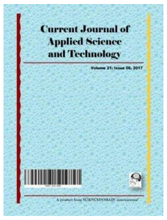

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The Energy Absorption Capability of Composite Materials for Use in Performance-Critical Applications: A Review

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Authors' contributions

This work was carried out in collaboration between all authors. Author SP designed the study, protocol and wrote the first draft of the manuscript. Authors KKS and NB managed the analyses and direction of the study. Author TSS managed the literature searches and edited the paper. All authors read and approved the final manuscript.

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ABSTRACT

Innovative and novel composite materials that can offer a healthy combination of properties to include physical, mechanical and thermal have in recent years been engineered for use in a spectrum of both performance-critical and non-performance-critical applications in industries spanning aerospace, automotive, defense, naval, civil construction and even consumer products. In the period spanning the last three decades, since the early 1980s, novel composite materials have been engineered for use in products that can withstand both the effects and after effects of shock loading. Based on the energy absorption capabilities and response characteristics of the chosen composite when subjected to the extrinsic influence of a blast load, valued observations in

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synergism with criterion for the design of both materials and structures were put forth. In this paper, an attempt is made at reviewing the energy absorption capabilities and blast response characteristics of structures made from novel engineered composite materials. The specific role of nature of composite material, processing technique used for the engineered composite and mechanical response is presented and briefly discussed.

Keywords: Composite material; processing; structures: monolithic; layered; blast loading; impact; energy absorption.

1. INTRODUCTION

Often, the use of real explosives is dangerous since it has a spherical wave front coupled with pressure signatures, which are spatially complex and difficult to measure. On the contrary, a shock tube does offer the advantage of a planar wave front along with wave parameters that can be controlled with relative ease. Furthermore, shock tube parameters are easy to replicate.

There are basically two types of energies associated with gas in a shock tube that does play a role in the shock loading process. These are the following:

(i) Incident energy, which is the energy stored in the gas behind the incident shock wave, and
(ii) Remaining energy, which is the energy stored in the gas behind the reflected shock wave. When the incident shock wave impacts upon a specimen that is located at the end of the muzzle, a reflected shock wave is generated. The energy that is behind this reflected shock wave does create a loading on the chosen specimen. Resultant modification in the amount of energy during an interaction of the reflected shock wave with the incoming gas is defined as the energy that is lost. It is also the difference between the incident energy and the remaining energy. A comprehensive understanding of these energies certainly helps in characterizing the blast mitigating behavior of the panels.

2. AN OVERVIEW OF RESEARCH DONE AND RELATED FINDINGS

Silva and Lu [1] examined the feasibility of using innovative composite materials for improving the blast resistance capacity of reinforced concrete slabs. To achieve this objective five slabs were tested under conditions of a real blast load. The test setup for the experimentation is given in Fig. 1.

The first slab was used to establish a base line and compared with the remaining four slabs, which were strengthened using carbon fiber-reinforced and steel fiber-reinforced polymers, essentially comprising of two slabs retrofitted on one side and two slabs retrofitted on both sides. Test results revealed a noticeable increase in the blast resistance when the slabs were retrofitted on a single side. However, the slabs retrofitted on both sides displayed a significant increase in blast resistance. This result can essentially be attributed to the negative moment that

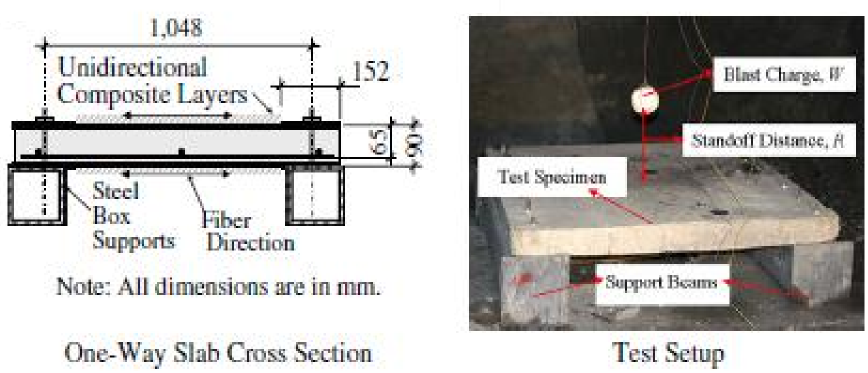

Fig. 1. Slab reinforcement details and test site setup

develops under the influence of a blast load. They also studied the feasibility of using modified displacement-based methodology to produce explosive charges and the weight and standoff distances required to impose a specified level of damage. The main reason for initiation of this study was an increase in terrorist attacks on both civilian and military structures. Blast protection of structures is never an absolute concept and there is always an associated high cost with an increased level of damage protection [2]. This necessitates the need for proper assessment tools to be employed for determining, within a reasonable degree of accuracy, the level of vulnerability of both new and existing structures. Equally important, design and construction techniques must be both developed and concurrently improved with the primary objective of increasing the blast resistant capacity of structures. In addition, a broader awareness in homeland defense concerns has increased the need to support the development of both new and affordable retrofit and/or upgraded technologies. Mosalam and Mosallam [3] carried out both an analytical and experimental study on two-way reinforced concrete slab both with carbon-fiber and without carbon-fiber-reinforced polymers (CFRP). An important observation resulting from this study was slabs retrofitted on one side were not as effective in resisting blast loads as those slabs retrofitted on both sides when the blast duration exceeds 20 ms.

Wobbe et al. [4] used a new class of composite composed of knitted high strength steel cords designated as steel fiber-reinforced polymers (SRP) under conditions of a blast load. Different retrofit schemes consisting of carbon fiber-reinforced polymer (CFRP) and steel fiber-reinforced polymer (SRP) strengthening were used on one side and both sides of the tested slabs and the results obtained. The SRP composite material i.e. steel cord, a product that is well used as a reinforcement in the manufacturing of radial tires has the strength and stiffness of carbon fiber but at a fraction of its cost. This makes the steel fiber-reinforced polymer (SRP) a potential material for strengthening of reinforced concrete members. The finished surface for both SRP and SRG can be seen in the Fig. 2.

Furthermore, few of the advantages of steel fiber-reinforced polymers (SRP) over carbon-fiber-reinforced polymers (CFRP) are the following:

(1) Its coarseness allows for fast and simple impregnation.
(2) No corner rounding is required as in typical applications of FRP, and
(3) Mechanical anchors, such as nails, can be used to improve bond rather than U-wraps.

Additionally, conductivity of the steel reinforcement can be put to beneficial use for electrical lightning strike and/or galvanic protection. Based on test results, the slabs that were fitted with the new steel wire reinforced polymer composite performed nearly the same as slabs retrofitted with the traditional carbon fiber reinforced polymer (CFRP) composite. As such, test results revealed the new cost-effective steel fiber reinforced polymer (SRP) technology to show great potential for improving the blast resistance capacity of concrete members [4,5].

Fig. 2. SRP Surface and SRG Surface

The work also focused on development of a stepwise methodology to predict the charges, weight and standoff distances using the method of displacement-based design (DBD). The DBD method, which is typically used for earthquake loads [6] was customized for the assessment of structures subjected to a real blast load [7]. For the DBD method to be applied to a blast load, three variables are needed and these are the following: -

(a) An Equivalent Viscous Damping (EVD) ratio
(b) The Dynamic Magnification Factor (DMF), and
(c) Dynamic Increase Factor (DIF).

The EVD ratio is a function of displacement ductility and does correlate the energy dissipated by the chosen nonlinear system to the energy that is dissipated by an equivalent damped linear system. The research focused on developing an estimate for the EVD ratio under the influence of a blast load and as a function of displacement ductility. However, information does exist in the “open” literature to indicate that damping is usually ignored during the design for blast resistance [8]. It is important to emphasize that in this research the EVD ratio was used as a mathematical tool to obtain the DMF necessary to correlate the static load to the dynamic blast load. Researchers have also presented a graphical correlation between the EVD ratio and displacement ductility to be dependent on relations specific to moment curvature of the reinforced concrete member. Moment curvature analyses for the tested slabs, under strain rate effects, were also undertaken and results of the analysis are briefly presented. In few independent studies, values of the established dynamic increase factor (DIF) were used to obtain the response of reinforced concrete members when subjected to high strain rates that often result under conditions of a blast load [9]. The methodology proposed by Fu et al. [9] in the study made use of equivalent viscous damping (EVD), dynamic magnification factor (DMF) and dynamic increase factor (DIF) to establish the response of reinforced concrete members under the influence of a blast load. The results were found to be promising for the prediction of blast load in terms of standoff distances and charge weight. The pressure wave on a structure resulting from a blast load, was characterized into three phases. However, for purpose of continuing study a simplified blast wave was used as shown in Fig. 3. A principle parameter that are required to define a simple blast load are the following: (i) peak over pressure (P_s), and (ii) duration of blast impulse (t_d). An expression can be used to relate weight of the charge [W] with the Standoff Distance [R]. The peak over pressure [P_s] can then be related to weight [W] and standoff distance [R] by a function designated as the blast load-scaled distance [Z] [9,10].

$$P_s = \frac{6.7}{Z^3} + 1 \ \text{bar} \qquad (P_s \geq 10 \ \text{bar})$$

$$P_s = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \ \text{bar} \qquad (0.1 \leq P_s \leq 10 \ \text{bar}) \tag{1}$$

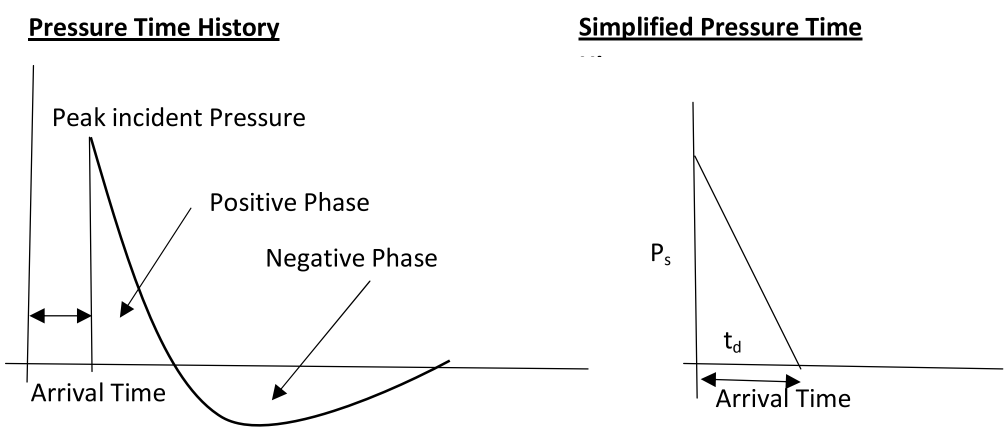

Fig. 3. A schematic of pressure-time history and simplified pressure-time variation

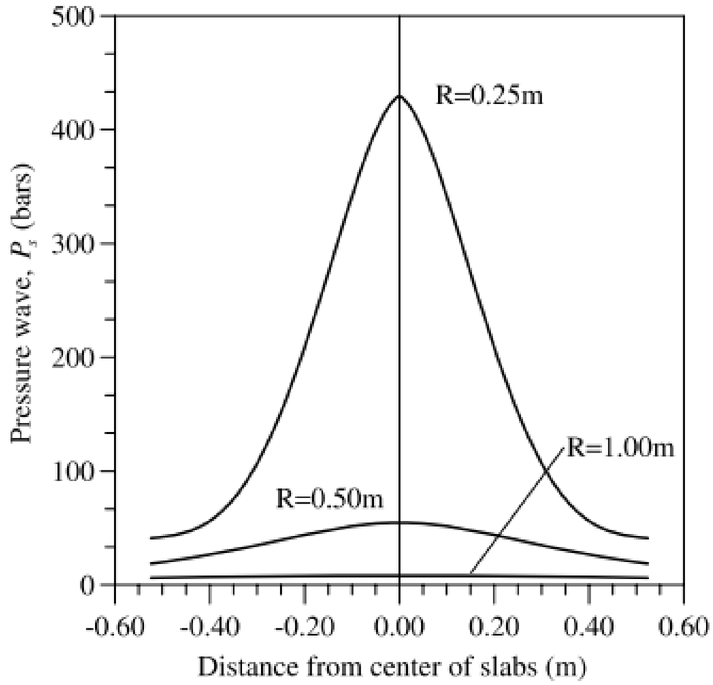

Fig. 4. Shape of the blast pressure wave

In this equation, the scaled distance (Z) is correlated with weight (W) and standoff distance [R] through the expression:

$$Z = \frac{R}{W^{1/3}} \tag{2}$$

The standoff distance [R] is measured in meters and the charge weight [W] is based on Kilograms. In Fig. 4 is shown the shape of the pressure wave for different standoff distances and for a charge weight equal to 1 Kg. As expected, for higher standoff distances the pressure wave reduces significantly to a negligible value that is uniformly distributed. However, as the standoff distance is reduced the peak pressure increases significantly and the pressure wave is significantly higher at the center of the slab and dissipates rapidly towards the end of the slab. Tekalur et al. [11] investigated the blast resistance of poly urea-based layered composite materials, which have been chosen for use in applications involving blast and ballistic impacts and are effective materials for absorbing the energy of a blast. Use of poly urea-based composites, as a shock mitigation material was a relatively new idea that these authors put forth. They examined both layered and sandwich composite materials, comprising of poly urea (PU) and E-glass vinyl ester (EVE) for effective blast resistance using a shock tube. A rectangular plate of the plain-woven composite and the layered composite that was simply supported along two edges and free along the other two was subjected to controlled blast. Results revealed the addition of poly urea layer on the impact face to considerably increase the blast resistance. Further, sandwich materials prepared by sandwiching poly urea between two composite skins was the best blast resistance composite for both the layered and the composite plates.

3. INFLUENCE AND ROLE OF BLAST LOADING ON MONOLITHIC, LAYERED STRUCTURES AND COMPOSITE MATERIALS

The response of a monolithic plate [12,13] and conventional sandwich structure [14,15] to blast loading has also been studied. There also exist studies on homogenous materials that are subjected to transient loading [15,16]. However, experimental observations on real-time response of both a composite and layered structure, under the influence of a blast load, is limited. A subsequent study by Fatt et al. [17] proposed a polymer-based coating on both buildings and structures for enhancing their blast resistance.

Spraying, or application, of the poly urea over conventional composite structures is one such approach. The addition of poly urea to the composite structures introduces complexity to the overall structural response due to the conjoint influence of non-linear material behavior, and disperse wave propagation in polyurea. The rate sensitivity behavior of polyurea has been of interest for research study [18] and has shown the material behavior of polyurea to be dependent on mutually interactive influences of the following: (i) constitution, (ii) loading rate, and (iii) temperature. In an earlier study, these researchers characterized the blast resistance of plain woven composites under different boundary conditions [19]. In Fig. 5. below the damage progression in E-glass/ vinyl ester composite is shown which is subjected to blast loading. The damage to the rear face at different blast pressure is shown.

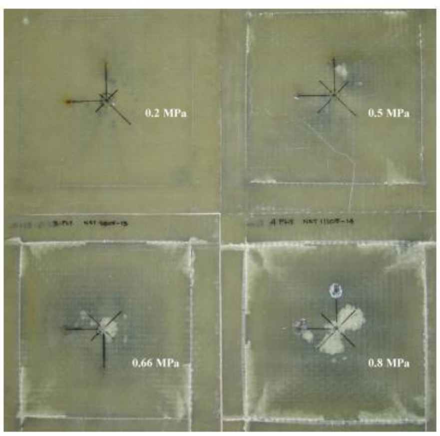

Fig. 5. Damage progression in E-glass/vinyl ester composites, subjected to shock blast loading

In this independent study, the dynamic response of a layered material along with blast resistance of structural elements fabricated by the application of polyurea over conventional composites was studied. These researchers used a Split Hopkinson Pressure Bar along with blast response and a shock tube for their study.

In addition to these layered materials, sandwich materials have also been fabricated and their blast resistance evaluated experimentally. The resin system used was Dow Chemical's Derakane 510A-40. The glass fiber chosen was woven E-glass. The areal weight was 610 g/m^2 with the unbalance construction having 59% fiber and 41% fiber along the wrap direction and fill direction. The fabric layup was 14 plies balanced/symmetric for a nominal vacuum thickness of 6.35 mm. The fiber volume fraction of the panel was 0.605. The cured panels were cut to the required size using a water-cooled diamond blade tile and then used as a casting substrate for the polyurea coating. They polyurea plain woven and layered material was then subjected to impact. The polyurea samples were subjected to a strain rate of 800 s^{-1} and the composite samples were subjected to a strain rate of 1900 s^{-1}. For the polyurea, a flow stress of 10 MPa was observed at 1% strain and this level was sustained up to 4% strain. Beyond 4% strain, a strain hardening effect was observed in this material, with the stress increasing in a linear fashion up to strain of 8%. For the composites, a peak compressive stress of 350 MPa was observed at 3 % - 4% strain. The blast resistance was characterized using three main parameters, and these are the following:

(i) Macroscopic visual examination.
(ii) Microscopic examination, and
(iii) Real time measurement.

Layering of the glass fiber composite with a soft layer provided for better blast resistance. An enhancement of the blast resistance was more pronounced when a soft material faces the blast. It was experimentally observed that for the different possible material construction, the sandwich materials made by sandwiching a woven composite skin offered the best blast resistant properties. Simultaneously, a weight addition for both the layered composite and sandwich composite was 60% more than for the plain composite. Also, performance enhancement of the layered composite material was about 25% better (when polyurea faces the blast). For the case of sandwich composites, the blast performance was enhanced by as much as 100%.

Buchan and Chen [20] studied the blast resistance of fiber-reinforced polymer (FRP) composites and polymer strengthened concrete and masonry structures. They conducted both experimental and finite element research for investigating the behaviors of fiber-reinforced plastics under the influence of a blast load. They found walls of the Concrete Masonry Unit (CMU) to be vulnerable to fragmentation. Though many options were available for retrofitting a structure, selection of the most suitable material is necessary for both optimal performance and cost. The test setup is given at Fig. 6.

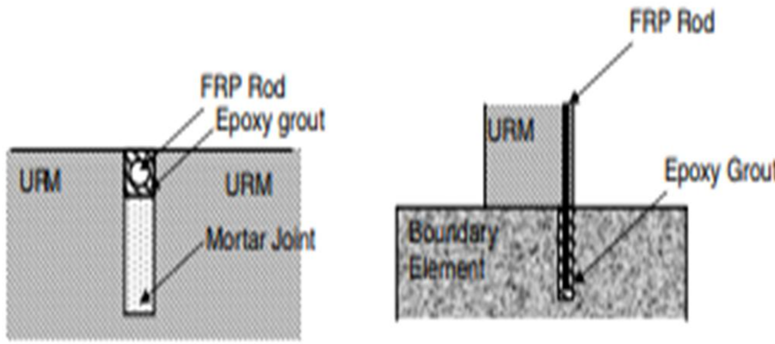

Fig. 6. Anchorage details of FRP rods

Apart from strap on composites, spray-on-polymer on one side of the wall provided the additional strength against a blast load. A coating on both sides of the wall was more effective but had the additional burden of cost associated with it. However, this research study was limited due to the following factors: (i) sensitive nature of work, (ii) cost, (iii) manpower intensive, (iv) very expensive instrumentation, (v) number of variables involved, (vi) charge weight, and (vii) standoff distance.

Mouritz [21] studied explosive and ballistic impact resistance of stitched composites. He determined the effectiveness of stitching in enhancing the damage resistance of polymer composites against ballistic projectiles and an explosive blast. He tested Glass-reinforced vinyl ester composites, stitched in the through thickness direction, with thin Kevlar® yarn for impact of a bullet that was travelling at 0.9 Km/sec and an under-water explosive shock wave that was moving at 1.5 Kms. He found the amount of delamination damage to be reduced by stitching.

In Fig. 7. it was evident that the delamination due to ballistic on entry side was less compared to the back face and the stitching had a substantial effect on the delamination on the rear side of the panel. As far as delamination due to blast was concerned Fig. 8., it was found that the delamination was much higher in blast as compared to ballistic impact and stitching played an important role in restricting the delamination in both high and low intensity blast.

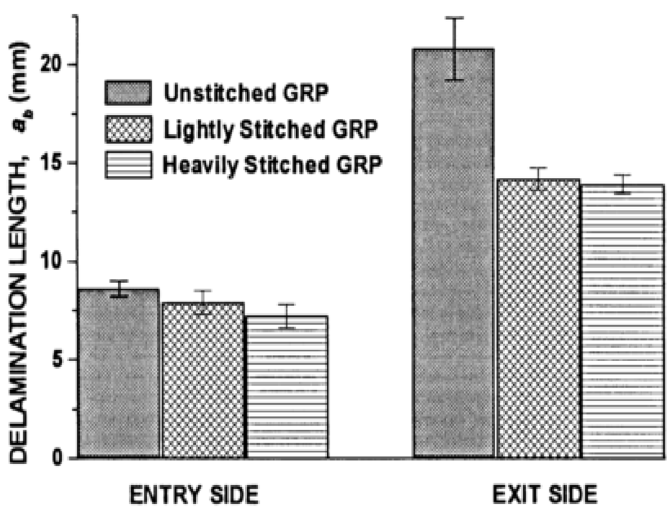

Fig. 7. Delamination crack length on the entry and exit sides of the ballistic impact targets

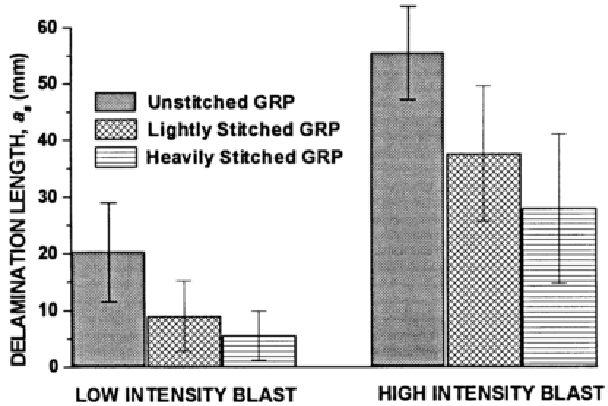

Fig. 8. Delamination crack lengths for the low and high intensity underwater blasts

The two dominant damage processes occurring are the following [22]:

(i) Dynamic compaction of GRP material that culminates in fracture of the fiber that is immediately ahead of the projectile, and
(ii) Delamination cracking around the impact site.

The damage processes were found to be highly effective in stopping, or slowing down, a high-speed projectile. The delamination of glass-fiber-reinforced polymer (GRP) can become an issue if it is used in load-bearing structure as its capability is gradually reduced. Composites also suffer extensive delamination damage when subjected to shock loading caused by an explosive blast and this causes a reduction in the mechanical properties of tension, compression, flexure and fatigue of the GRP laminates. However, according to Dransfield et al. [23] the delamination resistance of composites can be increased by stitching through the thickness. An improvement in the delamination resistance is well reflected by stitched composite having Mode I and Mode II inter-laminar fracture toughness that are much higher than an equivalent unstitched laminate. In some cases, the increase was as much as 20% to 30%, though the general value was around 2-10%. Liu [24] demonstrated the delamination damage to GRP composites caused by low energy impact to be reduced by up to 40% with stitching. The stitched composites exhibited higher post impact mechanical properties than an equivalent unstitched laminate. The composite sample made by Mouritz was an E-glass fiber in a vinyl resin matrix. Two types of glass were used for the composite and these are the following:

(i) A plain-woven roving fiber having an areal density of 0.6 Kg/m^2, and
(ii) A chopped strand mat having a density of 0.3 Kg/m^2.

The composite contained seven plies of each type of glass laid in an alternating ply sequence. The glass performs were then either `lightly stitched' to an areal density of three stitches/$cm^2$ or `stitched' to a six stitches/cm^2 using 2 x 20 tex spun (180 demier) Kevlar yarn. Due to fasteners of the stitches the performs were lightly compacted. The average thickness of the unstitched, lightly stitched and heavily stitched performs were 6.6 mm, 5.7 mm, and 6.2 mm, respectively. The performs were then infused with cold curing vinyl ester resin, using the vacuum-assisted resin transfer molding (RTM). After fabrication, the composites were cured at room temperature for several weeks. The average resin content of unstitched was 4.2, the lightly stitched was 36.5, and heavily stitched composite was 38.6. This study revealed the through thickness stitching to be effective in reducing the amount of damage due to delamination caused by an explosive blast, but had only a small effect in reducing the damage caused by a ballistic projectile. The damage resistance is improved primarily because the stitches increase the Mode – I inter-laminar fracture toughness. The flexure properties of the stitched composites were like the properties of the unstitched laminates when damaged by a ballistic projectile. This is because the amount of delamination damage is similar. On the other hand, when damaged by an explosive blast, the loss in properties experienced by the unstitched laminate is greater than that for the stitched composite counterpart. It is expected that damage tolerance can be further improved by reinforcing the composite with higher stitching (above 20 stitch/cm^2) coupled with use of a thicker yarn (1000 denier).

Morais et al. [25] evaluated the influence of laminate thickness on the resistance of repeated low energy impact of (a) glass fabric-reinforced composite, (b) carbon fabric-reinforced composite, and (c) aramid fabric-reinforced composite for two levels of energy impact. The results obtained revealed that below a certain energy level the cross section of the chosen laminate is a relevant variable that determines the impact resistance. Under these conditions, the experimental points of all tested laminates fall on a single curve, irrespective of the reinforcing fiber used. When the energy level of the impact is increased, characteristics of the fiber become relevant. Accordingly, the glass fabric-reinforced composites showed an increase in impact resistance with an increase in laminate thickness. This behavior ascribed to be due to the higher areal coverage of the glass fabric used. The isotropic behavior of the glass fiber in relation to the anisotropic character of aramid and carbon fiber was also of relevance. It was demonstrated that for an energy level below 3.7J, the cross section of the laminate at the point of impact governs the impact resistance. For a higher energy level, an increase in the resistance to repeated impact with laminate thickness is dependent on the following two factors:

(i) Fiber used, and
(ii) Spatial distribution of the fiber.

The better performance found for the glass fiber-reinforced composites was attributed to the fineness of glass fibers in relationship to aramid and carbon fibers, which results in a higher areal coverage.

Carrillo et al. [26] investigated the ballistic behavior of the following impact test specimens as given at Fig. 9.

(a) A multilayer Kevlar aramid fabric /Polypropylene (PP) composite laminate (CL), and
(b) Layered aramid fabric (AF) impact specimens.

The samples were tested in accordance with specifications detailed in the standard NATO STANAG-2920. It was found that the thermoplastic polypropylene matrix increased the ballistic performance of the composite laminate when compared one-on-one with the aramid fabric test specimen having near similar areal density. The result is less aramid fabric was needed to obtain the same level of protection when a polypropylene matrix was incorporated. It was also found that enhanced ballistic performance of the composite laminate was since polypropylene matrix enables different energy absorbing mechanisms to include the following: (i) a larger deformation of secondary yarns, (ii) fabric/matrix de-bonding, (iii) matrix cracking, and (iv) delamination, which was not observed in aramid fabric-reinforced systems. For the aramid fabric system, straining of the primary yarns was the primary mechanism for an absorption of energy. The ballistic limit and penetration threshold energy were predicted for both a composite laminate target and aramid fabric target using an empirical model. It was found that both the ballistic limit and perforation threshold energy increased for the composite laminate target. This is because the polypropylene matrix enables different energy absorbing mechanism to include the following: (i) a larger deformation experienced by the secondary yarns, (ii) fabrics/matrix debonding, (iii) matrix cracking, and (iv) delamination, which was not observed for the aramid fabric systems. For the aramid fabric system, straining of the primary yarns is the primary mechanism for absorption of energy. It was found that both the ballistic limit and perforation threshold energy increased for the composite laminate targets when compared to the aramid fabric target having a near similar areal density. This finding is important from design view point of soft armor primarily because less aramid fabric is required to obtain the same level of protection when a thermoplastic polypropylene matrix is incorporated, which can potentially lead to both savings in weight and a lower cost.

Tan and Khoo [27] investigated the response of flexible laminates to ballistic impacts by projectiles having various geometries, namely: (i) flat ended projectile, (ii) hemispherical projectile, (iii) ogival projectile, and a (iv) conical projectile. The laminate of interest was ‘Spectra Shield’ comprising [0°/90°] extended chain polyethylene filaments embedded in a thermoplastic resin. The laminate perforated by a hemispherical projectile showed many similarities with the laminate perforated by a flat-ended projectile. For both cases, the formation and presence of a generator strip was observed for the range of impact

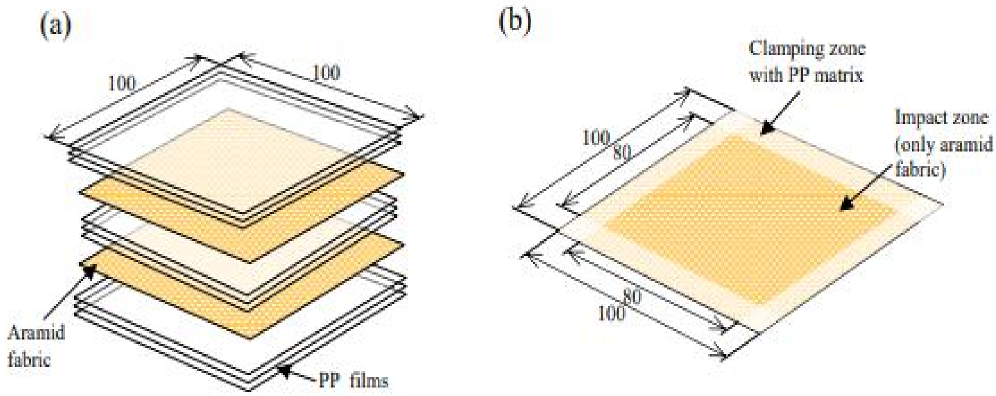

Fig. 9. Geometrical details of target configurations (mm) for (a) Composite laminates and (b) plain multi-layer aramid fabric

velocities reported. The generator strip manifests itself as a band of material within which there occurs no delamination. Outside of the generator strip, the laminates showed a region of delamination that was rhombic in shape and centered at the impact point. In addition to the generator strip, a strip of material is pushed out, which eventually detaches itself from the material at the exit face of the laminate. It is to be noted that size of the delamination, length of the generator strip, and amount of creasing observed on the laminate, are all dependent on the impact velocity. Although ballistic impact using a hemispherical projectile and flat ended projectile results in many similar observations, the hemispherical projectile perforates the laminate by stretching the spectra filaments to failure whereas the flat-ended projectile tends to shear the filament. Laminates perforated by a conical projectile showed evidence of "localized" damage and the region affected by the impact increased with an increase in impact velocity. There was no generator strip and no material was stripped off from the back when the projectile perforated the laminate. Tendency for the occurrence of delamination within the laminate was minimal. Instead of a diamond shaped delamination, the delamination area was a 'star' shape. This is because the delamination is caused by the filament being pushed aside as the sharp projectile perforates as opposed to the back ply being pushed away from the front ply.

Park et al. [28] studied kinetic dissipation during ballistic tests on soft body armor. They investigated the amount of energy that is transferred to the backing material of an oil-based clay (i.e. Kinetic dissipation). To determine the relationship between penetration depth (or dent volume) with impact velocity (energy), weight dropping tests, using a series of steel spheres, were carried out at a low velocity and direct shooting using a 5.56 mm fragment simulating projectile (FSP). The velocity of impact was directly proportional to the dent observed. A change in volume of the dent for a change in impact velocity, was proportional to 1.5th power of the mass of the impactor. The energy absorption per unit volume of the dent increased linearly with impact velocity. The relationship between trauma depth (or dent volume) and kinetic dissipation of a soft body armor panel subjected to a 9-mm bullet at 436 m/s was studied and presented. They used five steel balls for the weight dropping test. The steel balls had a diameter of 30.163 mm, 38.0 mm, 47.625 mm, 60.0 mm and 63.5mm, and weight of 0.1119 kg, 0.2241 kg, 0.4412 kg, 0.8822 kg, and 1.043 kg, respectively.

Gopalakrishnan and Senthil [29] investigated the failure analysis of a ballistic material. In their investigation they used glass fiber-reinforcing a polyester matrix. The glass fiber was in woven form. They maintained 10 m between the projectile and the target. The test set up is given in Fig. 10. Samples were test fired using a 9-mm revolver projectile having an impact velocity of 350 m/s. They used a gas gun for checking low velocity impact less than 100 m/s. By using thermography and X-ray radiography it was concluded that the material experienced damage through its full depth even though the bullet had not fully penetrated.

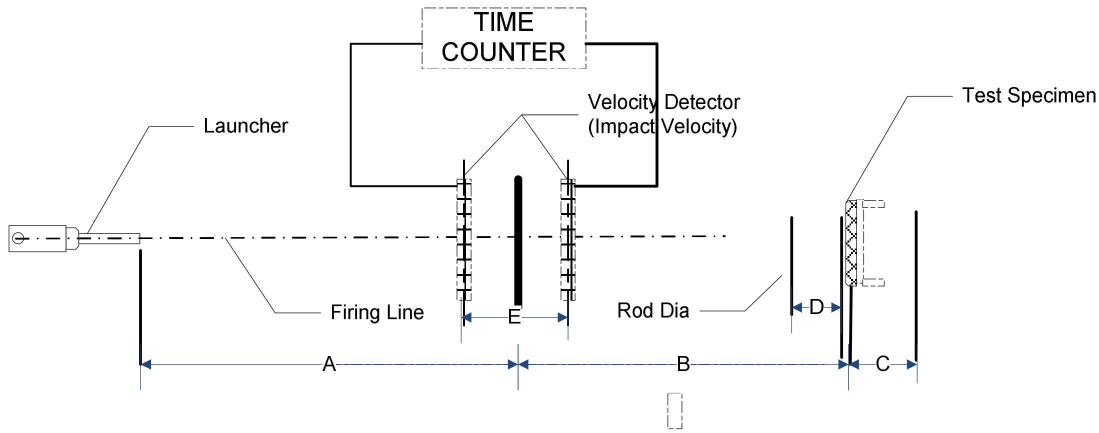

Fig. 10. Test set up for the laminates

Apart from this Corran et al. [30] investigated the effect of projectile mass, nose shape and hardness on the penetration of both steel plates and aluminum alloy plates having varying thickness. They used both blunt and a cylindrical-conical projectile and observed the ballistic limit of the plate to change with a change in both projectile mass and nose shape. TW and Recht [31] found a blunt projectile to penetrate the target more efficiently than a conical projectile when the thickness of the target was moderate. For the case of both a thin target and a thick target an opposite trend was observed.

Pandya et al. [32] investigated the ballistic impact of hybrid composites. The material considered for their study were four types of symmetric hybrid composites made using the following:

(i) Plain weave E-glass fabric, and
(ii) 8-H satin weave T-300 carbon fabric with epoxy resin.

Studies were also carried out on plain weave E-glass/epoxy and 8H stain weave T 300 carbon/epoxy for purpose of comparison. They found that by placing E-glass layers in the exterior and carbon layers in the interior provided for a higher ballistic limit velocity when compared to placing carbon layers in the exterior and E-glass layer in the interior. Although several techniques exist for enhancing the ballistic protection capability of a composite material, there does exist scope for even additional work. Ellis et al. [33] included the following in their independent study: (a) hybrid composites, (b) dispersion of nano particles having energy absorption capability in polymers/polymer matrix composites (PMCs), (c) development of sandwich structures with foam core [34], (d) a honeycomb core [35], and (e) use of foam materials [36]. Hybridization is one of the effective ways for improving the energy absorption capability of polymer-matrix composites [PMCs]. It was brought to light that the behavior of hybrid composites under conditions of ballistic impact loading should be well understood. When an impact event taken place, different type of waves propagates through an impacted body. The types of waves are classified based on the direction of motion of particles of the body relative to direction of propagation of the waves and the boundary conditions [37]. Hybridization is an effective way for improving the energy absorption capability of polymer-matrix composites. However, there are only limited studies available on ballistic impact behavior of hybrid composites. Factors affecting the response of composites to impact loading include the following: (i) type of fibers and matrix, (ii) laminate thickness, (iii) lay-up sequence, (iv) geometry, and (v) boundary conditions. The ballistic impact response also depends upon the size, shape and kinetic energy of the projectile.

Ellis et al. [33] studied the ballistic impact resistance of shape memory alloy (SMA) and spectra hybrid graphite composites. They observed a significant increase in energy absorption on adding both spectra and spectra/shape-memory alloy (SMA) layers to the back face of the composite. Muhi et al. [38] investigated the high velocity impact behavior of glass fiber-reinforced plastic and hybrid composites consisting of E-glass and Kevlar-29 fabric. They observed the penetration resistance to be enhanced by the addition of layers of Kevlar to layers of E-glass. They also presented an energy-based model for the prediction of penetration behavior of hybrid composites. The specific observations made by Pandya et al. [32] was that ballistic limit velocity can be increased by the addition of E-glass layers to T300 carbon layers when compared to the addition of carbon composites for the same target thickness. Placing E-glass layers in the exterior and carbon layers in the interior provided for a higher ballistic limit velocity when compared to placing carbon layers in the exterior and E-glass layers in the interior for the same target thickness. There was a good match between the experimentally obtained ballistic limit velocity [V_{50}] and the analytically generated ballistic limit velocity [V_{BL}].

Caprino et al. [39] investigated four stitched graphite/epoxy laminates having different thickness, which were subject to a high velocity impact test. Two steel spheres 12.7 mm and 20 mm in diameter were used as bullets for the tests carried out at two different speeds [(i) 65 m/s, and (ii) 129 m/s]. Perforation was observed to occur only under some of the experimental conditions adopted, whereas rebound occurred in the other cases. The laminates tested in this study were fabricated using blankets of un-impregnated carbon layers, each consisting of five tape plies that were oriented along the directions of 0°, -45°, 0°, +45° and 90°. From the blankets, four panels having a staking sequence $[0°/-45°/0°+45°/90°)_n]_s$, were made adopting a procedure based on the sequence required and stitched using Kevlar® 29 yarns, using a stitch spacing of 5-mm and stitch pitch of 5-mm, to obtain a preform. The preform was embedded in epoxy by resin film infusion (RFI). Curing of the resin was accomplished both in an autoclave and in vacuum at 178°C for 3 hours. The nominal thickness [t] of the cured panels was t =1.5 mm, 4.5 mm and 6 mm respectively and the fiber content were 55% by volume. From the panels, square specimens measuring 200 mm in side were cut using a diamond saw. The cut specimens were equipped on the back face with two strain gages, with each gage precision oriented to be parallel to one of the principal directions of the sample and located at 30-mm from the impact point. Impact test was carried out using an instrumented gas gun. The Reid & Wen model was found to be effective in predicting the influence of panel thickness on perforation energy. However, it did not account for diameter of the bullet. The modified Cantwell and Norton model provided a good estimate of both the perforation energy and the residual velocity as a function of coupon thickness and diameter of the impactor. The delaminated area was correlated with the maximum absorbed energy using a simple linear relationship, whose constant was independent of both laminate thickness and projectile diameter. These researchers also found that during high velocity impact, the damage area of sufficiently thin targets was noticeably lower than under low-velocity conditions. However, the difference disappeared for the thick specimens.

Gellert et al. [40] investigated the perforation of thin targets constructed of glass fiber-reinforced plastic, spectra composite (Allied Signal) and Kevlar composite (Du Pont) as well as Nylon and Kevlar fabric. All targets measured 300 mm square and made of woven fiber that was either impregnated or stitched along one axis using a line spacing of 30 mm. The composite panels were subsequently hand layered by brush-impregnating successive plies and subsequently curing the panels at ambient temperature (25 C) using a press at 2 MPa pressure. The samples were then post cured at a temperature of 90°C for 1 h and 2MPa. The ballistic testing was undertaken using a 5.59 mm diameter, 1.1 g mass fragment simulating projectile. This research study aimed at understanding the perforation of fiber composite and fabric materials for ballistic protection in terms of the energy absorbed as: (i) strain energy, (ii) delamination energy, and (iii) kinetic energy. For thin targets, a model assuming each layer to deform to a similar extent laterally and experiences delaminates for the case of composites and allows the sum of the energy terms to be of the correct magnitude compared to the energy lost by the projectile.

Ravikumar et al. [41] presented an analytical method for the prediction of compressive strength of composites under conditions of high strain rate loading. The method was based on a variable power law. A strain rate of up to 5000 S^{-1} for generating a compressive stress versus strain response was presented. They generated experimental results in the strain range of 472-1957 S^{-1} for a typically woven fabric glass/epoxy laminated composite along all three principal directions. The laminated composite was made using the resin film infusion (RFI) technique. It was generally observed that the compressive strength is enhanced under conditions of high strain rate loading compared to what occurs under quasi–static loading. There does exist a paucity of information in terms of studies on high strain rate behavior of materials. They considered the property change factor, which is defined as the ratio of the property at high strain rate loading to that at quasi static loading. If the property at quasi-static loading is lower than property at high strain loading, then the property change factor would be more than one. For such cases the property change factor was termed as the property enhancement factor. They tabulated the readings obtained for the property enhancement factor. The experiments were carried out was using a standard compressive apparatus. They observed the ballistic impact caused by a rigid projectile on a composite target placed at 11 mm and using a projectile mass of 7.5 gm at 245 m/s did induce compressive strain.

Jing et al. [42] investigated the dynamic response of cylindrical sandwich shells having metallic foam cores that was subjected to blast loading. Ultra-light, highly porous metallic materials [foams, honey comb and lattices] having a positive combination of physical and mechanical properties, to include: (i) high specific stiffness [E/ρ], (ii) high strength, (iii) good energy absorption capacity, (iv) high gas permeability, and (v) high thermal conductivity were chosen [43,44,45]. Most noticeably their cellular microstructure enables them with an ability to undergo plastic deformation at a nearly constant nominal stress, and this makes them an attractive choice for use as an energy absorption material in protective applications. The properties of the metal foam and other cellular metal structures depend upon the properties of the metal, the relative density and cell topology. Metal foams are made by the process given in the Fig. 11.

Common uses of cellular metals include light weight cores for use as sandwich structures with the intent of enhancing shock resistance. Experiments were carried out on two different radii of curvature and geometrical configurations. A four-cable ballistic pendulum system was employed to measure the impulse imparted to the specimens. Typical deformation and failure modes were classified and analyzed with the purpose of understanding the following: (a) the effects of face sheet thickness, (b) relative density of the core, (c) arrangement of the foam core layer having different densities, (d) specimen curvature, and (e) mass of the charge, on structural response. The results indicated that both deformation and failure modes and structural response of the shell are sensitive to both geometrical configuration and blast impulse.

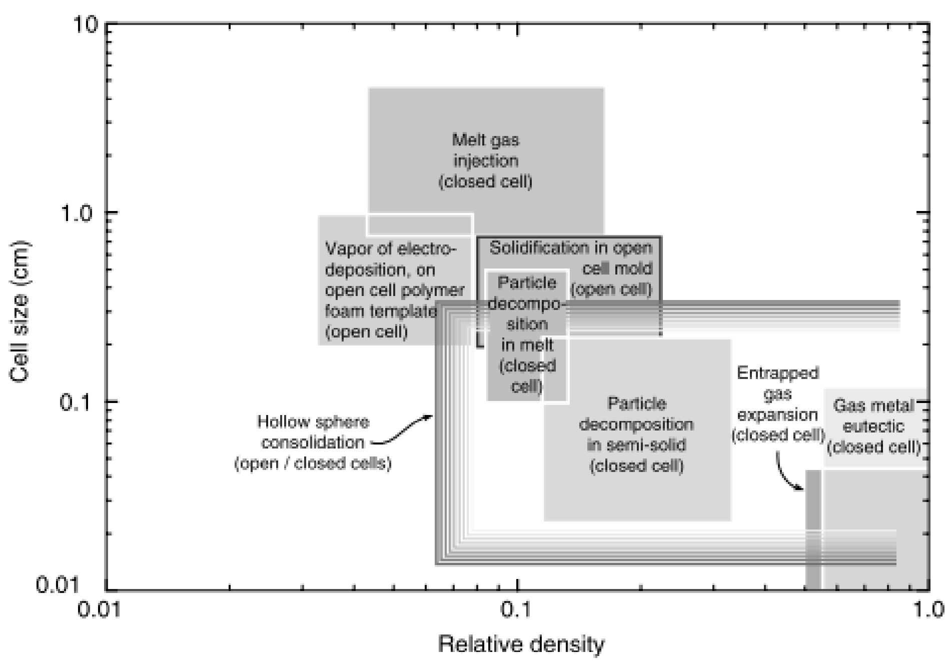

Fig. 11. The range of cell size and relative density for the different metal foam manufacturing *methods*

The various failure modes that were observed include the following:

(i) Indentation or tearing of the front face sheet.
(ii) Collapse of the core.
(iii) Severe inelastic deformation or tearing of the face sheet, and
(iv) Failure between the face sheets and foam core.

They applied blast loading on the specimen by detonating a cylindrical charge having a density of 1.55 g/cm^3, using a detonator that was inserted into a hole at the top end of the charge. Charges of different masses (10 g, 15 g, 20 g, 25 g, 30 g and 40 g) were obtained by systematically varying both the diameter and height, while maintaining a height-to-diameter ratio of unity. A total of 58 tests were carried out to observe both the deformation and failure modes. They also analyzed the influence of (a) blast impulse, (b) face sheet thickness, (c) core relative density, (d) core density variation, and (e) specimen curvature, on deflection-induced on the rear face sheet.

Whisler and Kim [46] developed a new impact-based system composed of high speed actuators (up to 66 m/s) and tuned pressure pulse generating projectiles. The system was used to impact a wide area [measuring 406 x 406 mm] on large size (measuring 610 x 610 mm) armor panels at a specific impulse of 7250 Pascals. These researchers also tested panels using a non-explosive blast simulator and compared the result with panels that were subjected to an actual blast using an explosive. Metrics of interest were the following: (a) damage modes, (b) extent of damage, and (c) pressure pulse attenuation relative to steel. The results indicated similar damage modes but more internal damage to the panel that was subjected to an actual blast tested. The composite sandwich panels had a similar level of permanent deformation experienced by the steel panels. The sandwich panels exhibited a 37-pct. reduction in average initial transmitted acceleration and a 75-pct. reduction in the peak transmitted acceleration when compared to the panels made from steel, with a noticeable savings in weight by as much as 49 pct. The non-explosive test allowed for generating consistent and repeatable pressure pulse loads to enable not only in a comparison of performance but also in optimization of the armor panel design. Sousa-Maritins et al. [47] stated that sandwich structures can sustain large deformation under a constant load, thereby enabling them to absorb a significant amount of energy. The mechanical properties of cork [i.e. low density and high specific stiffness and strength] suggested that this material and its compound have an excellent combination of properties for use in energy absorbing sandwich systems and structures. Cork is a natural material having a cellular structure (closed cell). Upon reaching yield stress, cork exhibits a region of constant stress for increasing strain until densification is reached thereby enabling it to absorb a considerable amount of energy. These researchers worked on two micro agglomerated cork (MAC) compounds incorporated as cores in a sandwich structure that was made using aluminum alloy (5754-H22) face sheets. The structures were fixed on a 4-cable ballistic pendulum and subjected to blast waves that originated from detonation of an explosive placed at a standoff distance of 300-mm. The deflection of both the front face sheet and back face sheet was measured along with the transmitted impulse and movement of the pendulum. This helped in determining the following: (a) structural response of the core through its thickness, and (b) density of the core. The specimens were cut into half width for determining the following: (a) internal compaction, (b) deformation, (c) eventual occurrence of damage within the core material, and (d) debonding between the core and the face sheet. In generic terms, a decrease in the impulse transmitted to the structure with an increase in thickness of the sandwich core was observed. They also measured maximum deflection that occurred on the front face, back face and at the center of the front face sheet. From the results it was concluded that based on deformation pattern, bending was the primary deformation mechanism and stretching could be conveniently neglected.

Lee and Toole [48] investigated an energy absorbing sandwich structure under blast loading. Experimental study revealed that flat panels having various foam or honey comb face plates transferred more energy to the structure under the influence of blast loading relative to a structure that had no energy absorbing face plate. Predicted deformation history for Honeycomb Sandwich under Blast load simulation is given at Fig. 12.

Ideally, a foam or honeycomb material would transfer less energy to the structure since it has the tendency to absorb energy while deforming plastically. Non-uniform deformation of the energy absorbing material does lead to an increased pressure on the panels, causing transfer of kinetic energy to the plate. The objective of this research study was to simulate the non-uniform response of honeycomb panels that were subjected to blast loading. The honey comb sandwich structure containing buckling (crushing) cores are often used as the main load bearing member in a structure. This is because they have the following to offer: (a) a high-strength- to-weight ratio [σ/ρ], and (b) excellent energy absorbing capabilities under dynamic loading condition. The core of the sandwich structure can withstand large deformation (strain) under a constant load thereby enabling it to absorb energy. Additional energy is absorbed by the face sheet should significant stretching occur in the structure. The use of sandwich panels is an effective method for either mitigating or reducing the damaging effect caused by blast loading on both vehicles and building structures. In one experiment these researchers observed that both the flat-foam and honey comb-faced panels transmitted more energy to the pendulum than a flat rigid panel without absorbing much energy. This phenomenon was due to non-uniform deformation of the front face, which tends to increase the overall pressure loading on the panel from a blast. A flat square panel was subjected to an explosive blast that is located at a fixed standoff distance from the center of the panel. The panel is free floating in space and symmetric about its center. Thus, a quarter symmetry model was used for simulation with the primary objective of determining the energy transmitted to the panel by calculating the following: (a) steady state velocity or Kinetic energy, and (b) peak acceleration of the panel.

Dong et al. [49] investigated the response of soldiers for the situation of landmine detonation. A numerical human body was used for simulating two types of experimental studies. The model was validated against test data in terms of the axial force and bone fracture pattern.

Gee et al. [50] conducted experimental, analytical and numerical studies to measure air pressure on the target surface near the point of impact. The impact speed varied from 0.9 to 3.8 Km/s. An analytical model of the air blast field resulting from the impact was developed employing the blast generated by a small explosive charge that was initiated both at the time and point of impact. They carried out numerical simulation of the impact using Eulerian hydrocode. This simulation study revealed a composite nature of the hyper-velocity blast pressure. This was a one-dimensional solution in which all characteristics of the blast field are a function of the following: (a) radius from the charge center, and (b) the energy released by the charge. Thus, a single empirically derived parameter, an equivalent explosive charge energy, completely defines the blast field. For each test this parameter was obtained using a least square fit of the pressures that were measured as a function of distance from the impact (explosion) center. They came up with the following conclusion. The air blast field contains about 0.7% of kinetic energy of the impacting projectile that comes from three sources: (a) the air entrained by the projectile, which impinges upon the target plate; (b) the air accelerated by the radially expanding crater lip, and (c) the air entrained by the induced impact while travelling away from the crater. Of the three mechanisms, the ejection and resulting entrapment of air appeared to play a major role in enhancing the blast pressure on the surface.

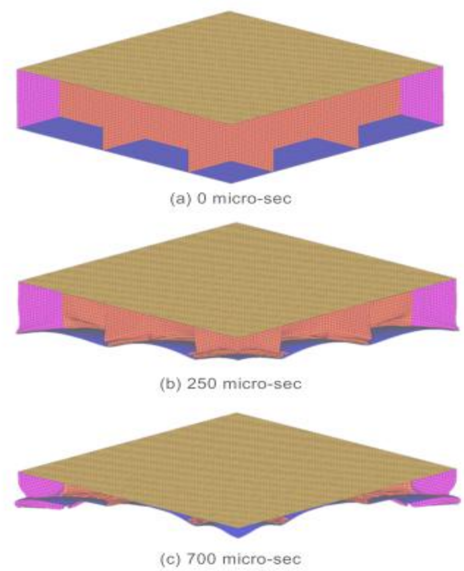

Fig. 12. Predicted deformation history for Honeycomb Sandwich under Blast load

Hoo Fatt and Surabhi [51] examined the through thickness stress wave response of a foam core, composite cylindrical shell under the influence of an external blast. They derived solutions for the transient response of the face sheets as stress waves propagated through an elastic-plastic, crushable foam core. Their solutions were found to be in good agreement with results obtained using finite element analysis as shown in Fig. 12

for Divinycell H100 foam Y= 1.66MPa and the resulting elastic-plastic stress-strain curve after numerical integration is. There was a very good agreement between the analytical and FEA solutions as shown in Fig. 13.

The blast response of the composite sandwich shell was found to be affected by the magnitude and duration of the pressure pulse. High amplitude, low duration (impulsive) pressure pulse-induced the greatest energy absorption. Low amplitude, long duration *pressure pulse caused minimum energy absorption.* The amount of energy absorbed increased while the failure load decreased with an increase in core thickness. Sandwich shells having foams of, (a) varying density, (b) compressive modulus, and (c) crushing resistance, were also examined. The sandwich shells having a foam of highest density, compressive modulus and crushing resistance (Divinycell HCP 100) were found to be the most resistant to failure due to a blast even though no energy was absorbed by them. However, the cylindrical shells with a lighter, less stiff and a strong foam core were observed to be most resistant to failure than the cylindrical shells having a foam core.

Qi et al. [52] worked on metallic aluminum foam cored sandwich panels (AFSP) armor against a blast loading. The dynamic responses of the aluminum foam cored sandwich panels [AFSPs] for various combinations of face sheet materials were analyzed using LS Dyna. It was found that a AFSP with aluminum alloy (AA2024 T3) on the front face and a steel back face outperformed the other panel configurations in terms of maximum back face deflection and areal specific energy absorption. It was also found that both boundary conditions and standoff distance between an explosive and a target surface had a remarkable influence on blast response of the aluminum cored sand panels. They used artificial neural network (ANN) approximation models, in synergism with multi-objective design optimization (MDO) of the steel panel to systematically study the panels both with and without variation in blast load intensity. Optimization results revealed the two objectives of minimization and maximization to conflict with each other and an optimal design had to be identified. The Pareto curves obtained were observably different for varied blast impulse levels. Consequently, it was concluded that variation in loading should be carefully considered when designing sandwich armors to achieve a more robust blast resistant performance. Three distinctive phases of dynamic response: (i) front face deformation, (ii) back face deformation, and (iii) structural vibration were identified. The simulation results indicated that a low stiffness front face results in large foam core compression and energy absorption, while a high stiffness back face is suitable for reducing the deflection of the aluminum foam sandwich panel [AFSP]. Few other researchers have worked on finding a solution for protecting structures using non-conventional methods and items.

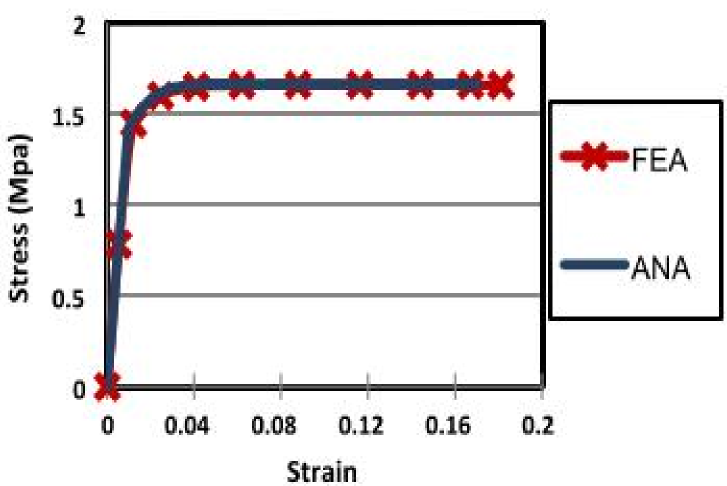

Fig. 13. Compressive Stress-Strain behavior of Divinycell H100 crushable foam

Palanivelu et al. [53] investigated the influence of close range blast loading on empty recyclable metal beverages cans for use in sacrificial cladding. They carried out both an experimental study in synergism with a numerical blast study on a single empty recyclable metal beverage can. The idea was to make a macro-foam (sacrificial cladding structure) out of these cans for protecting the primary load bearing members in civil engineering structures from an air blast load. Close range free air blast tests were conducted with the intent of understanding the crushing behavior of a single empty beverage can. For conducting an air blast test a special small scale set up was designed and manufactured. The effect of skin plate was also studied. They conducted tests using different plates (made of both aluminum and sandwich composite materials) having different masses, which represented the skin plate of the proposed sacrificial structure. The measured blast parameters from the experimental tests were compared with predicted data. Further, they also studied the influence of a finite surface area of the skin plate on clearing of the reflected pressure wave. During an experimental blast test, it was observed that part of the total reflected impulse (~30%) was lost prior to its transfer to a non-sacrificial structure.

Grujicic et al. [54] investigated the impact of energy absorption capability of polyurea coating. They found the mechanical response of polyurea under impact conditions to be sensitive to test temperature, or in the precise context to the difference between test temperature and the glass transition temperature. Specifically, at a high-test temperature, the polyurea displays high ductility typical of an elastomer in its rubbery-state. On the other hand, at a lower temperature, which is still above the glass transition temperature, the polyurea tended to transform to a glassy-state during deformation and this process is essentially associated with a viscous-type energy dissipation. They also found the computed levels of viscous type energy dissipation to be relatively small when compared one-on-one to the values reported in the published literature. Finite element analysis (FEA) of the projectile/coated plate interactions were carried out using the transient non-linear dynamic finite element approach.

The response of elements of structural concrete under short duration dynamic load is of concern. The prevailing method to this problem is based on a simplification of the SDOF approach. The SDOF model can reliably predict the response of the overall structural component only when the response follows a pre-defined damage mode, such as either the shear-mode or the flexural-mode. However, it cannot reliably predict localized failure of structures. Further, both reliable deflection shape and damage criterion, which are critical for the development of an equivalent SDOF model, and difficult to define. Therefore, while design and analysis continue to be based on use of the SDOF approach, more and more analysis are currently being conducted using Finite Element (FE) modeling. Li and co-workers [55] investigated a numerical approach, which substantially reduced both the modeling and computational effort for analyzing structural response to a blast load. In the method proposed by Li and Hao [55], response during the forced vibration phase is solved using the SDOF approach. Using an estimated response at the end of the vibration phase to be the initial condition, a detail finite element model was developed and the free vibration solved. This approach yielded reasonably accurate response while concurrently reducing both the modeling and computational effort. To demonstrate their method, a reinforced concrete beam was analyzed using the following two approaches: (a) conventional detailed FE modeling, and (b) the proposed approach. A comparison of the numerical results from the two methods did demonstrate the overall reliability of the proposed method. This method also yielded 90% savings in the tine required for computation.

Li et al. [56] presented an experiment to investigate the blast resistance of square sandwich panels having a hexagon aluminum honeycomb cores. Different height and length of the cell side of the honeycomb core were considered in this experiment. The impulse loading on the panel was calculated using displacement history of the ballistic pendulum. An interaction between the shockwave and panel as well as both the deformation mode and failure mode of the face sheet and core were presented by these authors. A finite element simulation was conducted to investigate the dynamic response of a sandwich panel. The simulation did capture all the details specific to the deformation pattern. The velocity, displacement strain history and energy absorption of the sandwich panel was analyzed. In fact, the sandwich structure did find for itself a wide range of applications to include the following: (a) aerospace, (b) marine, and (c) railway engineering [45,57]. This is primarily because it can dissipate a considerable amount of energy by plastic deformation under the influence of an impact blast loading. Fleck and Deshpande [14] were the first to develop a rigid-plastic model for analyzing the blast resistance of a clamped sandwich beam. According to their theory, the response of a sandwich beam can be split into three stages: (a) Fluid-structure Interaction, (b) Core Compression, and (c) Structure dynamic response. This model was extended to both clamped circular and square sandwich plates by Deshpande and Feck [58] and Zhu et al. [59]. A study by Jing et al. [42] concentrated on using five different configurations of an aluminum honey comb sandwich panel for purpose of testing in an air blast. The impulse applied on the panels was calculated by recording the displacement history of a ballistic pendulum. It was found that both the deformation mode and failure mode of the face sheets are controlled by the scaled distance of the explosive. When the scaled distance decreases, peak pressure on the face sheet is enhanced, favoring the occurrence of both pitting and fragmentation. However, upon a gradual increase in the scaled distance large plastic deformation was favored to occur.

Jing et al. [60] investigated the deformation mode and failure mode, blast resistance and energy absorption of metallic cylindrical sandwich shells having closed-cell aluminum foam cores. Based on experiments, corresponding finite element simulation were undertaken by employing LS-Dyna. The simulation results were presented are considered to include the following four aspects:

(i) Explosion and structural response process;
(ii) Deformation/failure modes of sandwich shells;
(iii) Back face sheet deflection; and
(iv) Energy absorption capability.

The entire explosion and structural response was divided into three stages

(1) Expansion of the explosive from time of detonation to interaction with the specimen (0-27μs);
(2) Stage-2 explosion product shell interaction (28-60μs), and
(3) Stage-3 deformation of the sandwich shell under the influence of its own inertia (61-8000μs).

The test setup is shown in Fig. 14. The sandwich shell, having a radius of curvature of 250 mm, face sheet thickness of 0.8 mm, a core thickness of 10 mm and core relative density of 15% and subjected to a charge blast using a mass of 20 g placed at 150 mm was undertaken. The major finding of this study was that energy absorption capability is not a monotonic increase or decrease with thickness of the face sheet. The energy absorption of the shell decreases with an increase in relative density of the core. It was also noticed that an increase in impulse leads to a rise in the dissipation of total energy.

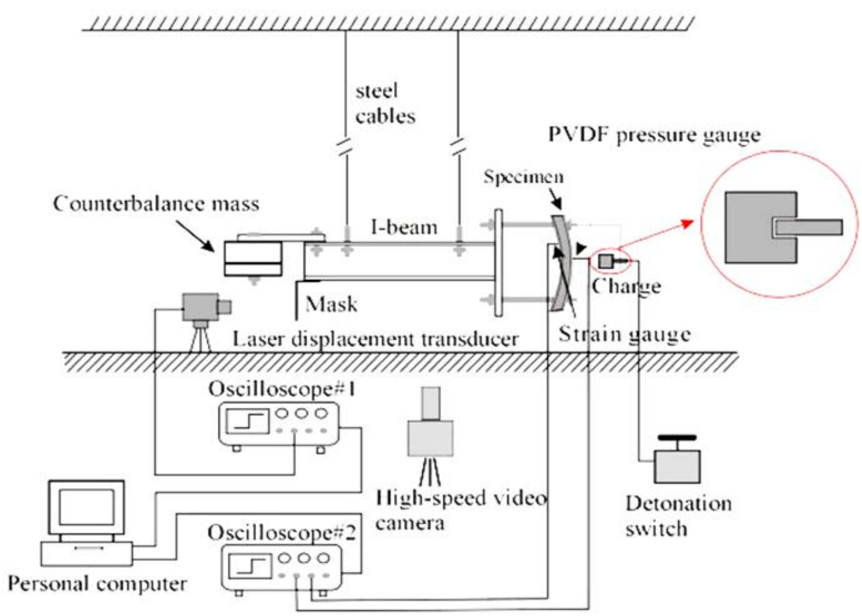

Fig. 14. Schematic diagram of air blast experimental arrangement

Huang et al. [61] used the Multi Material Arbitrary Lagrangian –Eulerian (MMALE) solver available with LS Dyna finite element analysis solver for Blast simulation. They presented a validation study on use of the LS Dyna approach with prevailing experimental studies pertaining to blast wave clearing and blast in an urban environment as well as numerical results from finite volume method software. It was demonstrated that results from LS Dyna produced excellent correlation with the experimental and 3-D simulation results, thereby enabling us to conclude that LS Dyna simulation capability is accurate for the cases studied. The schematic of test configuration is shown in Figs. 15 and 16.

With an emphasis on smaller but more mobile combat forces to meet a broad range of mission requirements, future weapon platforms and upgrades will require materials to do the following: (a) perform better, (b) do more, (c) weigh less, (d) size less, and (e) cost less. The US Army has established a focused research team composed of research labs both in academic units and small business. Chin [62] studied functionally graded armor composites. Their study included the following: (a) high strain rate testing and modeling, (b) microscale and nano-scale self-propagating high temperature synthesis reactions, (c) ballistic evaluation, and (d) pressure assisted costing. A major shift from the traditional paradigm of pursuing research is necessary to secure technological lead during the current period.

Dimeski et al. [63] investigated the behavior of composite made of Ultra High Molecular Weight Poly Ethylene (UHMWPE) woven fabrics and unidirectional tapes under the high speed ballistic

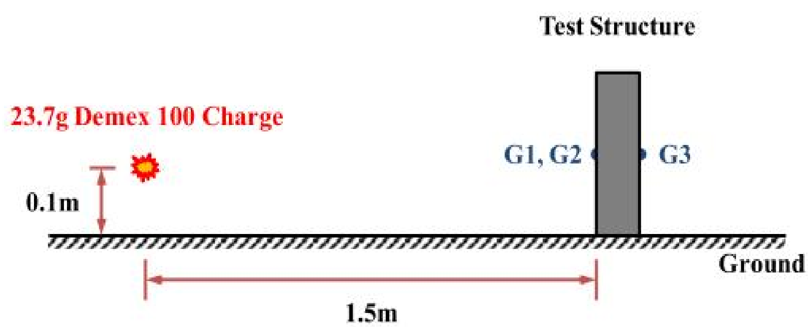

Fig. 15. Schematic of the test configuration

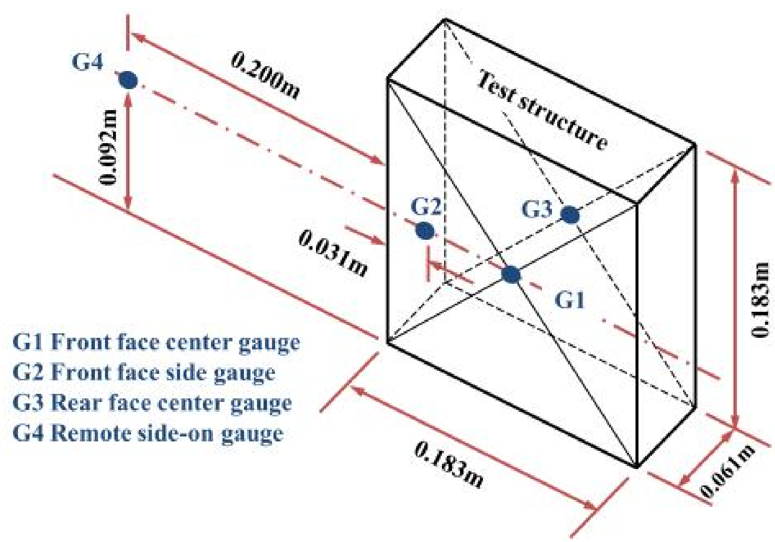

Fig. 16. Details of test structure and pressure gauges

impact. UHMWPE fiber are the strongest fibers in the world and find extensive use in items likes helmets, vests, and plates. They used the ballistic criteria [V_{50}] values as shown in Fig. 17.

They carried out tests in a ballistic laboratory where the high speed of the fragment simulating projectile was measured prior to its impact on the chosen composite. They also proposed the propagation including at the cross over point of the wave front across the yarn as shown in Fig. 18.

The unidirectional composites revealed a superior performance when compared to the bidirectional ones due to lower extension of the reflective impact wave. Although there are many synthetic and natural fibers, which are used in ballistic protection, only two types of synthetic fibers can be regarded as high performance-aramid and UHMWPE fibers also known as High Performance Poly Ethylene (HPPE). These fibers are characterized with parallel molecule orientation along the fiber axis greater than 95% and a high level of crystallinity as opposed to

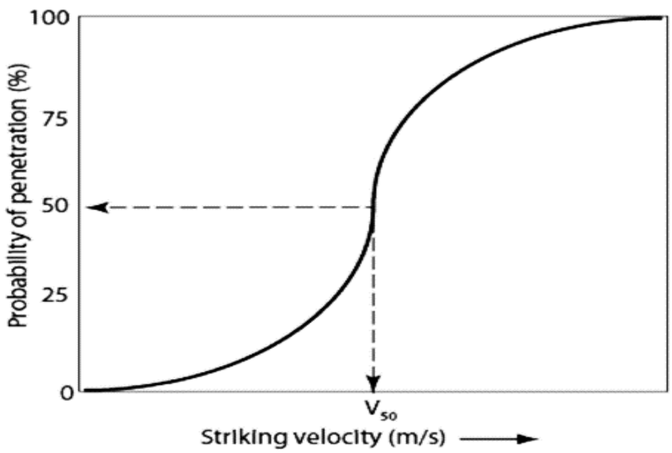

Fig. 17. Probability of penetration Vs. Striking velocity

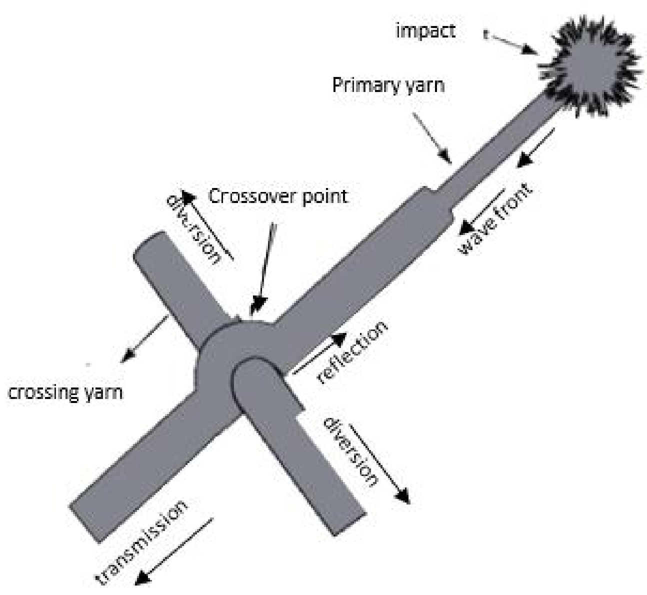

Fig. 18. Longitudinal wave propagation in a fabric after the ballistic impact

conventional poly ethylene fibers. This results in fibers having high strength and modulus of elasticity. The composites were constructed by laying up a multiple number of prepreg plies and cured at an elevated temperature. Each type of composite was manufactured in four different areal weight of 3 Kg/m^2, 5 Kg/m^2, 7 Kg/m^2 and 9 Kg/m^2. The composites were molded at 130°C under a molding pressure of 10 MPa. These researchers concluded that textile form that the fibers are processed into has an influence on ballistic resistance in a ballistic composite. When a projectile hits a ballistic fabric, the risk of the yarn break is highest at the crossover points.

Vogel and Bartelt [64] did try to study the various forms of warfare. Based on their comprehensive study, they concluded that it was possible to differentiate to some extent through the radiological findings of the casualties produced. These researchers could successfully differentiate between the following: air, guerrilla, civil, desert, gas, conventional and even annihilation warfare.

Shape Memory Polymers (SMP) are a fast and rising emerging family of polymers. To improve their properties and to concurrently obtain new and improved functions shape memory polymer composites and shape memory polymer blends were carefully engineered and prepared for commercial use. Meng and Hu [65] carefully investigated the research work done by various research groups scattered through the globe. From their detailed study, they found the shape memory polymer (SMP) composites and shape memory polymer blends were prepared for five specific reasons:

1. Improving shape recovery stress and mechanical properties;
2. Decreasing shape recovery induction time by increasing the thermal conductivity,
3. Creating new polymers/polymer blends possessing Shape Memory Effect (SME);
4. Tuning switch temperature, mechanical properties and biomedical properties of both existing and emerging shape memory polymers;
5. Preparing shape memory polymers (SMPs) sensitive to electricity, magnetic field, light and moisture/water.

Even though these objectives have been achieved, more work needs to be conducted. First, specific Applications necessitate the need for specific requirements on the properties of shape memory polymer composite and blends. Both extensive and intensive studies are needed for the following: (a) to establish a relationship between the structures of SMP composite and blend materials, (b) properties of the materials, and (c) requirements for a specific application. Further, the recovery stress of a shape memory polymer composite is still low, which does place a limit on many of their applications. Furthermore, both at and above the switch temperature of the specific SMP composite, the material becomes soft. However, shape recovery stress can be improved to a certain degree by compounding or blending with other materials.

Third most of the present shape memory effect (SME) is based on simple shape shrinkage during a binding process. Keeping the above facts in mind, it can be concluded that shape memory polymers (SMP) may not be an ideal material to be chosen for use in blast/ballistic protection.

Bastürk et al. [66] studied the non-linear dynamic response of a composite laminate made of Basalt which was subjected to blast loading. The laminate being clamped at all edges was investigated both numerically and using ANSYS and experimentally with the use of shock tube. The laminate in consideration was a 400 mm X 400 mm basalt dry fabric 200 g/m^2. Plain weave, thickness 2.5 mm and V_f =50%. For the experiment part, a shock tube was used at 6 Bar for blast loading of the laminate. For the numerical analysis, Galerkin Method was used to obtain non-linear differential equation. The code being written in Matlab and micro strain in ANSYS were obtained. It could be ascertained that ANSYS results and the experimental results were compatible especially for strong blast regime. Bastürk et al. [67] studied the non linear transient response of basalt/Nickel functionaly graded metal composite plate of size 220 mm X 220 mm and thickness of 5mm. The plate was modelled using Homogenous Laminated model (HML) and Power Law model (PLM). Results were validated using ANSYS. The equation of motion for the plates were derived by the use of virtual work principle. Galerkin method was used to obtain non linear differential equation in the time domain. The two different approximation method used concluded that HLM and PLM approach is same for n=1.0 while max deflection can be obtained for n=5.0. They also found that as the aspect ratio of the plate decreases, the amplitude of the plate decreases and the corresponding frequency increases.

Zima and Foglar [68] studied the influence of basalt mesh induced increase of heterogeneity of cement composites under blast loading. The experimental results were evaluated using numerical simulation. They could also study the influence of the presence and the location of basalt meshes on the damage of the specimen due to delamination. For the experiment 25 Kg of TNT was used at a standoff distance of 450mm. Also a pit was dug under the specimen for depth of 2m for avoiding the effect of reflection of the shock wave. For numerical simulation ANSYS was used with built in function Load Blast Enhanced, which converts the blast load into pressure impulse. They created three different numerical model, first with dispersed fiber second dispersed fiber and one layer of basalt mesh and third with dispersed fiber and five layer of basalt mesh. It was concluded that increase of heterogeneity by addition of basalt meshes into concrete can decrease the volume of concrete debris and also reduce the velocity of the ejected parts. Kamaludeen and Kani [69] studied the structural analyses of basalt fiber epoxy and glass fiber epoxy lap joints to predict the crack initiation and fracture based on Von Mises stress distribution under tensile loading. FEA ANSYS was used to obtain the local stress at the interface. They found that the basalt epoxy specimen had higher Von Mises stress values than glass epoxy specimen and also concluded that hybrid joints should be used for repair of composites instead of bonded joints.

4. CONCLUDING REMARKS

Based on a comprehensive and complete review of the published literature specific to the energy absorption capability of composite materials to facilitate their selection and use for performance-critical and demanding applications, following are the key findings or observations:

(a) With a gradually noticeable amount of low-intensity conflict occurring at different regions scattered through our planet, it has certainly become both essential and desirable to develop new and improved materials, which can be safely used for the sole purpose of absorbing energy that is released during the events of both blast and impact.

(b) While use of traditional metals to include their alloy counterparts have their own advantages to offer, their high density often becomes a hinderance for use in applications specific to personal body armor and for panels, which are retrofitted onto vehicles for protection against explosive devices.

(c) Efforts have been made with the sole intent of developing an understanding of the various aspects that are highly essential for the selection and use of innovative materials, like composites, for the sole purpose of absorbing energy that both occurs and is released during a blast event. Use of fiber metal laminates, functionally graded laminates, and other emerging and novel variations has become the new norm.

(d) A composite material primarily relies on the occurrence of fracture events at the fine microscopic level for the sole purpose of absorbing the energy that is often released during the events of a blast and an impact. The ultimate absorption of energy is largely controlled by strain to failure of the reinforcing fibers for the case of continuously-reinforced metal matrices.

(e) An attempt has also been made to systematically study, carefully analyze, and methodically categorize the results that have been published in the field specific to energy absorption capabilities of composite materials. The literature published in this field is carefully examined and critically analyzed with the primary intent of developing a better understanding of the effect of a parameter on energy absorbing capability of a candidate or specific composite material.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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