A Review on Exploring the Behavior of Multi-Layer Composite Structures Under Dynamic Loading

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***Abstract*—This paper reviews the recent research progress on multi-layer composite structures composed of variety of materials. The utilization of multi-layer composite system is found to be common in metal structures and pavement systems. The layer of composite structure designed to encounter heavy dynamic energy should have sufficient ductility to counteract the intensity of energy. Therefore, the selection of materials and enhancement of interface bonding become crucial and both are discussed in this paper. The failure modes have also been explored in conjunction with stresses at failures and inferred solutions are also revealed. The paper attempts to reveal all technical facts on multi-layer composite structure in a broad field.**

***Index Terms*—multi-layer composite, facesheet, impact, blast, load, fracture energy, delamination**

I. Introduction

Multilayer composite structure usually consists of several layers although the main function of the composite structure is served by the combined action of sacrificial layer and the core. However, the additional layers of multi-layer composites apart from the sacrificial or core layer enhance the dynamic load resistance capacity of the structure. The purpose of sacrificial layer is to protect the core from the initial load intensity. In general, the top facesheet portions of the composite structure act as the sacrificial layer to absorb the initial energy coming from the impact or blast loads. So, the probability of damage is high in these layers. In consequence, the core layer remains less effected by the intensity of the dynamic loads. Over the last few years, the usage of multilayer composites are is widely increasing in the purpose of strengthening structures. Several researchers have utilized various materials in the different layers of multilayer composite structures to balance the stiffness, flexibility and ductility of the composite structures. The composite structures are also becoming acceptable because of the high strength at comparatively low weight of the structure [1] since it is possible to impart the desirable properties in the individual layers of multi-layer composites. In addition, the rehabilitation of core portion of the composite structure is difficult and also costly and hence less or almost no damage is expected in this layer. Multi-layer composite structures ensure the unaffected condition of core of the structure under impact or blast loadings and thus it proves as an economical structure. Moreover, the mechanical properties of each layer of a multi-layer composite structure can be controlled according to the encountered dynamic energies by the corresponding layers. Therefore, high strength materials may not be desirable for every layer and therefore the overall cost of the structure could be reduced.

A. Types and Materials of Multi-Layer Composite Structures

Multi-layer composite structures are generally used to build the components of airplane and military vehicles. In addition, road pavement and airport runway pavement are also typical example of multi-layer composite structures. Several research works are carried out to explore the suitability of the materials used in multi-layer composite structure. For instances, Woo *et al*. [2] proposed a six layer hybrid multilayer composite structure consisted of S2-glass-1, CMC (ceramic matrix composite), EPDM rubber, Aluminum (Al 7039), Aluminum foam and S2-glass-2. In this structure, impact absorption energy was evaluated under high velocity impact load. Moreover, Tasdemirci and Hall [3] prepared a three layer composite structure made of Alumina Ceramic in front layer, EPDM (ethylene propylene diene monomer) rubber in the mid-layer and glass/epoxy plate in the back layer of the structure. The behavior of this structure was studied at high strain rate. In addition, Nayak *et al*. [4] conducted finite element analysis on a three layer composite structure to investigate the dynamic response (applied blast loading) of the structure. The bottom and top layer of the structure was composed of Graphite-Epoxy (GE) and interior layer was made up of PVC. Besides, Xue and Hutchinson [5] investigated the influence of blast loads on a three layer circular plate by finite element analysis. The structure was considered as elastic-perfectly plastic.

Wu and Chew [6] proposed a three layer composite system to be used for runway or concrete pavement. The

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multilayer system consisted of asphalt concrete at the top layer which was reinforced with Geogrid, high strength concrete in the interior layer and engineered cementitious composites (ECC) at the bottom layer. This multilayer pavement was subjected to field blast tests and its behavior was compared with the normal strength concrete slab. Again, Elmalich and Rabinovitch [7] studied the behavior of multi-layer composite wall under dynamic loading condition. Both sides of the wall were strengthened with FRP sheets and adhesive layers were used to bond the wall and the FRP sheet in both sides. Besides, Yang *et al*. [8] observed the influence of impact and blast loading on four panels of circular multi-layer composites. As core interlayers, a ductile elastometric layer of polyuria and a moderate compressible Divinycell-H200 foam layer was used which to enhance the blast resistance of the composite panels. Moreover, balsawood was also incorporated as the interlayers of the composite structure. The top level and the bottom level of the panels were made up of glass fiber reinforced plastic (GFRP). Soutis *et al*. [9] investigated the structural response of some quadrangular GLARE (glass fiber reinforced laminate) panels under air blast loading. Wei *et al*. [10] developed a nonlinear exogenous autoregressive moving average model (NARMAX) of a sixteen layer carbon fiber reinforced epoxy plates. Park *et al*. [11] conducted low velocity impact testing on multi-layer composite structure which was composed of Normex honeycomb as core and carbon/epoxy and glass/epoxy laminates as facesheets. Klasztorny *et al*. [12] introduced multi-layer composite structure in the preparation of protective shields. The layers of the composite structure consisted of PA11 aluminum, SCACS hybrid laminate, ALPORAS aluminum foam and SCACS hybrid laminate. The layers were joined together with SOUDASEAL chemo-set glue. The behavior of the structure was observed under blast shock wave and the maximum plastic deformation of the plate was fixed as the criteria to determine the suitability of the plate.

Moreover, Xiong *et al*. [13] explored the behavior of carbon fiber composite two layer panel with pyramidal truss cores under quasi static compression and low velocity impact loading. Again, Kazanci and Mecitoglu [14] investigated the nonlinear dynamic response of composite plates under blast loading condition. Fatt and Sirivolu [15] observed the response of multi-layer composite structures under the presence of high velocity impact provided by hemispherical nose cylindrical projectile. The panels of the composite structure were made up of E-glass polyester facesheets and Divinycell H130 foam core. Yiming *et al*. [16] conducted damage analysis of elasto-plastic laminated composite shallow spherical shell subjected to low velocity impact. Olsson *et al*. [17] utilized closed form approximation to investigate the initiation moment of delamination in a laminated plate under high velocity impact condition.

Malekzadeh *et al*. [18] explored higher order dynamic response of multi-layer composite panels under low velocity impacts. The composite panels were incorporated with transversely flexible core and few small impactors having small masses. Her and Liang [19] studied the behavior of composite laminated plate and shell structures under low velocity impact loading. Salami *et al*. [20] conducted experimental investigation to observe the behavior of multi-layer composite structure under low velocity impact loading by considering an additional interlayer in the composite structure. The panels of the structure was composed of polymer composite laminated facesheets, an additional interlayer sheets and two types of crushable foams as core materials. Karagiozova *et al*. [21] carried out experimental and numerical analysis to understand the behavior of multi-layer composite panels under blast loading. Two types of composite panels were prepared and compared by Karagiozova *et al*. [21]. One sample was made up of steel plates as facesheets and polystyrene core and the other one was built up of steel plates and aluminum honeycomb core. Librescu *et al*. [22] also conduct analysis to understand the linear and non-linear behavior of multi-layer composite flat panels in contact of blast loads.

II. Analysis Methods

A. Numerical Analysis

Several numerical methods have also been used by researchers to validate the experimental results or make comparisons with the experimental and finite element analysis results. For instance, Wei *et al*. [10] developed a nonlinear exogenous autoregressive moving average model (NARMAX) of a sixteen layer carbon fiber reinforced epoxy plates. Again, Kazanci and Mecitoglu [14] investigated the nonlinear dynamic response of composite plates under blast loading condition. A set of nonlinear differential equations were formulated by Kazanci and Mecitoglu [14] through the help of Galerkin method and finite difference method was used to solve the nonlinear equations. Moreover, Fatt and Sirivolu [15] observed the response of multi-layer composite structures under the presence of high velocity impact provided by hemispherical nose cylindrical projectile. The panels of the composite structure were made up of E-glass polyester facesheets and Divinycell H130 foam core.

In addition, Fatt and Sirivolu [15] derived a wave propagation model to determine the residual velocities of the selected composite structure panels as well as in the projectile and considered the solution as deterministic one. Larange’s equations of motion were applied for the projectile, facesheets and core at the time of propagating the wave through the composite panels. Besides, Olsson *et al*. [17] utilized closed form approximation to investigate the initiation moment of delamination in a laminated plate under high velocity impact condition. Moreover, Yiming *et al*. [16] used collocation point method and Newmark scheme to determine the behavior of composite structure under low velocity impact. Besides, Karagiozova *et al*. [21] and Elmalich and Rabinovitch [7] also carried out numerical analysis to explore the dynamic behavior of multi-layer composite panels.

In order to predict the dynamic response of multi-layer composite structure and also to verify the results with experimental analysis [4], [5], [7], [15] have conducted finite element analysis. Besides, Kumar *et al*. [23] also carried finite element analysis to observe the effect of static loading on multi-layer composite structures. Among the finite element softwares to conduct dynamic analysis, LSDYNA is most commonly used by the researchers [2], [3], [6], [9], [17]. Besides, commercial finite element software ANSYS has been used by [14], [19], [24] and ABAQUS has been used by [8]. To observe the effect of static loading, researchers also utilized several softwares. For instance, ANSYS was used by Herranen *et al*. [25].

B. Experimental Investigation

Various experimental strategies have been adopted to investigate the dynamic response of multi-layer composite structures. For example, Turkmen and Mecitoglu [24] conducted experimental study on stiffened laminated composite plates which were subjected to blast loading through denotation wave. Turkmen and Mecitoglu [24] prepared denotation wave from the reaction of LPG-O_2 mixtures in a cylindrical tube. Again, Wei *et al*. [10] carried out periodic signal tests on the samples to observe the dynamic response of composite structure. On the other hand, Wu and Chew [6] applied blast loading by placing 7.3 kg TNT charge weight 170 mm above and at the center of the multilayer composite slab. In addition, the impact tests were carried out by Park *et al*. [11] using impact testing machine and scanning acoustic microscope was utilized to determine the impact damages. Besides, Xiong *et al*. [13] carried out low velocity impact test with the help of a guided drop weight test rig with adjustable rebound catchers. Moreover, Salami *et al*. [20] used drop hammer impact testing machine to apply impact loads on composite panels and measure the top core deformation, deflection of composite panels and contact forces. Again, plastic explosive discs were exploded by Karagiozova *et al*. [21] at close distance of composite panels to apply blast loading. In addition, Tasdemirci and Hall [3] conducted SHPB test to observe the behavior of composite structure at high strain rate. In order to observe the static behavior of composite system, Herranen *et al*. [25] conducted four point bending testing by using electro-mechanical testing system Instron which was equipped with video extensometer and Bluehill software. Besides, Othman *et al*. [26] used GOTECH 100 kN universal testing machine to conduct the quasi-static crushing test on composite tubes.

III. Interfacial Bonding

Apart from the selection of appropriate materials for various layers of composite systems, enhance sufficient interfacial bonding between the layers of composite structure is of great importance. The capacity of interfacial bonding plays the vital role to hold the adjacent layers of the composite structure together and thus carrying the upcoming loads. The surface characteristics of materials have significant influence in the development of the quality of interface bonding [27]. However, critical stress condition can be developed at interface bonding of different materials rather than at interface of similar materials [28]. Few reasons of loss of bonding between metallic structures and advanced polymer composites are highlighted by [29]. Chen [30] also developed interface cracking test for composite pavement to observe the initiation and propagation of cracks by applying repeated tensile loading. Besides, Nguyen and Levy [31] analyzed the mechanics of interface failure of composite structure consists of three layers.

A. Studies on Interface Behavior Analysis of Multi-Layer Composite Structures

Several researchers have applied different numerical and finite element methods to define the interfacial bonding between the layers of composite structures. Among them, Soutis *et al*. [9] investigated the structural response of some quadrangular GLARE (glass fiber reinforced laminate) panels under air blast loading using the finite element software LSDYNA. The interfacial bonding between the adjacent plies was executed by a cohesive tie-break algorithm and the blast load was simulated by using ConWep algorithm.

Buryachenko *et al*. [32] used MEFM to understand the mechanics of nanoparticles use in the interfaces of composite structure. To simulate the behavior of nanoparticles, Zeng *et al*. [33] mentioned MC, MD, BD, LB Ginzburg-Landau theory, micro mechanics and FEM as the most commonly used methods along with DPD, equivalent-continuum and other self-similar approaches. To understand the influence of interface bonding on the behavior of composite structure, cohesive or interfacial elements is introduced between the adjacent layers. Ozer *et al*. [34] developed 3D finite element model for multi-layer pavement to observe the effect of interface on the overlay or bituminous surface. The acceptability of the model was previously verified by [34] and the model was based on fracture mechanics and capable of reveal the interface behavior from elastic state to fully debonded state. However, Ozer *et al*. [35] introduced the interface element between the concrete and the surface of hot mix asphalt and the condition of the pavement was noted by varying the quality of hot mix asphalt and also the friction of the interface bonding. In addition, the laboratory tests for the similar study was conducted previously by Leng *et al*. [36] using direct shear tests and Ozer *et al*. [35] found good agreement between the numerical and experimental results. Similar numerical analysis using interface element was also carried out by [37] and [38]. Baek *et al*. [38] conducted research on composite pavement in a similar way to explore the influence of interfacial bonding on reflective cracking of hot mix asphalt overlay. Baek *et al*. [38] inferred that low strength of interfacial bonding tends to increase the cracked area of overlay and low interface stiffness can decrease the cracked area slightly.

Park *et al*. [11] developed cohesive model to understand the phenomenon of mixed mode cohesive fracture. Fracture energy, cohesive strength and shape of cohesive interaction were selected as the parameters to observe the behavior of the structure. The model was capable of explore the behavior of structure in both linear and non-linear state and the model was validated by conducting a mixed mode bending test. In general, bi linear law and exponential law are commonly used to conduct the cohesive zone model to anticipate delamination. However, the results of dynamic analysis more resembles with the practical results when bi linear law is utilized in predicting delamination [39]. On the other hand, to observe delamination using exponential law in commercial software ABAQUS, the fracture energies of material required to provide since Kenane and Benzeggagh [40] correlated delamination growth rate with the strain energy release rate.

IV. Strategies to Improve Interfacial Bonding

Weak interface shear strength is one of the major reasons to initiate and propagate delamination in composite structure [41]. Due to this, Li *et al*. [42] emphasized to determine an optimal interfacial treatment for composite pavement based on the shear strength of the interlayers. However, Lei *et al*. [42] suggested the use of rough and exposed aggregate interface to increase the shear strength at the interface of composite pavement consists of asphalt and concrete. Mohammad *et al*. [43] also emphasized to increase surface roughness at interface to achieve better shear strength. Besides, to enhance the interface shear strength between cement and concrete, the introduction of superfine cement along with silica fume and super plasticizer is an efficient solution [44]. In addition, to maintain sufficient shear strength and stiffness at interface, the width of interlayer gap should be minimized as much as possible [45]. Yang and Ye [46] have developed accurate numerical method to predict interfacial shear stress and also interfacial transverse normal stress for a heterogeneous composite system.

The materials of different layers of composite can have sensitivity to temperature at different extent and this can lead to the reduction in shear strength at interface [47]. For instance, the interface shear strength of bi-layer composite made up of asphalt and concrete decreases with the increase of temperature [42]. Besides, optimum friction at the interface of adjacent layers can ensure better interfacial bonding. Smooth interface allow the movement of the layers at constant and variable temperature whereas rough interface offers more resistant in movement of layers and thus helps to reduce excess stress to add on the composite structure [48]. Zhang *et al*. [49] suggested that roughness index within the range of 0.9 mm to 1.1 mm can be used as the optimum interface roughness for polymer cement mortar and concrete composite. To achieve such extend of rough surface, Zhang *et al*. [49] recommended applying water jetting to a depth of 2 mm to 2.5 mm. Zhang *et al*. [49] inferred that increasing interface roughness by using such treatment increase the interface area of polymer cement mortar and concrete and consequently increases the fracture energy of the adhesion layer of these two materials and therefore enables to shift failure to the cohesion layer of concrete. Besides, the strength of the interface should be greater than the strength of substrate with a minimum interface to substrate strength ratio to avoid crack deflection at interface [50]. Parmigiani and Thouless [50] also inferred that difference in elastic modulus can also induce deflection crack at interface. Again, the adhesive of the multi-layer composite structure was identified as the sensitive issue as it combines the adjacent layers.

Masoumi and Emadoddin [51] applied roll bond process to enhance the interface bonding among multilayer metal composites. Besides, Cepeda-Jimenez [52] also inferred that the application of post rolling in metal layers by maintaining a temperature of 175 ℃ for 6 hours is effective to reduce stress at interface of composite structure and thereby develop a better interfacial bonding. Again, another type of treatment using peel ply can also be adopted to enhance the interface properties of composite structure [53]. In this method, peel ply is usually applied on the composite and remove afterwards. The interface bonding can be enhanced significantly by introducing interlocking elements at the faces of the two adjacent layers of multi-layer composite structures.

Dyskin *et al*. [54] suggested the use of tetrahedron shaped elements between the faces of composite system in order to impart greater mechanical strength. Sadd *et al*. [55] commented that presence of some micro particles might have resist to occur failure at the interface of this bi-layer composite system. Moreover, Thamboo *et al*. [56] also suggested the use of polymer cement mortar rather than only cement mortar to achieve strong bonding of concrete-cement in a concrete masonry. Buryachenko *et al*. [57] observed that electrochemical treatment can increase the amount of oxyzen which consequently increase the flexural modulus of nanocomposite made up with fibers and imparts strength when use at the interface of composite structure. Choi and Lee [58] observed 37% better performance of carbon fiber or epoxy composite adhesive by using aramid fiber if the surface of adhesive is mechanically treated. Sun *et al*. [59] observed the influence of aramid fiber as adhesive between aluminum foam core and carbon fiber/ epoxy composite facesheets. Lange *et al*. [60] suggested the use oily component as surface finishing component on aramid fiber in addition to amine group to improve adhesion with matrix. However, the surface of the aramid fiber composite can also be improved by fluorination of the aramid fiber [61]. In particular runway pavement condition, Yan *et al*. [62] suggested the use of fiber grid to enhance the interface bonding in a bi-layer runway pavement. Findings of Literatures on Composite Structures

V. Mechanical Properties

In general, the top facesheets portions of the composite structure act as the sacrificial layer to absorb the initial energy coming from the impact or blast loads or bears the initial effects of static loads. So, the probability of damage is high in these layers. In consequence, the core layer remains less effected by the intensity of the dynamic or upcoming loads. The phenomenon is observed by several recently conducted research works. For example, Woo *et al*. [2] proposed a six layer hybrid multilayer composite structure consisted of S2-glass-1, CMC (ceramic matrix composite), EPDM rubber, Aluminum (Al 7039), Aluminum foam and S2-glass-2. In this structure, impact absorption energy was evaluated under high velocity impact load. The composite structure was simulated by a 3D model in LSDYNA and the analysis result revealed significant damage in the S2-glass which acted as facesheet portion and low damage in CMC and aluminum foam. Moreover, Wu and Chew [6] proposed a three layer composite system to be used for runway or concrete pavement. The multilayer system consisted of asphalt concrete at the top layer which was reinforced with Geogrid, high strength concrete in the interior layer and ECC at the bottom layer. This multilayer pavement was subjected to field blast tests and its behavior was compared with the normal strength concrete slab. Although the top facesheet portion of the multilayer composite structure bears the initials energy of upcoming loads, the core portion also should have sufficient strength to resist the effects of static and dynamic loads.

Composite fabric layers can be a more beneficial option compare to the homogeneous layer to enhance the strength in multi-layer composite structure. Othman *et al*. [26] observed the behavior of two composite sample tubes under the application of quasi-static compressive loading. One sample had poltruded profile and another was composed of aluminum wrap. The poltruded sample was observed to crush slowly at higher crushing load and also energy absorption capacity was found higher in poltruded sample compare to the aluminum wrapped sample. However, if the composite structures are required to resist the transverse loading, Cantwell and Morton [63] emphasized toughness and compressive strength of the fiber as important factors to resist the damage effects by impact loading. Park *et al.* [11] conducted low velocity impact testing on multi-layer composite structure which was composed of Normex honeycomb as core and carbon/epoxy and glass/epoxy laminates as facesheets. Park *et al*. [11] observed from the test results that impact resistance of the composite structure depends on the quality of facesheets and the core thickness. Besides, Her and Liang [19] concluded that sufficient stiffness of composite structure results in a reduced deflection.

In addition to sufficient strength of the layers of composite structure, the energy absorption capacities of the layers should be high to resist failure. Jones [64] drew a general overview about the behavior of the structure subjected to huge impact and blast loadings. Jones [64] stated that large inelastic deformations of the structural members and specially designed energy absorbing systems can be effective to absorb the dynamic energies and hereby reducing the detrimental effects of impact and blast loadings by dissipating the energies. Similarly, to counteract the effect of low energy impact, Cantwell and Morton [63] selected strain energy absorbing capacity of fibers as the crucial factor. So, composite structure consists of flexible layers or combination of flexible and rigid layers can have better performance compared to a fully rigid composite system. Xue and Hutchinson [5] investigated the influence of blast loads on a three layer circular plate by finite element analysis. The structure was considered as elastic-perfectly plastic. The analysis results revealed greater strength and energy absorbing capacity when compared with a perfectly solid structure. The selection of material to be used for facesheet portion or sacrificial layer is crucial as this layer has significant contribution in energy dissipation. Materials with high tensile and compressive strength as well as high in plane shear strength and Young’s modulus are preferable as the top facesheet layer of multi-layer composite systems. Xiong *et al*. [13] explored the behavior of carbon fiber composite two layer panel with pyramidal truss cores under quasi static compression and low velocity impact loading. Xiong *et al*. [13] studied load displacement response in the both layer of the composite panels. It was observed from the study that the proposed composite structure had better energy absorption capacity in compare to glass fiber woven textile truss core. It happens since strengths and ductility of carbon fiber composites are much greater than that of glass fiber composites.

The core portion of multi-layer composite structure usually carries reduced amount of significant energies or loads next to the sacrificial layers and acts as the second crucial layer in load transmission. Salami *et al.* [20] conducted experimental investigation to observe the behavior of multi-layer composite structure under low velocity impact loading by considering an additional interlayer in the composite structure. The panels of the structure was composed of polymer composite laminated facesheets, an additional interlayer sheets and two types of crushable foams as core materials. The analysis results informed that the core material types had more significant effect compared to the presence or absence of additional interlayers to improve the behavior of composite panels. The materials preferred to be utilized as core portion of a composite system is usually rigid and should have high compressive strength. For example Wu and Chew [6] used high strength concrete in the interior layer of multi-layer composite system which acted as core layer. However, the uses of ductile and flexible materials are also suitable to be added in the core portion of the composite system. For instances, Karagiozova *et al*. [21] carried out experimental and numerical analysis to understand the behavior of multi-layer composite panels under blast loading. Two types of composite panels were prepared and compared by Karagiozova *et al*. [21]. One sample was made up of steel plates as facesheets and polystyrene core and the other one was built up of steel plates and aluminum honeycomb core. The analysis results expressed that aluminum honeycomb core sample has better performance compared with the polystyrene core sample due to higher energy absorption capacity.

In addition, Yang *et al*. [46] used a ductile elastometric layer of polyuria and a moderate compressible Divinycell-H200 foam layer as core to enhance the blast resistance of the composite panels. However, to counteract the static loading by the core of the composite structures, the materials to be used in core layer should have sufficient compressive strength, flexural strength and also shear strength. Herranen *et al*. (2012) investigated the behavior of composite structure by varying the materials of the core layer under static loading condition. High density polyethylene (HDPE), polyethylene-therephtalate (PET), polymrthyl-methacrylate (PMI) was used as core materials in the three composite samples and GFRP was used as the facesheet material. Herranen *et al*. [25] suggested the use of HDPE and PET because of the high mechanical strength under four point bending test. The utilization of nano-particles or polystyrene beads in the core layer also apart significant stiffness and mechanical strength to the matrix. Tjong [62] suggested the use of nanoclays, nanoceramic particles and carbon nanotube as the effective reinforcement material for the polymer nano-composites. In addition, Tjong (2006) pointed out carbon nanotube as the highest modulus and toughness contributor in composite structure. The multi-layer composite structures can be made to have better load-resistant capacity by the introduction of additional core layers or additional interlayers composed of ductile materials. The additional layers should have the ability to share loads or energy with the adjacent layers of the composite structure. Yang *et al*. [8] observed the influence of impact and blast loading on four panels of circular multi-layer composites. As additional core layers, a ductile elastometric layer of polyuria and a moderate compressible Divinycell-H200 foam layer was used which to enhance the blast resistance of the composite panels whereas balsawood was also incorporated as the core of the composite structure. The top level and the bottom level of the panels were made up of glass fiber reinforced plastic (GFRP). The analysis result confirmed the effectiveness of the additional core layers in absorbing blast energy and reducing the probability of shear failure. The stress distribution was also appeared as uniform. Moreover, Kazanci and Mecitoglu [14] also observed that the increase in the amount of layers in composite structure consisted of fiber glass fabric (E=24.14 GPa) in each layer decreases the vibration frequency and enhances the performances of the structure.

VI. Failure Modes and Stresses

The initiation of failures in multi-layer composite structures can occur in a number of ways. Among these, matrix cracking, delamination which results due fiber failure and penetration are remarkable [63]. Moreover, Langdon *et al*. [64] commented that delamination, interfacial bonding, fiber structure, plastic deformation of the material layers and rupture are the common failure modes when the composite structure undergoes blast loading. In general, the multi-layer composite structures are observed to be failed due to the contribution of in-plane stresses. At the heavily loaded situation, stresses in various layers of the composite structure are also appeared as non-uniform. For instances, Tasdemirci and Hall [3] prepared a three layer composite structure and the results informed that the failure initiates through propagation from front to back surface and also from back to front surface which results in axial split. It was observed from the study that the stress distribution in the composite structure is non-uniform at large strain rate. Again, Elmalich and Rabinovitch [7] studied the behavior of multi-layer composite wall under dynamic loading condition and the stress distributions are found as non-uniform pattern. In addition, Nayak *et al*. [4] conducted finite element analysis on a three layer composite structure to investigate the dynamic response (applied blast loading) of the structure. The highest response of the structure was observed when it was subjected to biaxial stresses. Moreover, Yiming *et al*. [65] conducted damage analysis of elasto-plastic laminated composite shallow spherical shell subjected to low velocity impact. The damage at the contact area where impact load applied was found to initiate by in-plane stress.

VII. Conclusions

The utilization of multi-layer composite system is found to be common in metal structures and pavement systems. This paper reviews the recent research outcomes conducted on multi-layer composite structures composed of variety of materials. The layers of composite structure designed to encounter heavy dynamic energy should have sufficient ductility to counteract the intensity of energy. Delamination, penetration and matrix cracking are the common failure modes of composite structure under impact or blast load and failure due to shear stress is also common. For metallic multi-layer composite structure, delamination is most significant compared to the other types of failures whereas in cement based composite structure penetration is a common type of failure. The occurrence of delamination can be controlled by improving interface bonding of adjacent layers of composite as summarized in the paper and enhancing the mechanical properties of individual layers of composite is the main key to resist penetration failure. Consequently, extensive research works need to be conducted to explore the strategies to improve interface bonding as well as mechanical properties of materials used in the multi-layer composite structures.

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