load-bearing ability of the structure, its effects can generally be predicted using fracture mechanics principles [19].

The term projectile is used for any item capable of being launched. The target is defined as any moving or stationary object struck by the projectile. Projectiles can be categorised as soft, semi-hard or hard depending on the material that is used and the degree of deformation they undergo during impact. Soft projectiles undergo significant deformation during impact, semi-hard projectiles experience some deformation, while hard projectiles experience small or negligible deformations and the response is dominated by the target response [20]. The ballistic limit velocity is commonly used to measure a material's ability to withstand impact by a certain projectile. The ballistic limit is defined as the greatest impact velocity that the material can withstand without being perforated. The ballistic limit is obtained from the average of the greatest velocity that does not lead to perforation and the lowest velocity leading to perforation. A low velocity impact happens when the contact time of the impactor is longer than the time for the lowest vibrational mode. The support conditions are important as the stress waves generated outward from the impact point have time to reach the edges of the structural element, causing its full-vibrational response. In a high velocity impact, the response of the structural element is governed by the 'local' behaviour of the material in the neighbourhood of the impacted zone, the impact response of the element being generally independent of its support conditions. The contact period of the impactor is much smaller than the time period of the lowest vibrational mode of the structure [21].

To simplify the problem, the target is classified according to its thickness. If there is no influence of the lateral boundary on the penetration process, the target is semi-infinite. The target is thick if there is influence of the lateral boundary only after significant travel of the projectile into the target. The target thickness is intermediate if the rear surface exerts considerable influence on the deformation process during nearly the entirety of the projectile motion. Finally, the target thickness is said to be thin if there is no through-thickness stress gradient. Other characteristics of the target include shape (flat, curved, serrated, irregular and circular or rectangular), composition (monolithic plate, composites, spaced plates, etc.) and boundary conditions (free, simply supported and clamped) [22]. Penetration means projectile entry into any region of the target and includes perforation, containment and rebound. Perforation means that the projectile passes through the target with a final residual velocity. Containment or embedment means that the projectile is stopped during contact with the target. Rebound or ricochet means that the projectile is deflected from the target with a final rebound velocity [22].

Table 1 provides very useful information about the different velocity regimes and their corresponding application and test methods [21].

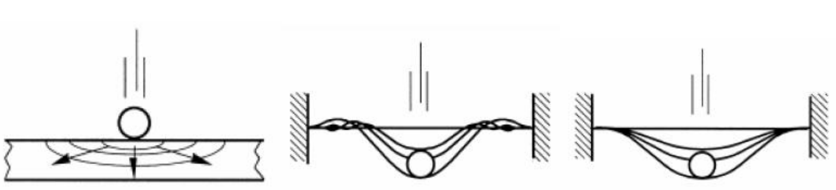
Table 1: Velocity regimes and corresponding applications for test methods [21].

Velocity regime	Impact test equipment	Material test method	Typical applications
Low velocity 0-50 m/s	▪ Drop hammer ▪ Pneumatic accelerator	Quasi-static testing machines: ▪ Hydraulic ▪ Servo-hydraulic ▪ Screw-driven	▪ Dropped objects ▪ Vehicle impact/ ship collision ▪ Crash-worthiness of ▪ Containers for hazardous materials
Sub-ordnance 50-500 m/s	▪ Compressed air gun ▪ Gas gun	▪ Pneumatic ▪ Hydraulic ▪ Taylor impact tests ▪ Split Hopkinson ▪ Pressure bar (SHPB) or Tension bar (SHTB)	▪ Design of nuclear containment ▪ Free-falling bombs & missiles ▪ Fragments due to accidental explosions
Ordnance 500-1300 m/s	▪ Compressed air gun gas gun	▪ Taylor tests ▪ SHPB/SHTB	▪ Military
Ultra-ordnance 1300-3000 m/s	▪ Powder gun ▪ Two-stage light gas gun	▪ Taylor impact test	▪ Military
Hypervelocity >3000 m/s	▪ Two-stage light gas gun	▪ Taylor impact test	▪ Space vessels ▪ Exposed to meteoroid impact& space debris

IV. CLASSIFICATION OF IMPACTS

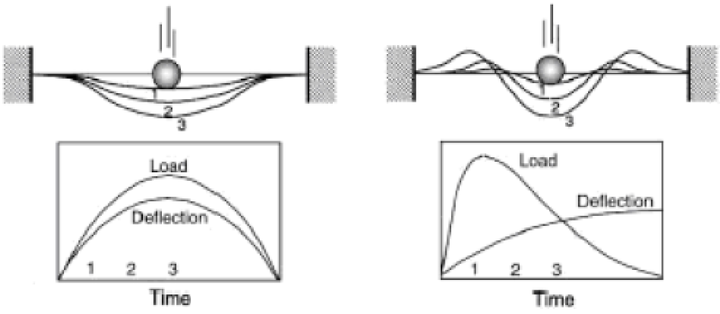
It is well-known that an impact initiates elastic waves propagating from the point of impact. Material damping and energy dissipation related to wave propagation will result in a decaying response. Therefore, the duration of impact plays a key rule in determining the type of impact responses. If the impact duration is in the order of the transition time for dilatational waves, the response will be dominated by through-the-thickness waves, as shown in Figure 1(a). For a longer impact duration, the response will be governed by flexure and shear waves, as shown in Figure 1(b). If the impact duration is much longer than the time for the waves to reach the structure boundaries, the resulting response will be quasi-static. This happens because the deflection and load would have a similar relation as in static loading, as shown in Figure 1(c). Typically, the response in Figure 1(a) is related to ballistic impact. The responses in Figure 1(b) and Figure 1(c) are usually associated with the impact of runway debris and the impact from drop-weights, respectively. In most cases, the response in Figure 1(a) will cause easily detectable impact damage. The responses in Figure 1(b) and Figure 1(c) can cause non-visible impact damage, i.e. barely visible impact damage (BVID). The responses in Figure 1(b) and Figure 1(c) are also designated as wave-controlled and boundary-controlled impacts, respectively [23, 24, 25].

For a boundary-controlled impact, the entire structure is deformed during the impact with the contact force and deformation in phase, as shown in Figure 2(a). However, for a wave-controlled impact, the deformation is localised to the region around the impact point with the contact force and deformation out-of-phase, as shown in Figure 2(b).



(a) (b) (c)

Figure 1: Classification of different impacts [23]



(a) Boundary-controlled (b) Wave-controlled

Figure 2: Comparisons between different impact responses [23]

V. IMPACT RESPONSE

It is important to relate the shape and dimensions of the damage to the geometric characteristics of the sample, the boundary conditions and the test parameters (impact velocity, energy, maximum force, etc.), to better understand the damage mechanisms. This characterisation of the damage will be very useful in the phase of the project of laminated composite components [26, 27]. When subjected to impact loading, fibre reinforced composite materials are capable of absorbing and dissipating large amounts of energy in a wide variety of elastic and fracture processes [27, 28]. Up to the point of initial failure, most of the incident energy of the projectile is absorbed by the elastic response of the structure. This ability to absorb energy elastically is dependent upon a large number of parameters including the mechanical properties of both the fibres and the matrix, the fibre/matrix interfacial strength, the velocity of the impinging projectile and the size of the structural component. In recent years, much work has been undertaken in order to assess the role of the inherent properties of the constituent materials on the impact response of a composite material.

Consequently, in a low velocity impact, the incident energy of the projectile is absorbed by the whole structure, whereas under high velocity impact conditions most of the available energy is dissipated over a small zone immediate to the point of contact. Under conditions of high velocity impact loading, the dynamic response of the target is much localised, the geometrical effects are very small and therefore simple beam-like specimens are capable of simulating the impact response of larger, more complex structures. For the case of drop-weight impact loading, where the contact time is greater and the target response more significant, geometrical effects are likely to be more important.

Usually, impact-induced damage is caused by the interaction of the local indentation and the global deformation of the structure. Impact damage in composite laminates includes a few common damage characteristics, such as matrix cracks, delaminations and fibre ruptures. Delaminations are particularly serious since they can occur at relatively low loads and have a major influence on the flexural stiffness degradation and buckling failure of composite laminated plates. Delaminations in impacted laminates are primarily driven by interlaminar shear stresses. Delaminations are also the main energy absorption mechanism of polymer composite materials, which consists of the creation of fracture areas at the weaker interfaces between the individual composite layers. A typical distribution of delaminations in composite laminates is shown in Figure 3. It indicates that the major axes of delamination are usually oriented in the direction of fibres at the interface of the plies [29].

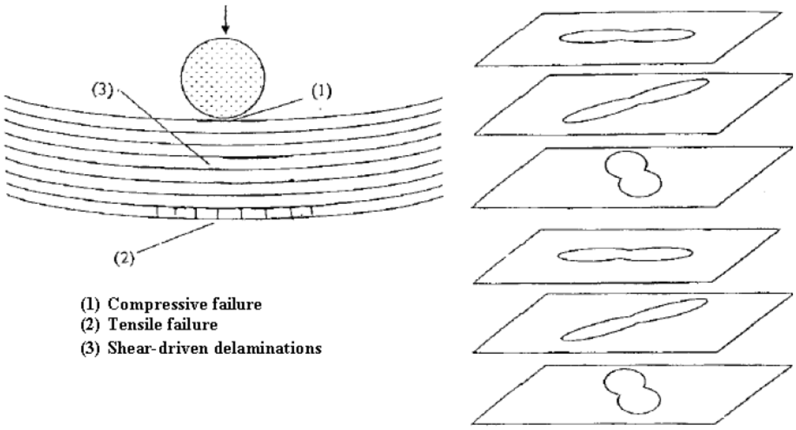


Figure 3: Delamination caused by impact [23]

An efficient approach to study the effect of impact on composite structures is to separately analyse two aspects of impact, namely impact damage resistance and impact damage tolerance. Impact damage resistance addresses the response and damage of the structures caused by an impact. On the other hand, impact damage tolerance deals with the effect of existing impact damage on the strength and stability of the structures.

VI. HIGH VELOCITY IMPACT

High velocity impact is dominated by inertial forces, wave propagation and changes in material stiffness, strength and fracture energy due to a high strain rate [30]. There are many parameters which influence the response of polymer composite materials under high velocity impact, and these include: type, architectures and volume fraction of the reinforcement, laminate thickness, matrix system, projectile geometry and mass [31].

Woven fabric composites exhibit a higher fracture toughness compared with unidirectional laminates under high velocity impact [32]. Mines et al. [33] reported experimentally measured perforation data for woven, woven z-stitched and through-thickness z-stitched E-glass/polyester laminates for high velocity impact tests in a velocity range of 570 m/s, for a variety of projectile nose geometries (cone, flat and hemispherical). They concluded that all three configurations behaved in a similar manner.

Ganesh Babu et al [34] conducted high velocity impact tests using a heavy mass projectile of around 550 g with three nose geometries (conical with sharp, round and flat tip) on one type of unidirectional glass fibre/epoxy composite plates. They reported less influence of nose geometry on the energy absorption and ballistic limit velocities for a thin section target, and a much greater role with increasing target thickness. One area which has received less attention is the response of polymer composite materials made from various reinforcements towards very sharp tip projectiles under relatively high velocity impact [35].

Usually, high velocity impact tests were carried out using a single stage gas gun. Figure 4 shows an example of a single stage gas gun used in the testing by Sultan et. al. [36]. The rig consisted of the pressure reservoir unit, the firing mechanism unit, the launching unit, the catch chamber unit and the velocity measurement unit. The gun is projected to have the capacity to launch a projectile with muzzle velocity of less than 700 m/s at a reservoir tank pressure of 150 bar.

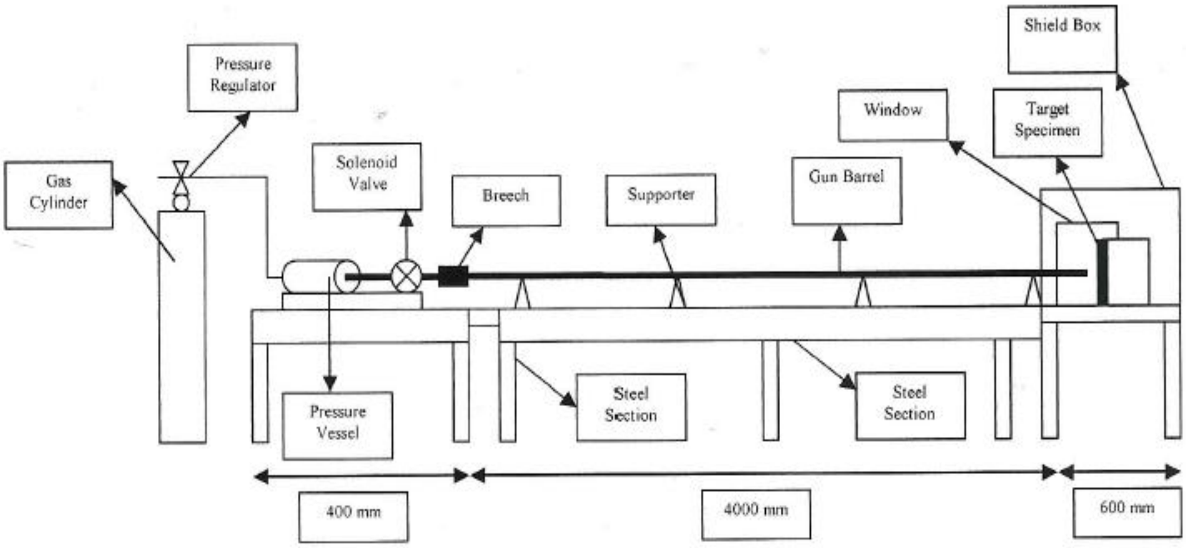


Figure 4: High velocity impact testing device (gas gun) [36].

Table 2 shows the historical developments in the study of composite structures under high velocity impact events from the year 2000 until 2014. The studies include experimental works, analytical formulation and also simulation.

Table 2: Historical developments in the study of composite structures under high velocity impact events.

Refs.	Year	Key aspects
[37]	2000	- High velocity impact on integral armour was studied using the finite element method DYNA3D.
[38]	2002	- Impact perforation behaviour of CFRPs was investigated using a high-velocity steel sphere.
[39]	2003	- Spherical-shaped ice simulating hailstones were projected onto woven carbon/epoxy composite panels to determine the damage resistance of thin-walled composite structures to ice impact, and to observe the resulting damage modes that occur over a wide range of velocity.
[40]	2004	- The high velocity impact response of composite and FML-reinforced sandwich structures has been investigated using a nitrogen gas gun.
[41]	2008	- Damage evaluation of the local damage of concrete plates caused by high-velocity rigid projectile impact.
[42]	2009	- A combined experimental and numerical approach was used to study the ballistic impact response of S2- glass fibre toughened epoxy composite beams using a high speed gas gun.
[43]	2009	- An analytical model was developed to predict the residual velocity of cylindrical projectiles under high velocity impacts on carbon epoxy laminates.
[30]	2010	- A solution methodology to predict the residual velocity of a hemispherical-nose cylindrical projectile impacting a composite sandwich panel at high velocity was presented.
[44]	2010	- Evaluation of the residual velocity of the projectile and the damage area were investigated through the experimental analysis of perforation of glass/polyester laminate structures subjected to high-velocity impact.
[45]	2010	- The influence of plasma spray surface coating on the ballistic performance of aluminium plates subjected to high velocity impact loads was investigated.
[46]	2010	- Sandwich panels of carbon/epoxy skins and an aluminium honeycomb core were modelled by a three-dimensional finite element model implemented in ABAQUS, subjected to high-velocity impact.
[47]	2011	- Another approach to a hybrid particle-finite element algorithm for high-velocity impact based on the Generalized Particle Algorithm has been introduced and compared to the other computation algorithm.
[31]	2011	- High velocity impact performance of glass reinforced polyester (GRP) resin composite plates with different type of reinforcement was investigated using a sharp tip conical head projectile and a smooth barrel gas gun.
[48]	2011	- The standard material characterisation under compression and fracture modes were

		observed under experimental study of high-velocity impact fracture of ice.
[49]	2011	- Numerical algorithms and material models for high-velocity impact computation were studied.
[50]	2011	- High velocity impact response/failure of sandwich plates, with E-glass fibre/polyester face-sheet and foam core were studied by using finite element models developed in ABAQUS explicit code.
[51]	2012	- Ballistic impact performance of hybrid composite made of Kevlar-29 and Al203 powder/epoxy targets under high velocity impact was studied.
[52]	2012	- The failure of fibre reinforced thermoplastic composites (polypropylene made of hybrid E-glass/PP yarns) was investigated under medium and high velocity impact loading conditions by electromagnetic and acoustic emission signal measurements.
[53]	2012	- Influence of adhesive thickness on high velocity impact performance of ceramic/aluminium composite targets was examined in this paper through numerical investigations.
[36]	2012	- Effect of thickness for glass epoxy laminated plates was examined under high velocity impact damage analysis.
[54]	2013	-The comparison between the mechanical and ballistic performance of composite laminates (Kevlar-29 multifilament yarn) produced from single-layer and double-layer interlocked woven structures was studied.
[55]	2013	- The effect of different construction textile designs of aramid fabric on the ballistic performances, specifically on the energy dissipation and projectile arrest for soft body armour, was investigated in this study.
[56]	2013	- The response of carbon fibre reinforced polymer (CFRP) laminates subjected to high velocity impact has been investigated by experimental and numerical methods using a two-stage light gas gun.
[57]	2013	- Energy absorption efficiency of different thickness was investigated.
[58]	2013	- High velocity impact response of sandwich structure composite laminated plates, Kevlar-29 epoxy and 6061-T6 aluminium, has been experimentally investigated using a nitrogen gas gun.
[59]	2013	- A bird strike was simulated by using the explicit finite element solver code LS-Dyna, and then SPH high velocity impact parametrics were studied.
[60]	2013	- High velocity projectile impact through different thickness of polyurea coated AA5083-H116 aluminium alloy plates has been studied in this paper.
[61]	2014	- Shielding performances of 2024 aluminium alloy panel, carbon fibre reinforced polymer composite (CFRP) panel and hybrid laminates with different stacking configurations were investigated being impacted by hypervelocity flyer.
[62]	2014	- The effect of impact force on Ti-10Mo alloy powder compaction by the high velocity compaction technique was investigated.
[63]	2014	- The effect of high velocity impacts and energy absorbed by the laminate on carbon/epoxy tape quasi-isotropic laminates was studied.
[64]	2014	- An experimental and numerical study of the influence of tensile and compressive preloading on the high velocity impact performance of T800S/M21 carbon/epoxy plates was conducted.
		- The effect of foam density variations in composite sandwich panels under high velocity impact loading was investigated in this study.

VII. ENERGY ABSORPTION AND IMPACT FORCE OF COMPOSITE

Impact forces are forces due to a collision between two objects. Impact force can also be described as a force that delivers a shock or a high impact, normally for a short period of time. The impact force's effect is dependent on the relative velocity of those bodies with respect to one another. The faster the bodies are moving, the higher the impact's force will register. When two materials collide with one another at normal speeds, one will absorb most of the impact by deforming and then dispelling the energy in the form of heat and/or sound energy as a result of the deformations and vibrations induced in the struck object [65].The time response for a high velocity impact is very short and it is unlikely that the material's deformations and vibrations will occur. Thus, the struck material behaves as if it was more brittle than it is, and the majority of the applied force goes into fracturing the material. Or, another way to look at it is that materials actually are more brittle on short time scales than on long time scales [66]. To simplify it, the faster the impact, the more it may impact a material, causing it to act as if it were actually a brittle material.

The behaviour of composite energy is affected by several factors, such as the composite material and properties, condition, geometry, and dimension of the structural component and finally the test condition [67]. The absorbed energy required to produce fracture surfaces in a specimen will be recorded in the unit of Joule. The impact test is useful to determine the material toughness and it is also defined as the energy absorbed by a specimen without fracture [68]. A highly stressed and greatly deformed material is able to withstand a higher impact and is tougher.

The energy absorption characteristics of a crashworthy composite structure can be tailored by controlling various parameters like fibre type, matrix type, fibre architecture, specimen geometry, process conditions, fibre volume fraction and testing speed. Changes in these parameters can cause subsequent changes in the specific energy absorption of composite materials up to a factor of 2 [69].

There are several factors influencing energy absorption characteristics, which are [69]:

1. **The type of reinforcing fibre used in a composite material determines to a very large extent its energy absorption characteristics such as:**
   a. A decrease in the density of the fibre causes an increase in the specific energy absorption capability of the fibre-reinforced tubes.
   b. The higher the strain to failure of the fibre, the greater the energy absorption capabilities of the fibre reinforced tubes.
   c. When the fibre reinforced tubes crush in similar modes, changes in the fibre stiffness affect the energy absorption capability less than fibre failure strain.

2. **The effects of the matrix on the energy absorption capability of a composite material are:**
   a. A higher interlaminar fracture toughness of the thermoplastic matrix material causes an increase in the energy absorption capability of the composite material.
   b. An increase in matrix failure strain causes greater energy absorption capabilities in brittle fibre reinforcements. Conversely, the energy absorption in ductile fibre reinforcements decreases with increasing matrix failure strain.
   c. Changes in matrix stiffness have very little effect on the energy absorption capability of composite materials with ductile fibre reinforcement.

The energy absorption of materials that fail by transverse shearing or brittle fracturing is little affected by matrix stiffness. However, materials failing due to lamina bending can be more significantly affected by matrix stiffness. Any changes in matrix stiffness can cause brittle fibre composites to fail in a different mode. However, changes in matrix stiffness have very little effect on the energy absorption of ductile fibre reinforcements [70].

3. **The fibre orientations that enhance the energy absorption capability of the composite material are:**
   a. Increase the number of fractured fibres.
   b. Increase the material deformation.
   c. Increase the axial stiffness of the composite material.
   d. Increase the lateral support to the axial fibres

The orientation of fibre, θ is varied from 0^o to 90^o on glass/epoxy, carbon/epoxy, and Kevlar/epoxy. The specific energy of the carbon/epoxy tubes initially decreased with increasing θ up to 45^o and then remained constant. This initial decrease in the energy absorption is attributed to the reduction in axial stiffness of the composite material with increasing θ. The specific energy of the glass/epoxy and Kevlar/epoxy tubes remained constant with increasing θ up to 45^o and above this value it increased. The increase in energy is due to the increased lateral support to the axial fibres with increasing θ. Thus, it can be concluded that for carbon/epoxy, the energy absorption decreases nonlinearly as θ increases and the mode of damage is primarily brittle fracture. While for glass/epoxy, the energy absorption increases nonlinearly with an increase in θ and the mode of failure is lamina bending [70].

4. The effects of projectile nose shape on the energy absorption capability of a composite material are:

The nose shape of projectiles is an important factor affecting the mechanism of deformation of the target plates [71]. The blunt projectile can penetrate more efficiently an aluminium alloy specimen, followed by hemispherical and conical nosed projectiles, with the condition target thickness to projectile diameter ratio being less than one [72]. Blunt projectiles penetrated the target more efficiently than conical projectiles when the thickness of the target was moderate [73]. For the case of thin and thick targets, however, an opposite trend was observed. Borvik et al. (2002) [74] studied the impact behaviour of steel plates when struck by blunt, hemispherical and conical nosed projectiles. They found from experiments that blunt projectiles were more efficient penetrators than hemispherical and conical projectiles at low velocities. However, at higher impact velocities, the conical projectile required less energy to perforate the target.

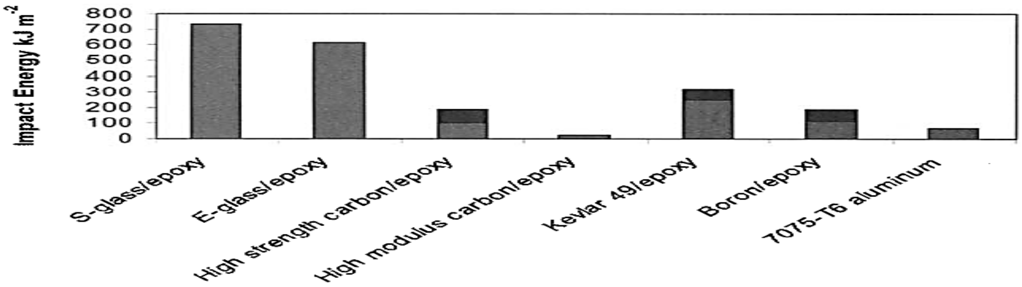


Figure 5: Charpy impact energy absorption of some composite and non- composite materials

Figure 5 illustrates the relative energies for failure under impact of fibre glass and other materials. The test was measured with the Charpy test method. Based on the Figure 5, S-glass-fibre composites have the highest capacity for energy absorption followed by E-glass and then aramid composites. High-strength carbon/epoxy has a significantly lower energy-absorbing capability than these materials and high-modulus carbon/epoxy, the lowest of all the composites. The exceptionally high impact toughness of S-fibre glass has led to its application in ballistic protective materials. This research has shown that glass/epoxy composites have the highest impact energies, with S-glass/epoxy composites being 4-7 times more impact-resistant than high strength carbon/epoxy laminates and about 35 times more resistant than high-modulus carbon/epoxy materials. Glass/epoxy composites are 9-11 times more impact resistant on this basis than aircraft grade aluminium alloy [75].

VIII. MODES OF FAILURE

The properties of fibre, matrix and the inter phase region, affect the threshold energies or stresses required to initiate the different failure modes induced by impact [76]. Types of impact can be classified according to the damage incurred. High velocity can be characterized by penetration induced fibre breakage, and low velocity by delamination and matrix cracking.

The kinetic energy of the projectile when impacted into the target is dissipated and absorbed in various ways by the target. The main energy absorbing mechanisms during ballistic impact are:

a. Kinetic energy absorbed by the moving cone formed on the back face of the target.
b. Shear plugging of the projectile into the target.
c. Energy absorbed due to tensile failure of the primary yarns.
d. Energy absorbed due to elastic deformation of the secondary yarns.
e. Energy absorbed due to matrix cracking and delamination and frictional energy absorbed during penetration.

A variety of failure modes may lead to perforation. The failure modes of the target will vary depending on the material's properties, impact velocity, projectile nose shape, target geometry, support conditions, relative mass of projectile and target, etc. The most common failure modes are shown in Figure 5 [20].

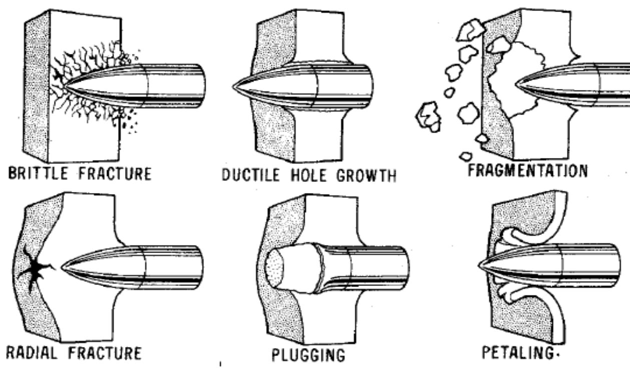


Figure 5: Common failure modes of target

The most relevant failure modes in the present research are brittle fracture and petaling. A brittle fracture occurs as a result of tensile stress acting normal to the crystallographic planes with low bonding when the projectile hits the material's surface. Petaling occurs when the tensile strength is exceeded at the rear side of the target and a star-shaped crack develops around the tip of the projectile. The sectors formed are then pushed back by the motion of the projectile, forming petals.

The heterogeneous and anisotropic nature of fibre reinforced plastic (FRP) laminates result in four major modes of failure due to low velocity impact:

a. Matrix failure: The cracking occurs parallel to the fibres due to tension, compression or shear.
b. Delamination: This is produced by interlaminar stresses.
c. Fibre failure: Tin-tension fibre breakage and in compression fibre buckling.
d. Penetration: The penetrator completely perforates the impacted surface. [77]

a. Matrix damage

Matrix damage is the first type of failure induced by a transverse low-velocity impact. Normally, this takes the form of matrix cracking and bonding between the fibre and the matrix. Matrix cracks occur due to property mismatching between the fibre and the matrix, and are usually oriented in planes parallel to the fibre direction in unidirectional layers.

b. Delamination

Delamination is a crack which runs in the resin-rich area between plies of different fibre orientation; it is not between lamina in the same ply group. Delamination is a result of the bending mismatch coefficient between the two adjacent laminates, such as different fibre orientations between the layers. The greater the mismatch (0/90 is the worst-case fibre orientation), the greater the delamination area will be [75]. This will affect the material's properties, stacking sequence and laminate thickness. Both bending cracks and shear cracks could initiate delamination, but the delamination induced by shear cracks is unstable and the bending crack induced delamination grows in a stable manner and proportional to the applied load.

c. Fibre failure

This damage mode generally occurs much later in the fracture process than matrix cracking and delamination. Fibre failure occurs under the penetrators due to locally high stresses and the indentation effects of shear forces, and on the non-impacted face due to high bending stresses. Fibre failure is a precursor to the catastrophic penetration mode.

d. Penetration

Penetration is a macroscopic mode of failure. It occurs when the fibre failure reaches a critical extent, enabling the penetrators to completely penetrate the material. It is easy to predict the orientation of matrix cracking fibres of unidirectional layers, while the crack patterns of randomly oriented layers are less easy to establish.

IX. CONCLUSIONS

As composite materials have been introduced into aerospace industries, unexpected impacts also may occur. These may be due to many impact scenarios such as runway debris and bird strikes. Composite structures are brittle not ductile. Most composites can only absorb energy through damage mechanisms and in elastic deformation, but not via plastic deformation. Thus, composites can fail in a wide variety of modes and these severely reduce the structural integrity of the component. Impact damage on composite aircraft can go undetected for long periods until catastrophic failure, such as the separation of major structures. The drastic reduction in residual compression strength and less reduction in tensile strength resulting from impact damage, are a major issues in the design and airworthiness certification of these composites. Therefore, there is a need to study impact damage and the mode of failure so that continuous structure health monitoring can be performed to prevent any major incident and catastrophic failure. It is important to know the impact response, impact energy and impact force absorbed by the material before its failure in order to produce an effective design for a structure. Based on previous research, studies on experimental, analytical formulation and simulation were carried out to mimic the real impact in evaluating impact damage progression.

ACKNOWLEDGEMENT

This work is supported by UPM under GP-IPM grant, 9401300.

REFERENCES

[1]. G. Zhou, "*Damage Mechanisms In Composite Laminates Impacted By A Flat-Ended Impactor"*, Department of Aeronautics, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BY, UK, Composites Science and Technology 54 (1995) 267-273.

[2]. S.I. Ibekwe, P.F. Mensah, G. Li, and S.S. Pang, "*Impact and post impact response of laminated beams at low temperatures"*, Stubblefield MA, Compos Struct (2007), 79:12–7.

[3]. V.J. Hawyes, P.T. Curtis, and C. Soutis, "*Effect of impact on the compressive response of composite laminates"*, Compos Part A-Appl S (2001), 32:1263–70.

[4]. J. Seelenbinder, "*Composite heat damage measurement using the handheld Agilent 4100 ExoScan FTIR, Easy, non-destructive analysis of large parts*", Agilent Technologies, Connecticut, USA, (2011), 5990-7792EN.

[5]. K. Anefaie, M. Abd-Rabou, and N. Bajaba, "*Finite Element Modeling of multi-Layer Composite Plates with Internal Delamination*", Jeddah, Saudi Arabia, ICSV14 Cairns, Australia, COMPOS STRUCT (2009), 90(1):21-27.

[6]. T. Børvik, "*An introduction to impact and penetration dynamics*", Department of Structural Engineering, Norwegian University of Science and Technology (2003).

[7]. M.A. Meyers, "*Dynamic behavior of materials*", Wiley, New York (1994), ISBN 0-471-58262-X. Vlot, and J.W. Gunnink, "*Fibre metal laminates, an introduction*", Dordrecht, the Netherlands: Kluwer Academic Publishers (2001).

[8]. A. Vlot, and J.W. Gunnink, "*Fibre metal laminates, an introduction*", Dordrecht, the Netherlands: Kluwer Academic Publishers (2001).

[9]. W.J. Cantwell, and J. Morton, "*The impact resistance of composite materials---a review*", Composites. (September 1991), Volume 22, Number 5, 347–362.

[10]. S. Abrate, "*Impact on composite structures*" Cambridge, UK: Cambridge University Press (1998), ISBN 0-521-47389-6.

[11]. C.H. Harris, J.H. Starnes Jr., and M.J. Shuart, "*Design and Manufacture of Aerospace Composite Structures, State-of-the Art Assessment*", Journal of Aircraft (2002), Vol. 39 No. 4, pp. 545-560.

[12]. W.T. Freeman, "*The Use of Composites in Aircraft Primary Structure*", Composites Engineering (1993), Vol. 3, DOI:10.1016/0961-9526(93)90095-2.

[13]. S.K. Mazumdar, "*Composites Manufacturing Materials, Product, and Process Engineering*", CRC Press (2001).

[14]. J. Pora, "*Composite Materials in the Airbus A380, From History to Future*", Airbus, Large Aircraft Division (2001).

[15]. M.C. Niu, "*Composite Airframe Structures*", Materials, Conmilit Press Ltd, Third edition, Hong Kong (2010).

[16]. J.F. Laliberté, C. Poon, P.V. Straznicky, and A. Fahr, "*Applications of fibre-metal laminates*", Polym Composite (2004), Vol. 21, Issue 4, pages 558–567, August 2000.

[17]. F.J. Bradshaw, G. Derey, and G.R. Skley, "*Impact resistance of carbon reinforced plastics*" RAE TR (1972), 72240.

[18]. Retem, "*Residual flexural strength of FRP composite specimens subjected to transverse impact loading*" SAMPE Journa124 (1988) No 2, 24:19–25.

[19]. J.G. Avery, "*Design Manual for Impact Damage Tolerant Aircraft Structures*", AGARDograph No 238 NATO, (1981), ISBN92-835-1403-3.

[20]. JA. Zukas, et al. "*Impact dynamics*" John Wiley & Sons, New York; (1990).

[21]. F. Grytten, "*Low-Velocity Penetration of Aluminium Plates*" Norwegian University of Science and Technology (2008) NTNU, ISSN 1503-8181; 2008:46.

[22]. M.E. Backman, and W. Goldsmith, "*The mechanics of penetration of projectiles into targets.*" Int. J. Eng. Sci (1978) Vol. 16, Issue 1, Pages 1–99.

[23]. Daihua Zheng." *Low Velocity Impact Analysis of Composite Laminated Plates"*. Ph.D. Thesis. The Graduate Faculty of the University of Akron, (2007).

[24]. W. J. Cantwell and J. Morton. " *Impact Perforation of Carbon Fibre Reinforced Plastic*." Department of Aeronautics, Imperial College, Exhibition Road, London SW7, UK, (1990) Vol. 38, Issue 2, Pages 119–141.

[25]. M. Uyaner and M. Kara. " *Dynamic Response of Laminated Composites Subjected to Low-velocity Impact*. "Journal of Composite Materials, (2007), vol. 41 no. 24 2877-2896

[26]. Y.P. Siow, and V.P.W. Shim, "*An Experimental Study of Low Velocity Impact Damage in Woven Fibre Composites*", Journal of Composite Materials, (1998) vol. 32 no. 12 1178-1202.

[27]. N.F. Rilo, and L.M.S. Ferreira, "*Experimental study of low-velocity impacts on glass-epoxy laminated composite plates*", Portugal, (2007) Vol. 4, Issue 3, pp 291-300.

[28]. W. J. Cantwell, and J. Morton. "*Geometrical Effects in the Low Velocity Impact Response of CFRP*". Department of Aeronautics, Imperial College of Science and Technology, London SW7 2AZ, UK, (1989) Vol. 12, Issue 1, Pages 39–59.

[29]. G.A.O. Davies, and R. Olsson, "*Impact on Composite Structures*", The Aeronautical Journal, Vol. 108, No. 1089, pp. 541-563, 2004.

[30]. Michelle S. Hoo Fatt*, and Dushyanth Sirivolu, "*A wave propagation model for the high velocity impact response of a composite sandwich panel"* Department of Mechanical Engineering, The University of Akron, Akron, OH 44325-3903, USA International Journal of Impact Engineering 37 (2010) Vol. 37, Issue 2, Pages 117–130.

[31]. Alireza Sabet, Narges Fagih b, and Mohammad Hosain Beheshty a,* "*Effect of reinforcement type on high velocity impact response of GRP plates using a sharp tip projectile"* Tehran, Iran International Journal of Impact Engineering 38 (2011) Vol. 38, Issues 8–9, Pages 715–722.

[32]. J.K. Kim, and M.L. Sham, "*Impact and delamination failure of woven-fabric composites"*. Compos Sci Technol (2000), Vol. 60, Issue 5, Pages 745–761.

[33]. R.A.W. Mines, A.M. Roach, and N. Jones, "*High velocity perforation behavior of polymer composite laminates"*. Int J Impact Eng (1999), Vol. 22, Issue 6, Pages 561–588.

[34]. M. Ganesh Babu, R. Velmurugan, and N.K. Gupta, "*Energy absorption ans ballistic limit of targets struck by heavy projectile"*. Latin Am J Solids Structures (2006) vol. 3, pp 21-39.

[35]. N.K. Naik, P. Shrirao, and B.C.K. Reddy. *"Ballistic impact behavior of woven fabric composites: formulation"*. Int J Impact Eng 2006, Vol. 32, Issue 9, Pages 1521–1552.

[36]. M.T.H. Sultan, S. Basri, A.S.M. Rafie, F. Mustapha, D.L. Majid, and M.R. Ajir, "*High Velocity Impact Damage Analysis for Glass Epoxy – Laminated Plates*", Advanced Materials Research (2012) Vols. 399-401 pp 2318-2328.

[37]. Hassan Mahfuz, Yuehui Zhu, Anwarul Haque, Abdelmoniem Abutalib,Uday Vaidya, Shaik Jeelani, Bazle Gama, John Gillespie, Bruce Fink, "*Investigation of high-velocity impact on integral armor using finite element method*", *USA,* International Journal of Impact Engineering 24 (2000) 203-217.

[38]. Keisuke Fujii, Motokazu Aoki, Noriyuki Kiuchi, Eiichi Yasuda, Yasuhiro Tanabe, "*Impact perforation behavior of CFRPs using high-velocity steel sphere*", Japan, International Journal of Impact Engineering 27 (2002) 497–508.

[39]. Hyonny Kim, Douglas A. Welch, Keith T. Kedward, "*Experimental investigation of high velocity ice impacts on woven carbon/epoxy composite panels*", USA, Composites: Part A 34 (2003) 25–41.

[40]. G. Reyes Villanueva, W.J. Cantwell, "*The high velocity impact response of composite and FML-reinforced sandwich structures*", UK, Composites Science and Technology 64 (2004) 35–54.

[41]. M. Beppu, K. Miwa, M. Itoh, M. Katayama, T. Ohno, "*Damage evaluation of concrete plates by high-velocity impact*", Japan, International Journal of Impact Engineering 35 (2008) 1419–1426.

[42]. Ercan Sevkat, Benjamin Liaw, Feridun Delale, Basavaraju B. Raju, "*A combined experimental and numerical approach to study ballistic impact response of S2-glass fibre/toughened epoxy composite beams*",USA, Composites Science and Technology 69 (2009) 965–982.

[43]. J. López-Puente, D. Varas, J.A. Loya, R. Zaera, "*Analytical modelling of high velocity impacts of cylindrical projectiles on carbon/epoxy laminates*",Madrid, Spain, Composites: Part A 40 (2009) 1223–1230.

[44]. Brenda L. Buitrago, Shirley K. García-Castillo, Enrique Barbero, "*Experimental analysis of perforation of glass/polyester structures subjected to high-velocity impact*",Madrid, Spain and Venezuela, Materials Letters 64 (2010) 1052–1054.

[45]. Evren Ozzahin, Suleyman Tolun, "*Influence of surface coating on ballistic performance of aluminum plates subjected to high velocity impact loads*",Turkey, Materials and Design 31 (2010) 1276–1283.

[46]. Brenda L. Buitrago, Carlos Santiuste, Sonia Sánchez-Sáez, Enrique Barbero, Carlos Navarro, "*Modelling of composite sandwich structures with honeycomb core subjected to high-velocity impact*", Madrid, Spain and Venezuela, Composite Structures 92 (2010) 2090–2096.

[47]. G.R. Johnson, S.R. Beissel, C.A. Gerlach, "*Another approach to a hybrid particle-finite element algorithm for high-velocity impact*", USA, International Journal of Impact Engineering 38 (2011) 397-405.

[48]. Combescure, Y. Chuzel-Marmot, J. Fabis, "*Experimental study of high-velocity impact and fracture of ice*", France, International Journal of Solids and Structures 48 (2011) 2779–2790.

[49]. Gordon R. Johnson, "*Numerical algorithms and material models for high-velocity impact computations*", USA, International Journal of Impact Engineering 38 (2011) 456-472.

[50]. Ivañez, C. Santiuste, E. Barbero, S. Sanchez-Saez, "*Numerical modelling of foam-cored sandwich plates under high-velocity impact*", Madrid, Spain, Composite Structures 93 (2011) 2392–2399.

[51]. A.R. Abu Talib, L.H. Abbud, A. Ali, F. Mustapha, "*Ballistic impact performance of Kevlar-29 and Al2O3 powder/epoxy targets under high velocity impact*", Selangor, Malaysia, Materials and Design 35 (2012) 12–19.

[52]. V.V. Astanin, G.O. Shchegel, W. Hufenbach, A. Hornig, A. Langkamp, "*Characterising failure in textile-reinforced thermoplastic composites by electromagnetic emission measurements under medium and high velocity impact loading*", Ukraine and Germany, International Journal of Impact Engineering 49 (2012) 22-30.

[53]. Amar Prakash, J. Rajasankar, N. Anandavalli, Mohit Verma, Nagesh R. Iyer, "*Influence of adhesive thickness on high velocity impact performance of ceramic/metal composite targets*", India, International Journal of Adhesion & Adhesives 41 (2013) 186–197.

[54]. Abdul Jabbar, Mumtaz Hasan Malik, Tanveer Hussain, Adeel Zulifqar, Muhammad Tausif, "*Comparison of Mechanical and Ballistic Performance of Composite Laminates Produced From Single-layer and Double-layer Interlocked Woven Structures*", Pakistan, Published online in Wiley Online Library (wileyonlinelibrary.com), POLYMER COMPOSITES 2013.

[55]. A.R. Othman, M.H. Hassan, "*Effect of different construction designs of aramid fabric on the ballistic performances*", Pulau Pinang, Malaysia, Materials and Design 44 (2013) 407–413.

[56]. Bing Wang, Jian Xiong, Xiaojun Wang, Li Ma, Guo-Qi Zhang, Lin-Zhi Wu, Ji-Cai Feng, "*Energy absorption efficiency of carbon fibre reinforced polymer laminates under high velocity impact*", PR China, Materials and Design 50 (2013) 140–148.

[57]. A.A. Ramadhan, A.R. Abu Talib, A.S. Mohd Rafie, R. Zahari, "*High velocity impact response of Kevlar-29/epoxy and 6061-T6 aluminum laminated panels*", Selangor, Malaysia, Materials and Design 43 (2013) 307–321.

[58]. Grimaldi, A. Sollo, M. Guida, F. Marulo, "*Parametric study of a SPH high velocity impact analysis – A birdstrike windshield application*", Italy, Composite Structures 96 (2013) 616–630.

[59]. Damith Mohotti, Tuan Ngo, Priyan Mendis, Sudharshan N. Raman, "*Polyurea coated composite aluminium plates subjected to high velocity projectile impact*", Australia and Malaysia, Materials and Design 52 (2013) 1–16.

[60]. Hong Wan, Shuxin Bai, Shun Li, Jianjun Mo, Shicao Zhao, Zhenfei Song, "*Shielding performances of the designed hybrid laminates impacted by hypervelocity flyer*", PR China, Materials and Design 52 (2013) 422–428.

[61]. Dil Faraz Khan, Haiqing Yin, He Li, Zainul Abideen, Asadullah, Xuanhui Qu, Mujtaba Ellahi, "*Effect of impact force on Ti–10Mo alloy powder compaction by high velocity compaction technique*", PR China and Pakistan, Materials and Design 54 (2014) 149–153.

[62]. J. Pernas-Sánchez, J.A. Artero-Guerrero, D. Varas, J. López-Puente, "*Experimental analysis of normal and oblique high velocity impacts on carbon/epoxy tape laminates*", Madrid, Spain, Composites: Part A 60 (2014) 24–31.

[63]. S. Heimbs, T. Bergmann, D. Schueler, N. Toso-Pentecôte, "*High velocity impact on preloaded composite plates*", Germany, Composite Structures 111 (2014) 158–168.

[64]. Rasoul Nasirzadeh, Ali Reza Sabet, "*Study of foam density variations in composite sandwich panels under high velocity impact loading*", Tehran, Iran, International Journal of Impact Engineering 63 (2014) 129-139.

[65]. E.C. Frederick, J.L. Hagy, "*Factors Affecting Peak Vertical Ground Reaction Forces in Running*". International Journal of Sport Biomechanics (1986) Vol. 2, Issue 1, 41 – 49.

[66]. *Impact (mechanics)* Retrieved December, 2013 from http://en.wikipedia.org/wiki/Impact_(mechanics)

[67]. G. Lu, and Y.Y. Tongxi, "*Energy Absorption of Structures and Materials*", Woodhead Publishing (2003).

[68]. Rattan "*Strength Of Materials*", Tata McGraw-Hill Education (2011)

[69]. G.C. Jacob, J.F. Fellers, S. Simunovic, and J.M. Starbuck, "*Energy Absorption in Polymer Composite Materials for Automotive Crashworthiness*" (2002). vol. 36 no. 7 pages 813-850.

[70]. G.L. Farley, "*Relationship Between Mechanical Property and Energy Absorption Trends for Composite Tubes*", NASA TP-3284, ARL-TR-29 (1992).

[71]. N.K. Gupta, M.A. Iqbal, and G.S. Sekhon, "*Effect of projectile nose shape, impact velocity and target thickness on deformation behavior of aluminum plates*" International Journal of Solids and Structures 44 (2007), Vol. 44, Issue 10, Pages 3411–3439.

[72]. A.L. Wingrove, "*The influence of projectile geometry on adiabatic shear and target failure*" Metallurgical Transactions (August 1973), Vol 4, Issue 8, pp 1829-1833.

[73]. T.W. Ipson, and R.F. Recht, "*Ballistic Perforation by Fragments of Arbitrary Shape*" University of Colorado, Denver Research Institute, Denver, Co (1977).

[74]. T. Borvik, M. Langseth, O.S. Hopperstad, and K.A. Malo, "*Perforation of 12 mm thick steel plates by 20 mm diameter projectiles with flat, hemispherical and conical noses part II: numerical simulations.*" International Journal of Impact Engineering 27, 37–64 (2002), Vol. 27, Issue 1, Pages 37–64.

[75]. Drzal, L. T., Herra-Franko, P. J., and Hoe, H. "Fibre-Matrix Interface Tests", Comprehensive Composite Materials, edited by A. Kelly and C. Zweben, Elsevier (2000) Vol. 2.

[76]. D. Liu, and L.E. Malvern, "*Matrix cracking in impacted glass/ epoxy plates*". J. Compos. Mater (1987) vol. 21 no. 7 594-609.

[77]. M.O.W. Richardson and M.J. Wisheart, "*Review of low-velocity impact properties of composite materials*", Institute of Polymer Technology and Materials Engineering, Loughborough University of Technology, Loughborough, Leicestershire LEll 3TU, UK, Composites Purr A 27A (1996) Vol. 27, Issue 12, Pages 1123–1131.