The Energy Absorption Capability of Composite Materials and Structures: Influence of Impact Loading

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Abstract: In this paper, the energy absorption capability of composite materials and performance-critical structures made from using these materials under conditions of impact loading is presented and discussed. An overview is provided of the key events associated with detonation and decomposition of an explosive that eventually culminates in the generation of a shock wave that exerts an impact type of loading on structures both in contact and in the immediate vicinity. The blast loads that culminate from an explosive often tend to generate very high strain rates in the range of 10^2/sec to 10^4/sec. The resultant high rate of loading does tend to exert an influence on dynamic mechanical properties of the targeted structure besides exerting an influence on damage mechanisms experienced by the structural element. The progressive use of composite materials for structures, such as sandwich panels, that essentially comprise of a mixture of composite face sheets and foam cores was shown by researchers, based on actual field test data, to offer few to many advantages over usual metal counterparts when it came to the purpose of offering acceptable blast resistance. Thus, it became both essential and desirable to assess the blast response of composite structures made using appropriate selection of composite materials. Through the years several independent research studies have been conducted to understand the influence of blast loading on the response kinetics of sandwich panels. Key highlights of the research done and resultant findings obtained from these studies is presented and briefly discussed The importance of both material selection and resultant structure for providing adequate protection against an impact type of loading caused by an explosive device, such as Improvised Explosive Device (IED), is highlighted through appropriate summary of research conducted and published in the open literature. The need and necessity for developing new and improved materials, composite in nature, that can be used for performance-critical structures that can also offer an enhanced level of safety to all personal involved in emphasized.

Keywords: Composite materials, composite structures, sandwich panels, impact loading, mechanical response.

1. INTRODUCTION

A blast can be categorized to be an event where considerable amount of energy is both released and dissipated in a relatively short span of time. A blast wave is often a layer of compressed air that lies in front of the hot gas that is generated during detonation of an explosive. The blast wave tends to immediately decay at its pressure head and gradually elongates with time as it tends to diverge outward from the point of explosion. A blast wave is often characterized by its peak value of: (i) pressure, (ii) duration, and (iii) specific impulse. Values of these parameters are a function of the dimensional parameter referred to as scale distance, which is defined as the actual distance divided by the cube root of weight of the explosive. This can be best described by the cube root scaling law.

1.1. The Cube Root Scaling Law

According to this law let D_1 be the distance or slant range from a point of explosion of a weapon with a yield of W_1 kilotons (KT) at which point a certain pressure is attained [1]. Then for weapon having or producing a yield of W_2 kilotons (KT) the same pressure will tend to occur at a distance D_2 and can be expressed by the relationship:

$$\frac{D2}{D1} = \sqrt[3]{\frac{W2}{W1}} \quad \text{or } D2 = D1\left(\frac{W2}{W1}\right)^{1/3}$$

By using the scaling law other characteristics of a blast, such as: (a) arrival time of shock front, (b) positive phase duration, (c) dynamic pressure, (d) positive phase impulse, and (e) wind velocity can be calculated.

$$\frac{t_2}{t_1} = \frac{d_2}{d_1} = \sqrt[3]{\left(\frac{W_2}{W_1}\right)}$$
$$\frac{I_2}{I_1} = \frac{d_2}{d_1} = \sqrt[3]{\left(\frac{W_2}{W_1}\right)}$$

In this expression, t_1 is the arrival time or phase duration and I_1 represents the impulse for reference explosion of energy W_1.

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2. UNDERSTANDING AN EXPLOSIVE SUBSTANCE OR MIXTURE

An explosive is a substance (or a mixture of different substances) that can develop sudden high pressure with a concomitant evolution of a sizeable volume of gaseous products as a direct consequence of rapid decomposition coupled with simultaneous evolution of large quantities of heat in a short period of time (nano-seconds to micro-seconds) when suitably initiated. The events associated with detonation and decomposition of an explosive is shown in Figure **1**. A flow chart depicting the fundamental classification of explosives is shown in Figure **2**.

The use of lightweight armor in defense systems against ballistic or blast threats is important with specific respect to providing the desired protection level while concurrently increasing the mobility of both personnel and vehicles. This requirement, or need, is gradually on the increase.

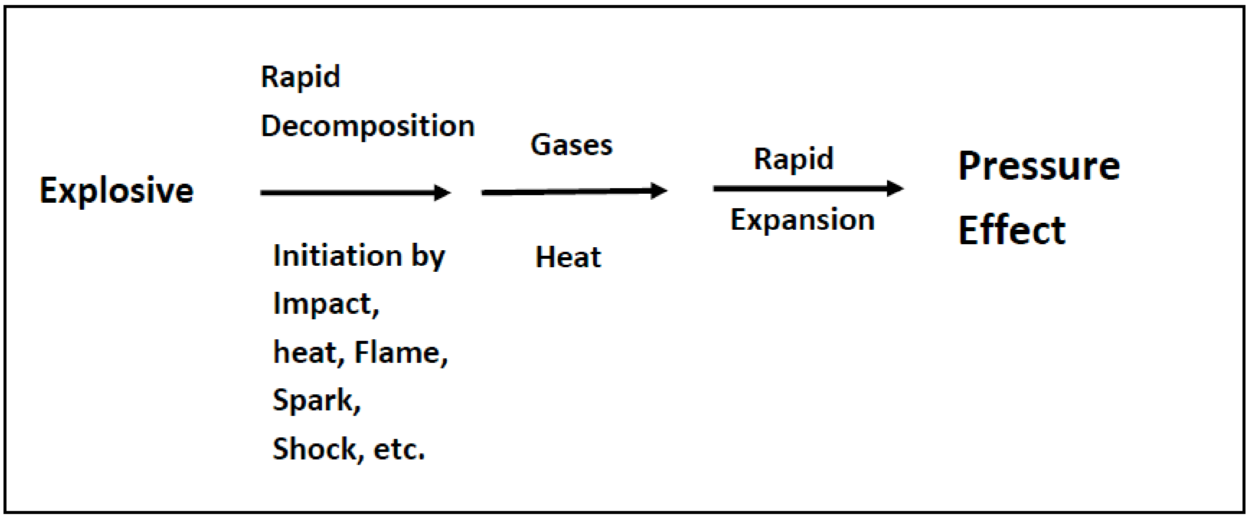

Figure 1: Detonation and decomposition of an explosive culminating in the release of pressure.

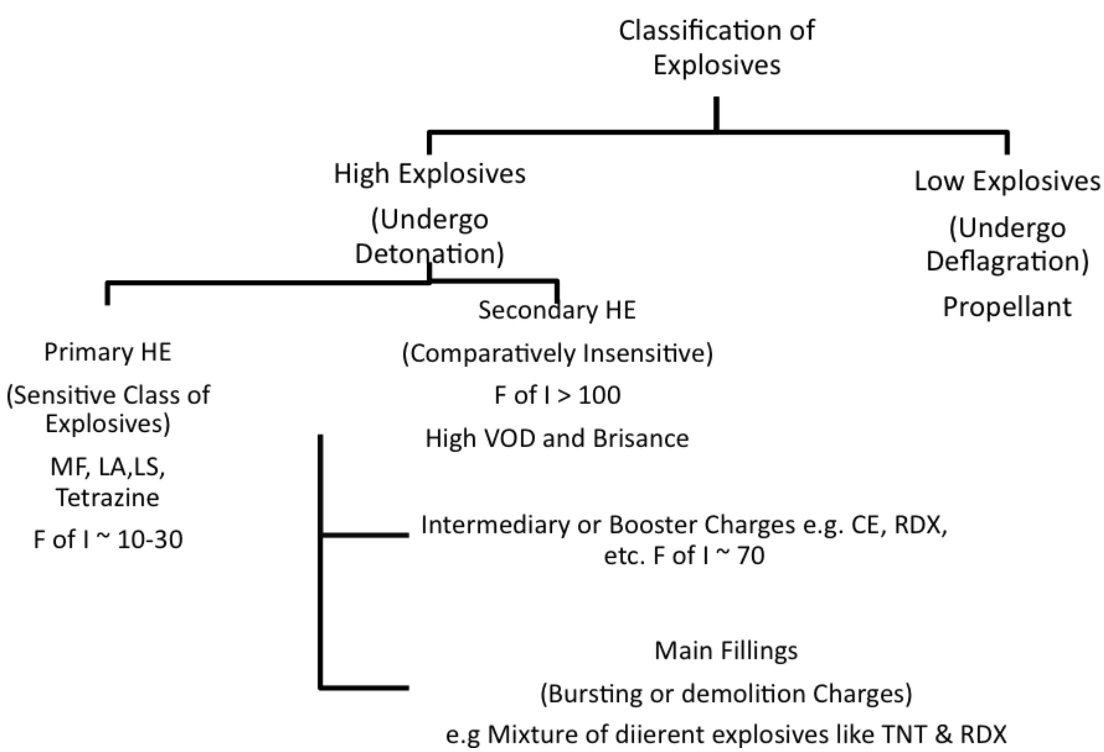

Figure 2: Flow chart depicting the classification of explosives and their characteristics and outcome.

Both metals and ceramics have for long been chosen and prudently used for a spectrum of armor-related applications. This is because they offer the advantage of a large technological database while offering the additional advantage of being able to be easily produced at an affordable cost. Furthermore, they tend to have a range when it comes to mechanical properties. However, for emerging and other performance-critical applications metals are not an ideal candidate for use as lightweight armor since they have a high density. The high-density disadvantage of metallic armor provided both an impetus and inspiration for researchers to investigate different types of engineering materials with the prime objective of engineering light-weight materials that could be used in armor-related applications while concurrently offering the desired level of protection in defense systems. With the prevailing security scenario in several nations scattered through the globe the need for an effective ballistic protective is becoming increasingly important.

The response of armor to an impact, blast, perforation and penetration is complex from an engineering perspective. An experimental approach does even extend the most accurate results of the response. However, it is expensive and has too often be supplemented by extensive mathematical simulations to provide an understanding the behavior of different configurations / layups / architectures and mechanics to both understand and rationalize the deformation kinetics and failure response. The modeling and simulation of materials for ballistic impact is often done in two stages.

From the materials science and engineering point of view, composite structures that are often subject to ballistic impact have been evaluated extensively on the following: (i) the E‑glass/epoxy composite, (ii) the T300 carbon/epoxy, and (iii) Aluminum‑bonded glass fiber-reinforced polymer composites, by several researchers with the primary purpose of enabling a better understanding of their response and kinetics and not for applications. Several damage and energy absorbing mechanisms were identified to include the following: (a) deformation of fibers/yarns, (b) de-lamination, (c) matrix cracking, (d) shear plugging, and (e) friction during penetration.

There does exist a growing need for a greater understanding of deformation behavior of materials under conditions of high strain rate loading. Through the years, a sizeable number of studies have been carried out with the primary purpose of understanding the deformation behavior of metals at both low strain rates and medium strain rates. Results obtained from these studies were used to publish a sizeable number of technical papers both in journals and other resources. However, a different situation does exist when it comes to strain rates, which are greater than 1000/s. Above this strain rate range, the flow stress increases rapidly with an increase in strain rate for a few materials having commercial interest and application. The role and/or contribution of material inertia forces cannot be easily neglected in this region. The strain rate sensitivity of a material depends on the strain rate range in which the chosen material is mechanically deformed. At high strain rates, the energy is dissipated rapidly because of an increase in temperature within the material. Due to the rise in internal temperature the microstructure of the material within shear bands does tend to undergo an observable change. Thus, a comprehensive description of the properties of a chosen material at high strain rates cannot be easily extrapolated from conventional test data and/or models. The development of new dynamic material property tests coupled with an improved ability to detect intrinsic microstructural changes have resulted in enlarging the scope with an intent of better characterization of materials when subjected to deformation at high strain rates. An actual simulation of the events occurring during a blast is often a complex problem that necessitates the need for a careful consideration of the blast wave pressure - time history and response of the structure to the blast loading. Interaction of the structure with the blast waves has been proven to make significant change in pressure distribution within the structure [1]. Simulation of the blast also necessitates the need for special attention to material behavior at high strain rates.

3. HIGH STRAIN RATE PHENOMENON

Blast loads typically produce very high strain rates in the range of 10^2 s^{-1} to 10^4 s^{-1}. This high a loading or straining rate would tend to alter the following:

(a) The dynamic mechanical properties of the targeted structure, and

(b) The expected damage mechanisms experienced by the various structural elements.

For reinforced concrete structures that are subject to blast effects the strength of the concrete and the reinforcing steel bars can increase significantly due to strain rate effects. The approximate ranges of the

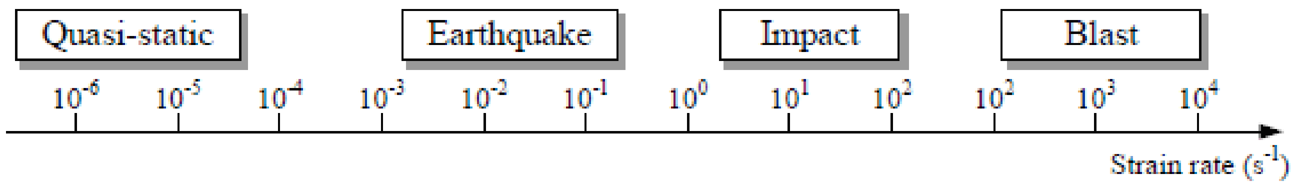

Figure 3: Strain rates associated with different types of loading.

expected strain rates for the different loading conditions is shown in Figure **3**. It should be noted that ordinary static strain rate is in the range: 10^{-6} s^{-1} to10^{-5} s^{-1}, while blast pressures normally yield loads associated with strain rates in the range: 10^{2} s^{-1} to 10^{4} s^{-1}.

Blast loading effects on structural members often tend to produce both local and global responses associated with the different failure modes. The type of structural response depends on the following: (a) the loading rate, (b) orientation of the target with respect to the direction of the blast wave propagation, and (c) boundary conditions. The general failure modes associated with blast loading can be the following: (i) flexure, (ii) direct shear, and (iii) punching shear. Local responses are often characterized by localized bleaching and spalling that results from the close-in effects of an explosion, while global responses are often manifested through flexural failure.

4. COMPOSITE STRUCTURES FOR PURPOSE OF BLAST RESISTANCE

Composite materials and resultant structures, such as sandwich panels having composite face sheets and foam cores, offer few to many advantages over usual metal construction for purpose of good to acceptable blast resistance.

An assessment of the blast response of such composite structures is critical to ensure their survivability under realistic and/or prevailing conditions. The problem of blast loading on sandwich panels has in recent years received a significant amount of attention. A few of these studies have attempted to focus on the following:

(i) Detailed analyses of sandwich panel dynamics [2].

(ii) An analysis of sandwich panels with metal face sheets and cellular metal cores [1], and

(iii) Study of a sandwich panel with composite face sheets and metal foam core [1].

The blast loading characteristics of composite sandwich panels having foam cores has been both simulated and examined using metal foam projectiles [1].

5. HIGHLIGHTS OF RESEARCH ACCOMPLISHED IN THIS AREA

Structural fiber-reinforced plastic (FRPs) composites have been preferentially chosen and used in several high performance-critical structural applications due primarily to their high strength-to-weight [σ/ρ] ratio. Other positive attributes of FRPs include their manufacturing flexibility, which allows composites to achieve material properties that are often difficult to attain using single-phase materials. However, typical structural composites exhibit limited ductility, which limits their ability to absorb energy under impact loading and culminating in their early failure by rupture. The limited energy absorption capability of a structural composite can be related to the lack of plasticity mechanisms coupled with the occurrence of de-bonding at the weak interfaces. The dominant failure mechanism in composite laminates subjected to impact-loading is a complex combination of the following:

(a) Delamination predominantly caused by Mode II shear.

(b) Matrix cracking caused by transverse shear, and

(c) Translaminar fracture due to both fiber fracture and kinking.

Depending on the chosen composite and resultant intrinsic microstructural effects there exists several factors that dictate the fracture processes occurring at both the microscopic and macroscopic level. These include the following:

(i) Material variables,

(ii) Nature of loading,

(iii) Prevailing environmental conditions, and

(iv) Source of impact.

Among the material variables, the mechanical properties of both the fiber and matrix, particularly the failure strains, interface properties, fiber configuration and stacking sequence in angle-ply laminates play an important role in determining the impact damage resistance of both the composite material and the composite structure. A significant amount of research effort aimed at developing blast-resistant composites has been conducted during the last three decades. One such research study undertaken reported a composite material resulting from a glass–ceramic matrix that was reinforced with silicon carbide fibers [SiC_f] that exhibited both acceptable mechanical strength and toughness. Toughness measurements of new silicon carbide fiber-reinforced composites were reported to be 50 times that of a typical ceramic composite. Much interest has also been directed towards examining the impact strength of carbon/epoxy composites. Researchers have also reported an observable improvement in energy absorption capability of multi-laminate carbon composites resulting from both chain and plain stitching. Research has also been devoted towards the development of computational tools to simulate composite behavior under impact loading conditions and to concurrently quantify damage in laminated composites.

During past conflicts that have occurred during the by-gone years, fragmentation and bullets accorded for most injuries experienced by the human beings in the role of soldiers deployed in both combat operations and peace keeping operations. The Personal Protective Equipment (PPE), in the form of ballistic vests and helmets, were designed to protect regions of the thorax and head against such threats. However, current military operations exhibit a significant shift in injury patterns because of Improvised Explosive Device (IEDs) becoming the prevailing threat. The Current Personal Protection Equipment (PPE) was not designed for providing significant protection against blast effect caused by an Improvised Explosive Device [IED], which often resulted in a change in injury pattern experienced by the face, head and other parts of the body. Moreover, the exposed areas of the body, particularly the extremities are often made to both endure and withstand a multitude of debilitating (with specific reference to impaired strength and/or vitality) injuries. Francois and co-workers [1] studied the blast threat to an unprotected individual, representing the gunner standing in the cupola of a High Mobility Multi Wheel Vehicle (HMMWV) using Computational Fluid Dynamics (CFD) analysis and evaluated the protection provided by a new Cupola Protective Ensemble (CPE).

The injury pattern sustained by the soldiers stationed at key locations scattered through the globe did prompt this study because the conventional Personal Protection Equipment [PPE] worn by military personnel, which was designed to protect vital areas of the body (head & thorax) against the traditional threat of fragmentation of bullets did prove to be inadequate against an Improvised Explosive Device [IED] blast. In the first stage of study, the blast threat of interest was characterized to optimize the distribution of protection and the resultant balance between protection and weight. A Computational Fluid Dynamics [CFD] simulation of an unprotected gunner who is exposed to a blast from an explosive charge while standing in the cupola of HMMWV was performed. In the second stage, the CPE concept that was developed was tested against real explosive charges. For these full-scale blast tests, two Hybrid-II anthropomorphic mannequins were dressed in the Cupola Protective Ensemble [CPE], and placed in the cupola of a High Mobility Multi-Wheel Vehicle [HMMWV] and then exposed to the blast from base charge of 10 Kg C4 explosive placed on the ground. The tests were also used to compare the protection provided by the Cupola Protective Equipment [CPE] to that of the Advanced Combat Helmet (ACH) and the Interceptor Body Armor (IBA), comprising of an Outer Tactical Vest (OTV) coupled with small arms protective inserts (SAPI), currently being extensively used by even the United States [US] military, for providing enhanced fragmentation and bullet protection. The test results revealed that qualitatively both the Cupola Protection Equipment [CPE] and ACH+IBA Personal Protection Equipment [PPE] remained intact following the blast with only the straps and /or zippers tearing, or opening, on both the Interceptor Body Armor [IBA] and Cupola Protection Equipment [CPE] jackets. The resultant (RMS) head acceleration signals were found to be lower for the CPE (85g's) than the standard ACH (372 g's). Thus, it was observed that the Cupola Protection Equipment [CPE] provided a strong reduction in damage occurring to the head relative to the Advanced Combat Helmet (ACH).

Jackson and Shukla [2] studied the effect of sequential impact and air blast loading on sandwich composites due to an increase in blast loading events occurring as a direct result of increasing threats induced by the terrorists. The performance of sandwich structures was found to be better during blast events than traditional materials and offered additional benefit of a high strength-to-weight [σ/ρ] ratio that allowed for additional armor to be installed on Military vehicles. A sizeable number of structures constructed using sandwich composites are likely to experience events that would degrade the shock mitigation properties arising from exposure to UV light and thermal cycling. The properties also degrade due to high and low velocity impact. It has been shown that response of sandwich composite structures when subject to different shock loading conditions to include air blast is superior to the response of a monolithic structure having the same areal density. The effect of fire damage on the impact response of components was studied by Ulven and Vaidya [3]. These researchers performed an experimental study in conjunction with a mechanical property estimation model to determine the effects of fire damage on impact response of composite structures. Specimen included E-glass vinyl ester laminates and sandwich structures with E-glass vinyl ester face sheets and balsa wood cores. Both types of structures were exposed to an 800^{o}C flame for varying durations of time before being subjected to low velocity impact. The impact was made possible by using a drop tower and an impact energy of 6.5J. For a composite test specimen following 100 seconds of exposure to a flame at 800^{o}C:

(a) The peak force and contact stiffness of the laminates was reduced by as much as 20-30%, and,

(b) For the sandwich specimen, a 65-75% reduction was observed.

Schubel and co-workers [4] experimentally studied the effect of drop weight impact on sandwich composites constructed using carbon fiber epoxy face sheets and PVC (Divinycell H250) cores. The impact energy varied from 78J to 108J. After the test, the impact specimens were subjected to compression. Delamination, not visually detectable, was responsible for the observed decrease in compressive strength. Higher energy impact was basically needed to develop significant damage with residual compressive strength being less than 50% of the undamaged strength. The material selected for the study was created using scrimp process and consisted of laminate face sheets and a Styrene Acrylo-Nitrile (SAN) foam core. The face sheets were constructed with a vinyl ester matrix and 24 oz./yd^2 E-glass woven roving in a layup of $[0/45/90/-45]_s$. Overall specimen dimensions measured 102 x 254 x 60 (mm) with a face sheet thickness of 5-mm. The average areal density of the specimens was 27.9 kg/m^2. High velocity impacts were obtained using a 300 Winchester Magnum rifle firing into an enclosed test chamber where the test specimen was held under clamped conditions on both the top edge and bottom edge. The bullets used in the study were copper jacketed stainless-steel armor piercing type. The primary reason for the selection of this type of bullet was that it does not experience damage during impact, and the change in kinetic energy of the bullet can be equated to the energy absorbed by the test specimen during impact. Low velocity impact included the following key events:

(i) Puncture at the impact site, and

(ii) Delamination in the immediate area around a puncture coupled with cracking of the matrix.

For blast loading a shock tube was utilized to simulate shock loading from an explosive event. The test data collected during the experiment revealed the following:

(a) The damage occurring during high velocity impacts was most prominent on the exit face sheet of the sandwich composite specimens while specimens subjected to low velocity impacts developed damage that was confined to the impact face sheets and cores.

(b) Specimen that were struck by high velocity projectiles absorbed a higher level of energy during the impact process when compared to the test specimens struck by low velocity high mass weight.

(c) Experiments revealed that the damage to the front face sheet is more detrimental to performance of the sandwich composite than damage to the back-face sheet.

(d) Performance of the sandwich specimen that was previously subjected to high velocity impact is noticeably superior to the blast performance of sandwich composite specimens that was subjected to low velocity high mass impacts.

The effect of ballistic impact and the effect of an explosive blast on flexural properties of stitched composite structures was studied by Mortiz [11]. The stitching enabled in increasing the Mode I inter laminar fracture toughness but had little influence on flexural properties. The stitched laminate subjected to submerged explosive blast showed an improvement over the unstitched laminate that was subject to the same explosive level. The damage caused to the laminate due to the passage of a bullet was also studied by Mortiz [11]. The passage of a bullet through the exit face sheet of the laminate results in the development of greater out of plane strain near the exterior surface of the exit face sheet since it is an unsupported free surface. Damage to the exit face sheet was found to increase through the thickness of the sheet with less damage occurring to the interior and greater damage to the exterior.

Renfu and co-workers [12] studied point-wise impulse (blast) response of a composite sandwich plate to include core compressibility efforts. The independent study analyzed the nonlinear response of a composite sandwich panel exposed to sudden point wise transverse loading on the top face sheet. The nonlinearity arising from core compressibility in the thickness direction was modeled and incorporated into the constitutive relations. The sandwich panel consisted of two thin stiff metallic or composite face sheets separated by a soft honey comb or a foam thick core having low density. This configuration gave the chosen sandwich material both high stiffness and strength with little resultant weight penalty coupled with high energy absorption capability related to the application of sandwich structures for the construction of: (i) aerospace vehicles, (ii) naval vehicles, and (iii) civil structures. It was revealed from most of the studies on sandwich composites neglected the transverse deformation of the core as detailed in the books on Sandwich Structure [Plantema, 1966 [13]; Allen, 1969 [14], Vinson 1999 [15]]. A core of the sandwich structure is essentially considered to be infinitely rigid in the thickness direction and only shear stresses are considered. This assumption works well in the analysis of response of sandwich structures to both a static loading and dynamic loading of long duration. However, several independent studies [Kwon 2002 [16]; Xue and Hutchinson 2004 [17]; Fleck and Deshpande, 2004 [18]; Lie et al; 2008 [19] have convincingly shown that the core transverse deformation/strain experienced by a sandwich structure that is subject to impulsive loading has a highly non-linear profile with respect to the thickness direction.

This study also revealed that the top face, the core and the bottom face behave differently during transient response. The transverse stress profiles in the core revealed a high degree of non-linearity with maximum amplitude occurring at the interface between the core and top face sheet on which the blast loading occurs. Therefore, debonding does initiate at the interface and was observed in preliminary experiments. Both the stress amplitude and displacement amplitude decreased rapidly from the point of loading. These guidelines should prove to be helpful in the design of an optimal sandwich plate.

Arife and co-workers [20] studied the design of blast resistant composite laminates incorporating carbon nanotubes (CNT). Their research article examined the possible design of CNTs – Carbon Polymer Composites for purpose of blast resistance. A simplified stress wave propagation method was considered to simulate stress accumulation in a multi-layer carbon epoxy composite laminate when subject to a blast event. A system reliability approach was proposed to consider the level of uncertainty associated with the blast event and resultant material response. An optimization method was used for identifying the optimal distribution of carbon nano-tubes (CNTs) in the Carbon Polymer Composite. A case study for the design of a fine layer CNTs – Carbon Polymer composite was considered for demonstrating the proposed design method. The research also provided an insight of the one method to compute the stress development in a composite laminate. This was by considering the blast wave propagation in the composite layer in the framework of elastic wave propagation. There are three approaches for analyzing transient wave propagation in composite laminates [21].

(i) The first approach is based on plate theory and is effective for low frequency waves when the wavelength is longer than the thickness of the plate [22].

(ii) The second approach provides an exact solution of the equation of motion typically solved in the time domain as proposed by Kolsky [23] and Van der Hijden [24] or in the frequency domain [25].

(iii) The work was also done to identify the optimum content of carbon nanotube (CNT) to minimize the probability of failure of the composite laminate. Both gradient and non-gradient based optimization methods were used.

For their study, the researchers attempted to use a fine layer composite. The layers were carbon fiber, epoxy, carbon fiber, epoxy, carbon fiber. All layers had a thickness of 150 µm. The carbon nanotubes (CNTs) were assumed to be incorporated in the epoxy mix to strengthen the layer # 2 and layer # 4 such that overall probability of failure of the composite laminate under conditions of blast is minimized. Research studies have also demonstrated a systematic method for reliability-based design of blast resistant carbon epoxy composite using carbon nanotubes (CNTs). Research studies have revealed that by using single simulation method the stress in each layer of a composite laminate, arising because of an uncertain blast event, can be easily calculated and compared to the strength of the uncertain layer. Langdon and co-workers [26] studied both the experimental and numerical approaches to the response of sandwich panels, containing PVC cores and glass fiber-reinforced vinyl ester face sheets, when subject to blast loading. They also reported on the response of an equivalent mass glass fiber-reinforced vinyl ester panels. The loading was generated by detonating discs of a plastic explosive at a small standoff distance of 50-mm. Multiple failure modes were exhibited by the panels, to include the following:

(i) Core compression.

(ii) Fragmentation and complete penetration.

(iii) Debonding between face sheet and the core.

(iv) Delamination between fiber layers, and

(v) Rupture of the fibers.

The sandwich panels exhibited failure due to complete penetration, while no penetration was observed in an equivalent mass composite panel. The composite only panels performed better than the sandwich panels having a PVC foam core. This was attributed to the lower transverse stiffness of the individual components of the sandwich panel. The performance of a sandwich panel was significantly influenced by both the geometry and material properties of the constituents. The face sheets essentially control structural rigidity of the panel and provide protection from the environment, such as ingress of water. The face sheet also helps to maintain core integrity during high intensity blast loading by delaying fragmentation [27]. The core controls the energy absorption and force transfer through the structure [28-29].

Closed cell polymeric foams are a popular choice for use as the core in composite sandwich panels of commercial products, such as: (i) Divinycell [30], (ii) Core Cell, and (iii) Airex [31]. Tekalur and co-workers [32] characterized the tensile properties, compressive properties and sheet properties of composites having vinyl ester matrices under both quasi-static loading and dynamic loading. It was observed that fiber breakage and delamination were the common damage mechanisms. In the blast test on both glass and carbon fiber poly-ether panels the occurrence of localized delamination within the panel was evident. It can be concluded that breakage of the complete panel occurred rapidly once rupture of the back-face fiber occurred. Comtois and co-workers [33] investigated the effect of explosive loading on response of both carbon-fiber and glass-fiber-reinforced plastic laminates and found the extent of damage to be a function of both applied impulse and peak pressure. Damage of the laminates initiated at fixed points during testing and fiber damage and was found to be more severe in the glass fiber system. The shock wave loading response of composite sandwich panels is extremely complex. It was shown that greater levels of damage were present in the shock tested panels that were previously subjected to low velocity impacts when compared to those that were previously subjected to high velocity impact. Not surprisingly, multiple impacts only resulted in the accumulation of greater damage within the specimens resulting in the following:

(i) Increased specimen compliance.

(ii) Lowered impulse transfer, and

(iii) Reducing the energy absorption capacity of the sandwich panels subjected to shock loading.

The detonation of an explosive near the sandwich panel surface can initiate a highly localized pressure pulse, which can cause a loss in structural integrity to include delamination of the composite layers due to the conjoint and mutually interactive influences of large in-plane stresses and fiber rupture. While compaction of the core can lead to blast mitigation and resultant improved resistance to a more uniform blast, the localized pressure can initiate failure of the material on the face sheets of the panel, which can lead to ultimate failure of the structure itself. Recently, Jacob and co-workers [34] reported results from localized blast loading experiments on sandwich panels having 4.5mm thick glass fiber-reinforced face sheet and 25-mm thick PVC foam cores. An analysis of the failure revealed multiple failure modes to be present in the panel and an energy partition analysis revealed the following: (a) delamination, (b)core compression, and (c) fiber fracture to be the significant energy absorption modes. Panels with a denser core exhibited a lower level of damage. This is primarily because a denser core of the foam offered greater resistance to front face sheet deformation, thereby delaying rupture of the reinforcing fiber to a higher impulse. The response of sandwich panels having PVC foam cores and glass fiber-reinforced vinyl ester (GFRVE) was investigated. Air blast loading experiments, conducted at a small standoff distance revealed the panels to exhibit multiple failure modes to include the following:

(a) Core compression,

(b) Fragmentation,

(c) Complete penetration debonding between the face sheet and core,

(d) Delamination between the fiber layers, and

(e) Rupture of the fibers.

The core compression was more evident on the side nearest to the blast indicating that the front face sheet had deformed significantly into the core before recovering elastically. At higher impulses, the back-face sheets were also permanently deformed and deboned from the core. Panels having a dense core exhibited a lower level of damage. The equivalent mass (EM) panels exhibited failure due to delamination, but did not exhibit penetration failure at impulses that promoted the occurrence of penetration failure in sandwich panels. A high-density core reduces the damage experienced by the glass fiber-reinforced vinyl ester [GFRVE] sheets in the sandwich panels due to a slight reduction in maximum velocity of the front sheet coupled with a considerable increase in the energy absorbed by the foam during deformation.

Langdon, Klemperer and co-workers [35] suggested that the response of composite sandwich structures to blast loading has received little attention form researchers when compared to the research performed on the metallic counterparts, even though composite sandwich panels are becoming increasingly used in practice. They carried out an experimental investigation on the response of sandwich panels, comprising E glass fiber-reinforced vinyl ester face sheets and closed cell PVC foam cores, to localized blast loading. The loading was generated by detonating a disc of plastic explosives near the panels (50-mm). Multiple failure modes were exhibited by the sandwich panels. They could identify a pattern for the progression of failure with an increase in impulse. The pattern followed the sequence of (i) Front face sheet, (ii) delamination, (iii) core compression, (iv) back face sheet delamination, (v) fiber fracture, (vi) core fragmentation, (vii) plastic deformation, (viii) debonding of the back sheet, followed by (ix) complete core penetration. However, no rupture of the back-face sheet was observed primarily because it was the next failure mode at a higher impulse.

The panels having a dense core exhibited a lower level of damage. The energy partition revealed the following:

(a) Delamination, core compression, and fiber fracture to be the significant energy absorption mode, and

(b) Fiber fracture energies to exceed the core compression and delamination energies for the higher impulses.

The performance of a sandwich panel is significantly influenced by both the geometry and material properties of the core, since these essentially control the energy absorption capability and force transfer through the structure. Cellular material are popular choices for the core, since many exhibit stress-strain curves (under quasi –static compression) that has an initial elastic region followed by a relatively constant stress (known as the Plateau Stress). Over a wide range of strains Gibson & Ashby [36] described such foams to be ‘plastic foams’ and included foams based on both metals and polymers like polyurethane. The region of constant plateau stress prior to densification of the cellular core was identified to be an important contributor to the ability of the material structure to mitigate a blast load for sandwich panels having a metallic core.

A typical two face sheet sandwich panel, the outer face sheet easily deforms and compresses the cellular core, and this results in limited stress transfer to the rear face sheet. Hence, a high magnitude, small duration pressure pulse can be converted to a smaller magnitude but longer duration loading (due to conservation of momentum). It has been anticipated by researchers that this modification results in less damage to the sandwich panels although complications, such as: dynamic stress enhancement (due to shock front formation), and core densification, mean this does not happen in actual practice.

Tekalur and co-workers [37] concluded that shock wave loading response of composite sandwich panels to be extremely complex and required additional

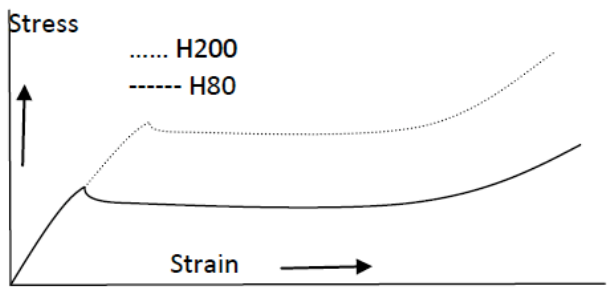

Figure 4: Graph showing typical engineering stress versus engineering strain curves obtained from compression test conducted on a Divinycell foam.

studies. The shock wave tests conducted using stepwise graded foam core revealed the panels whose foam density increased through the thickness to outperform the other configurations [38]. In two independent studies [34,35], the panels were subjected to shock tube loading rather than blast loading generated by detonation of an explosive. The stepwise graded foam cores can be regarded as a type of functionally graded material, where the properties of the core vary through the core thickness to improve their blast resistance [35]. A typical stress versus strain curves for the two cores is shown in Figure **4** and is typical for a cellular material having an initial elastic phase, long plateau region and a strain hardening phase as the compression tends towards densification.

It might be expected that panels having a denser core would be more resistant to a blast than others. This is because a denser core offers higher strength in compression. However, while this would be the case for static testing, the response of sandwich panels to blast loading is considerably more complex. In some cases, particularly for low impulses, a low-density core may improve blast resistance as lower forces are transmitted through the core to the back-face sheet. The progression of damage through the composite strip is as shown in Figure **5**.

A pattern of failure impression with an increase in impulse was identified for the sandwich panels, beginning with delamination of the front face sheet and ending with (expected) rupture of the back-face sheet.

Mahmood and co-workers [39] studied the multi-objective optimization approach for design of blast-resistant composite laminates using carbon nanotubes (CNT). The use of carbon nanotubes (CNT) to enhance the mechanical properties of composite interface layers was considered. The use of carbon nanotubes (CNT) not only enhances the strength of an interface but also tends to alter stress propagation through the composite laminate. A simplified wave propagation simulation was developed and an optimal content of carbon nanotube (CNT) in the interface layer was determined using multi-objective optimization paradigm. The optimization process targets minimizing the ratio of stress developed in the layers to strength of the specific layer for all composite laminate layers. These researchers used two optimization methods to identify the optimal carbon nanotube (CNT) content. A case study demonstrating the design of five-layer composite

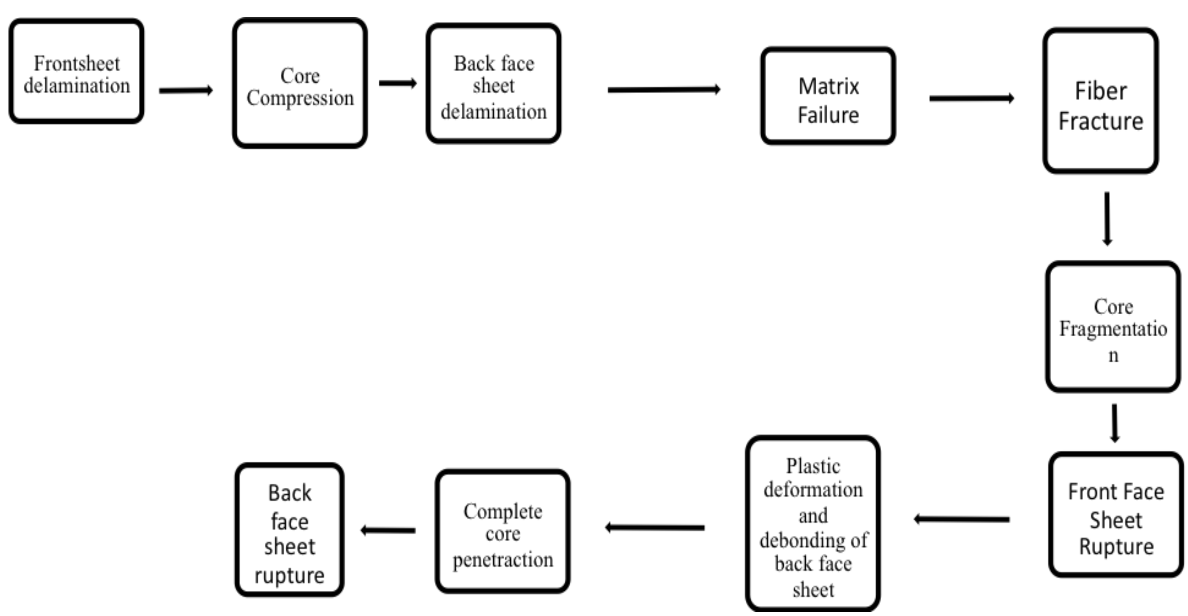

Figure 5: Flow chart or sequence depicting the progression of damage through a composite strip.

laminate subjected to blast event was also used for demonstrating the concept. It was shown that addition of 2 pct. CNT and 4 pct. CNT, by weight, to the epoxy interface results in significant enhancement in the ability of the composite structure to resist a blast. However, a typical composite often exhibits limited ductility, which limits its ability to absorb energy under conditions of impact loading and culminating in its failure by rupture or fracture. This limited energy absorption is related to the lack of plasticity mechanisms coupled with the occurrence of debonding at weak interfaces.

Brennan and co-workers [40] reported a composite that was made of a glass ceramic matrix reinforced with silicon carbide fibers that exhibited a combination of exceptional mechanical strength and toughness. The toughness measurement of emerging silicon carbide fiber-reinforced composites was reported to be 50 times that of a typical ceramic composite. Kang and Lee [41] reported a significant improvement in energy absorption of multi-laminate carbon composites by both chain stitching and plain stitching. Carbon nanotubes (CNT) have drawn noticeable attention from the research community due essentially to a combination of attractive mechanical properties they had to offer. Basically, carbon nanotube (CNT) represents a unique form of carbon that can be easily visualized by considering a single graphene sheet representing a lattice of carbon atoms distributed in a hexagonal pattern [42]. A Single Wall Carbon Nano Tube (SWCNT) is about 1-3 nm in diameter [43]. The attractive properties of SWCNT can be attributed to their unique nanostructure. Furthermore, SWCNT possess exceptional mechanical properties coupled with superior thermal and electric properties when compared to macroscale fibers, such as: (i) graphite, (ii) Kevlar, (iii) Silicon carbide (SiC), and (iv) alumina. The strength, elastic modulus and overall fracture properties of carbon nanotubes are an order of magnitude higher than those of most common composite materials.

Mahmood and co-workers [39] demonstrated an integration of five-layer carbon fiber. A blast event was simulated using the scaling laws put forth by Smith & Hetherington [44]. The blast was aimed to produce an incident pressure of 140 MPa at the surface of the composite to assure failure of the composite prior to the addition of carbon nanotubes (CNT). By using the approach of stress wave propagation, the stresses-induced in the structural composite layers, at different time steps, were simulated using a step-by-step analysis. The stress at each layer was subsequently compared with strength of the material in that layer. Carbon Nanotubes (CNTs) were then added to an epoxy interface at layer # 2 and layer # 4. Addition of Carbon Nanotubes (CNTs) had the following effects:

(a) Increased the strength of the interface.

(b) Altered the stiffness distribution in the composite, and

(c) Exerted an influence on stress propagation through the composite structure.

These researchers demonstrated the use of CNTs with a polymer interface (Epoxy) can contribute to altering stress wave propagation through the structural composite thereby contributing to an observable enhancement in resistance of the structural composite to events resulting from a “blast”. (Figure **6**)

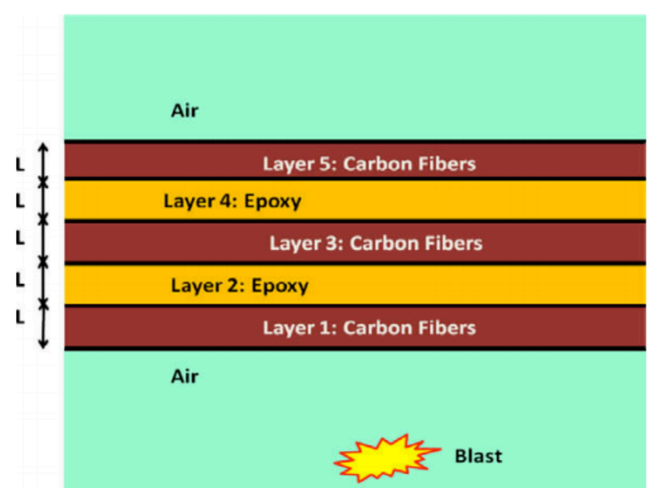

Figure 6: Schematic representation of a five-layer composite laminate.

Digital Image Correlation (DIC) technique is a recent non-contact optical method for analyzing full field shape and deformation. It involves both the capture and storage of high speed digital images and subsequent post processing of these images using commercially available software to get both the full-field shape and deformation measurement. The post processing software helps in obtaining the full-field shape and deformation measurement by mapping the predefined points on the test specimen. Capturing the three-dimensional response of the panels requires two cameras, which must be calibrated while concurrently offering a synchronized image recording throughout the event. Calibration of the camera is often performed by placing a pre-defined grid pattern in the test space where the carbon fiber specimens are located during the experiment. The grid is then translated and simultaneously rotated both in and out of plane while recording the images. Since the chosen grid pattern has pre-determined distances between the speckles, the coordinate of the center of dot is extracted uniquely since each camera allows for a correspondence of the coordinate system of the specific camera. Digital Image Correlation (DIC) is then performed on the pairs of images that are recorded during the shock event. Prior to testing, the back face of the sample is painted white and subsequently coated with a randomized speckle pattern. Post processing was performed using a software package [VIC-3D], which helps in matching common pixel subsets of the random speckle pattern between the deformed and un-deformed images. Matching of the pixel subsets is subsequently used to calculate the three-dimensional location of distinct points on the face of the panel.

Puneet and co-workers [45] conducted experiments to study the effect of plate curvature on the blast response of a 32 layered carbon composite panels. They utilized a shock tube apparatus to impart controlled blast loading on carbon fiber panels having three different radii of curvature; (i) infinite, (ii) 305-mm, and (iii) 112-mm. The panels were held under clamped boundary condition during the blast loading. A 3-D Digital Image Correlation (DIC) technique coupled with high speed photography was used to obtain the following:

(a) Out-of-plane deflection and velocity, and,

(b) In-plain strains on the back face of the panels.

Two types of dominant failure mechanisms were observed for the three chosen panels. These are (i) Fiber breakage, and (ii) inter-layer delamination. An energy loss analysis revealed that the panel having a radius of curvature of 112-mm had the best energy dissipation property. Results of Digital Image Correlation (DIC) also revealed that the panel could mitigate higher intensity blast waves without initiation of catastrophic damage. A panel with 305-mm could sustain least blast intensity and exhibited catastrophic failure.

Chun and co-workers [46] attempted to investigate the free vibration and the dynamic response of clamped laminated curved panels subjected to loadings of the nature of step, triangular and explosive. They used the Rayleigh-Ritz method to obtain the natural frequencies of the clamped laminated curved panels and developed a numerical model to analyze the following:

(i) Symmetric angle-ply,

(ii) Symmetric cross laminated, and

(iii) Anti-symmetric cross laminated panels.

Kumar and co-workers [47] also reported the effect of transient boundary conditions by experimenting on the dynamic response of curved aluminum panels using high speed photography and three-dimensional DIC. They found curvature to have an influence blast response of the aluminum panels. LeBlanc and co-workers [48] studied underwater shock loading response of E-glass/ Vinyl ester curved composite panels. They used a three-dimensional Digital Image Correlation (DIC) system for measuring transient response during the experiment. The results were compared to a finite element code. The comparisons revealed an acceptable level of correlation.

Shen and co-workers [49] through the aid of experiments investigated the response of sandwich panels having an aluminum face sheet and aluminum foam cores. The panels with varying curvature, and different core/face sheet configuration were tested at three different blast intensities. They found the initial curvature of the sandwich panel to change the deformation mode while concurrently improving performance of the structure when compared to an equivalent flat plate. Hause and co-workers [50] developed a closed form solution for comparison with numerical solutions based on the extended Galerkin method for designing doubly curved sandwich panels operating under conditions of dynamic loading.

CONCLUDING REMARKS

In this paper, several aspects are neatly delineated and discussed with specific reference to the importance that needs to be given in materials selection for use in structures that are likely to experience an impact type of loading arising from a blast that results from the detonation of an explosive. The specific role of material variables to include mechanical properties of both the reinforcement, such as fibers, and the matrix coupled with failure strains, properties of the interface, configuration of the chosen reinforcement, i.e., fiber, and even stacking sequence for the case of angle-ply laminates, does play an important role in determining the damage resistance, due to impact, of not only the composite material but also the resultant composite structure. Through the years few independent studies have examined the response of sandwich composite structures when subject to shock loading based on both laboratory-scale tests and actual field results have engineered the development of composite materials having an acceptable combination of mechanical strength and toughness as viable materials for use in performance-critical structures that are subject to impact loading while in service.

Also, the results and interpretations of several independent studies based on actual field test results is neatly presented. Several of these studies did establish the fact that the response of sandwich composite structures when subject to shock loading conditions, to even include an air-blast, was noticeably superior to the response of a monolithic structure having the same areal density. Composite test specimens that were subjected to a flame following exposure to an elevated temperature for a defined period the observed loss in peak force and contact stiffness was only minimal. Drop weight tests conducted on sandwich composite structures made from using carbon-fiber epoxy face sheets and a PVC core the tendency for delamination was minimal while a higher energy was required to develop any observable damage both to the composite material and resultant composite structure.

A structure made using a prudent combination of laminated face sheets and styrene Acrylo-nitrile foam core was subject to blast loading that was caused by an explosive event. The resultant composite structure experienced damage from high velocity impact only on the exit face sheet. The same structure when subject to low velocity impact developed damage that was confined to the face sheet and the core. For this composite, the test specimens that were struck by high velocity projectile absorbed a higher level of energy during impact when compared to the test specimens that were subject to low velocity impact.

The influence of ballistic impact in synergism with an explosive blast was examined for a stitched composite structure. Overall, the stitched laminate when subjected to a submerged explosive blast revealed an observable improvement over the unstitched laminate that was subject to the same explosive level. Other studies have attempted to establish the response of sandwich plates when subject to an impulse blast response. Several of these studies did find and show that the core-transverse deformation and resultant strain experienced by the sandwich structures that was subject to impulse loading revealed an overall nonlinear profile through the thickness direction. This technical manuscript goes on to detail the research work and findings of few other researchers though the years. The key finding in all these studies is that the composite material and resultant structure withstood observably less damage and/or degradation when compared one-on-one with the monolithic counterpart when both were subject to blast or impulse loading often resulting from detonation of an explosive.

REFERENCES

[1] Dewey JM. Spherical Shock Wave in Expanding Spherical Shock Wave. Chapter 13.1; p. 456.

[2] Ngo T, Mendis P, Gupta A and Ramsay J. Blast loading and blast effects on structures - An overview. Electronic Journal of Structural Engineering 2007; 7: 76-91.

[3] Hause T and Librescu L. Flexural free vibration of sandwich flat panels with laminated anisotropic face sheets. Journal of Sound and Vibration 2006; 297: 823-41. https://doi.org/10.1016/j.jsv.2006.04.024

[4] McShane GJ, Deshpande VS and Fleck NA. The underwater blast resistance of metallic sandwich beams with prismatic lattice cores. Journal of Applied Mechanics 2007; 74: 352-64. https://doi.org/10.1115/1.2198549

[5] Sriram R, Vaidya UK and Kim JE. Blast impact response of aluminum foam sandwich composites. Journal of Materials Science 2006; 41: 4023-39. https://doi.org/10.1007/s10853-006-7606-4

[6] Tagarielli VL, Deshpande VS and Fleck NA. The dynamic response of composite sandwich beams to transverse impact. International Journal of Solids and Structures 2007; 44: 2442-57. https://doi.org/10.1016/j.ijsolstr.2006.07.015

[7] Francois-Xavier Jette Team Phillppe and Aris Makris. Need for enhanced protection against blast threats for soldiers exposed to roadside IEDs. Med Eng. System, 2400 St Laurent Blvd, otherwise, ON Canada, K166C4.

[8] Mathew Jackson and Arun Shukla. Performance of sandwich composites subjected to sequential impact and air blast loading, Composites: Part B 2011; 42: 155-166. https://doi.org/10.1016/j.compositesb.2010.09.005

[9] Ulven CA and Vaidya UK. Impact response of fine damaged polymer-based composite materials. Composites: Part B 2008; 39(1): 92-107. https://doi.org/10.1016/j.compositesb.2007.02.008

[10] Schubel PM, Luo JJ and Daniel M. Impact and post impact behavior of composite sandwich panels. Composites: Part A 2007; 38(3): 1051-7. https://doi.org/10.1016/j.compositesa.2006.06.022

[11] Mouritz AP. Ballistic Impact and explosive blast resistance of stitched composite. Composites Part B 2001; 32(5): 431-9. https://doi.org/10.1016/S1359-8368(01)00015-4

[12] Renfu Li, George A and George J. Point wise impulse (blast) response of composite sandwich plate including core compressibility effects. International Journal of Solids and Structures 2009; 46: 2216-2223. https://doi.org/10.1016/j.ijsolstr.2009.01.036

[13] Plantema FJ. Sandwich Construction. Wiley, New York 1966.

[14] Allen HG. Analysis and Design of Structural Sandwich Panels. Pergamon. Press Oxford 1969.

[15] Vinson JR. The Behaviour of Sandwich Structures of Isotropic and Composite. Materials. Techonomic Publishing Company, Lancaster, PA 1999.

[16] Kwon YW and Lannamann DL. Dynamic numerical modelling and simulation of interfacial cracks in sandwich structures for damage detection. Journal of Sandwich Structures and Materials 2002; 4(2): 175-199. https://doi.org/10.1177/1099636202004002706

[17] Xue Z and Hutchinson JW. A comparative study of impulse-resistant metal sandwich plates. International Journal of Impact Engineering 2004; 30: 1283-1305. https://doi.org/10.1016/j.ijimpeng.2003.08.007

[18] Fleck NA and Deshpande VS. The resistance of clamped sandwich beams to shock loading. Journal of Applied Mechanics (ASME) 2004; 71(3): 386-401. https://doi.org/10.1115/1.1629109

[19] Li R, Kardomateas GA and Simitses GJ. Non-linear response of a shallow sandwich shell with compressible core to blast loading. Journal of Applied Mechanics (ASME) 2008; 75(6): 061023-1-061023-10. https://doi.org/10.1115/1.2937154

[20] Arife B. Altunc, Jung J Kim, Marwan Al-Haik, Mahmoud M Reda Taha. Reliability-based design of blast-resistant composite laminates incorporating carbon nanotubes. Composite Structures 2011; 93: 2042-2048. https://doi.org/10.1016/j.compstruct.2011.02.017

[21] Liu GR and Xi ZC. Elastic waves in anisotropic laminates. Boca Raton (FL): CRC Press; 2002.

[22] Sun TC and Tan TM. Wave propagation in a graphite/epoxy laminate. Journal of Astronautical Science 1984; 32: 269.

[23] Kolsky H. Stress waves in solids. NY (USA): Dover; 1963.

[24] Van der Hijden JHMT. Propagation of transient elastic waves in stratified anisotropic media, Amsterdam, North-Holland; 1987.

[25] Christoforou AP, Elsharkawy AA and Guedouar L.H., An inverse solution for low velocity impact in composite plates. Computer Structures 2001; 79(29-30): 2607-19. https://doi.org/10.1016/S0045-7949(01)00113-4

[26] Langdon GS, Karagiozova D, Klemperer CJ, Nurick GN, Ozinsky A and Pickering E.G.: Air Blast response of sandwich panels with composite face sheets and polymer foam cores: Experiment & Prediction; International Journal of impact Engineering 54 (2013) 64-82. https://doi.org/10.1016/j.ijimpeng.2012.10.015

[27] Langdon GS, Klemperer CJ and Rowland BK. Response of sandwich structure with composite face sheets and polymer foam cores to air blast loading. Engineering Structure 2012; 36: 104-12. https://doi.org/10.1016/j.engstruct.2011.11.023

[28] Qi UX, Deshpande VS and Fleck NA. Dynamic response of a Clamped circular sandwich plates to shock loading Journal of Applied Mechanics, 2004; 71; 637-45. https://doi.org/10.1115/1.1778416

[29] Karagiozova D, Nurick GN and Langdon GS. Response of flexible sandwich type panels to blast loading. Composites Science Technology 2009; 69: 754-63. https://doi.org/10.1016/j.compscitech.2007.12.005

[30] Diab, Divinycell H Tech Manual; 2008' [6] Gurit Composite Technology Core Cell.

[31] Alcan Composite Material, Airex C70 Data Sheet, 2009.

[32] Tekalur SA, Shivakumar K and Shukla A. Mechanical behavior and damage evolution in E glass vinyl ester and carbon composites subjected to static and blast loads. Composites Part B 2008; (39): 57-65. https://doi.org/10.1016/j.compositesb.2007.02.020

[33] Comtois J, Edwards M and Oakes M. The effect of explosives on polymer matrix composite laminates. Composites Part A: Applied Science Manufacture 1999; 30(3): 181-90. https://doi.org/10.1016/S1359-835X(98)00172-9

[34] Jacob N, Nurick GN and Langdon GS. The effect of stand-off distance on the failure of fully clamped circular mild steel plates subjected to blast loads. Engineering Structure 2007; 10: 2723-2736. https://doi.org/10.1016/j.engstruct.2007.01.021

[35] Langdon GS, Klemperer CJ, Rowland BK and Nurick G.N., Response of Sandwich structures with composite face sheets and polymer foam cores to air blast loading. Engineering Structures 2012; 36: 104-112. https://doi.org/10.1016/j.engstruct.2011.11.023

[36] Gibson IJ and Ashby MF. Cellular solids: Structure and properties 2nd ed. Cambridge University Press; 1997. https://doi.org/10.1017/CBO9781139878326

[37] Tekalur SA, Bogdanovich AE and Shukla A. Shock loading response of sandwich panels with 3D woven E glass composite skin and stitched foam core. Composites Science and Technology 2009; 69(6): 736-53. https://doi.org/10.1016/j.compscitech.2008.03.017

[38] Wang E, Gardner N and Shukla A. The Blast resistance of sandwich composites with stepwise graded core. International Journal of Solid Structure 2009; 46: 3492-502. https://doi.org/10.1016/j.ijsolstr.2009.06.004

[39] Mahmood M, Arife B, Colak A and Marwan AN. A multi-objective optimization approach for design of Blast resistant composite laminates using CNT. Composites B 2009; 40: 522-529. https://doi.org/10.1016/j.compositesb.2009.04.020

[40] Brennan JJ and Prewo KM. Silicon carbide fiber reinforced glass-ceramic matrix composites exhibiting high strength and toughness. Journal of Materials Science 1982: 17(8): 2871-83. https://doi.org/10.1007/BF00543747

[41] Kang T.J., Lee S.H., Effect of stitching on the mechanical and impact properties of woven laminate composites. Journal of Composite Materials 1994;28(16):1574-87. https://doi.org/10.1177/002199839402801604

[42] Sinnot SB and Andrew R. Carbon Nanotubes. Synthesis, properties and applications Critical Review Solid State Materials Science 2001; 26(3): 145-249. https://doi.org/10.1080/20014091104189

[43] Lima S. Helical microtubules of graphite carbon. Nature 1991; 354:56-8. https://doi.org/10.1038/354056a0

[44] Smith PD and Hetherington JG. Blast and ballistic loading of structures. Oxford UK: Butterworth Heinemann: 1994.

[45] Puneet K, David SS and Arun S. Effect of plate curvature on blast response of carbon composite panels. Composite structures 2013; 99: 19-30. https://doi.org/10.1016/j.compstruct.2012.11.036

[46] Chun L and Lam KY. Dynamic analysis of clamped laminated curved panels. Composite Structures 1995; 30: 389-98. https://doi.org/10.1016/0263-8223(94)00056-5

[47] Kumar P, LeBlanc J, Stargel DS and Shukla A. Effect of plate curvature on blast response of aluminum Panels. International Journal of Impact Engineering 2012; 26: 74-85. https://doi.org/10.1016/j.ijimpeng.2012.02.004

[48] LeBlanc J and Shukla A. Dynamic response of curved composite panels to underwater explosive loading. Composite Structures 2011; 93: 3072-81. https://doi.org/10.1016/j.compstruct.2011.04.017

[49] Shen J, Lu G, Wang Z and Zhao L. Experiments on curved sandwich panels under blast loading. International Journal of Impact Engineering 2010; 37: 960-70. https://doi.org/10.1016/j.ijimpeng.2010.03.002

[50] Hause T and Liberscu L. Dynamic response of doubly curved anisotropic sandwich panels impacted by Blast loading. International Journal of Solids Structures 2007; 44:6678-700. https://doi.org/10.1016/j.ijsolstr.2007.03.006

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