Study on Blast Proof Composite Plate Structures

Ahmed Mohamed Hassan[1], Abdolreza Toudehdehghan[1*]

[1]Faculty of Engineering and Quantity Surveying INTI International University Persiaran Perdana BBN Putra Nilai, 71800 Nilai, Negeri Sembilan

[*]**Email:** abdolreza.toudehdehghan@newinti.edu.my

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Abstract: Considering the remarkable growth in research activities and publications on blast-proof materials and structures in recent years, this article is trying to identify and highlight topics related to blast-proof structures and review representative papers that are related to the topics. A study of the research done in the domain of blast-proof structure and materials with an emphasis on recent works. Due to the wide development in blast-proof structures in the last decades, it is reasonable to cut down the study to a limited area by focusing on the blast-proof plate issues only. The study is related to deformation-fracture behavior, blast-loading, materials selection, and fabrication techniques of blast-proof. This study is planned to present the readers with a big-picture of studies and applications related to blast-proof. An attempt has been made here, to contain all the main portions in the blast-proof.

Keywords: proof-blast composite plates; blast loads; explosive types; energy absorption; honeycomb

Introduction

Terrorist attacks against civilian targets have become a hallmark of modern warfare and a growing hazard to civilian and military people (Ritenour & Baskin, 2008). Suicide attacks have hampered society's progress and even jeopardized its survival. Explosive attacks can occur at any time and place causing many explosions, deaths, and fires globally. Several disasters such as the bombings of The Federal Building in Oklahoma City (1995)(Smith, Christiansen, Vincent, & Hann, 1999), the Khobar Tower of Saudi Arabia (1996), the US embassy in Nairobi, Kenya, and Dar el-Salaam Tanzania (1998), the Oslo bombing (2011) (Chun, 2020). and recently Beirut explosion (2020) Although these kinds of attacks are rare, they may or may not be caused by humans.

Over the years, several approaches and field tests have been carried out to explore the behavior of a specific material under the explosion and to investigate the decrease of deformation behind the plate as well as the peak pressure produced by the shockwave. Recent research, on the other hand, has discovered that adding two or more layers of material and a structure to the same plate might minimize the deformation caused by the blast (Hou et al., 2019). As most developing countries with a high rate of terrorist attacks have lack of materials necessary to construct and deploy a composite plate for protection (Arko-Achemfuor, 2017), additional research is required to help to reduce the occurrence of terrorist attacks, as well as to fill up this gap.

Several research has revealed that composite materials are more effective compared to raw materials for energy absorption (Birman & Kardomateas, 2018; Mohammed, Ansari, Pua, Jawaid, & Islam, 2015). A composite material combines at least two components to generate characteristics superior to those of the ingredients. Some of the composite materials used in industry, for example, multilayered surfaces of graphite-epoxy and carbon-epoxy are common for aerospace applications, whereas glass-epoxy or glass-vinyl esters are utilized in civilian and marine surfaces. The fundamental construction of aerospace is generally aluminum or Nomex. In addition, the advantages of composite material (Randjbaran, Majid, Sultan, Mazlan, & Zahari):

- High strength and stiffness-to-weight ratio
- Low weight
- Excellent corrosion resistance
- Excellent fatigue resistance

Explosion and blast-loading

Today, there are various sorts of explosives. In most situations, the usage of solid explosives is very straightforward to produce because of the transportability of improvised explosive devices (IEDs). The vast range of explosives has resulted in the acceptance of a universal amount used to calculate the blast characteristics required. TNT (Trinitrotoluene) has been chosen because its explosion properties match the most solid explosives. The equivalent TNT weight is calculated according to the following Formula 1. which relates the explosive to the equivalent TNT weight by using the thermal ratio generated after detonation (Acosta, 2011).

$$w_e = w_{\exp} \frac{H^d_{\exp}}{H^d_{TNT}}$$

w_e : TNT equivalent weight [kg] $w_{\exp}$: Weight of the actual explosive [kg]

$H^d_{\exp}$: Heat of detonation of the actual explosive [MJ/kg] H^d_{TNT} : Heat of detonation of the TNT [MJ/kg]

Formula 1. TNT weight(Acosta, 2011)

Directly after an explosion, as seen in Figure 1, the phenomena of pressure-time correlations occur in milliseconds. An explosive triple point is produced when the blast wave interacts with other objects, causing an intense shock wave known as Mach's stem. Using the equation of Friedlander (Bhatti, Ahmad, Rodrigues, & Brandonisio, 2018) enables us to determine the blast wave both in the free air and for the surface explosion (Formul 2). The blast wave can be classified as a simple blast wave (i.e., free-field, open-air blast waves) depending on the level of injury and standoff distance, size of the charge, height, and geometry type of charge (Bhatti et al., 2018).

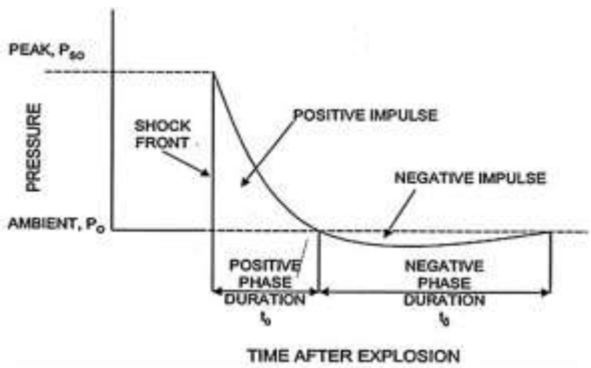

Figure 1. Relationships after an explosion (Bhatti et al., 2018)

$$p(t) = P_{so}\left[1 - \frac{t}{t_0}\right] e^{\left[\frac{-\alpha(t - t_A)}{t_0}\right]}$$

$p(t)$: Pressure at a certain time (N/m^2)

P_{so} : Peak incident pressure (N/m^2)

t_0 : Positive phase duration

t_A : Arrival time

α : Wave decay factor

Formula 2. Friedlander formula (Bhatti et al., 2018)

Hopkinson-Cranz (Tang, Bird, Rigby, Tyas, & Warren, 2017) and Sachs each separately created a scaling law formulation for their respective fields as shown Formula 3. It is believed that when two charges of the same explosive with similar geometry and distance but different weight are exploded at the same time, they will produce a similar blast wave at the point of interest as long as they are subjected to the same atmospheric conditions and nomenclature are used.

$$Z = \frac{R}{\sqrt[3]{W}}$$

Z : Scaling law (m/(Kg)^(1/3))

R : Standoff distance (m)

W : Charge mass of TNT (Kg)

Formula 3. Scaling Law of Blast Loading (Tang et al., 2017)

The categories of blast loading are as follows:

Blast-loading types

- **Free-air bursts:** The explosive charge is detonated in the air, propagated by blast waves, without any contact with other obstacles or the ground.
- **Air bursts:** This type of explosive need to have an interacted first with the ground in order to; create a Mach wave front.
- **Surface bursts:** The blast waves contact with the ground locally, then spread the hemisphere to the outside and influence the structure.

An equivalent mass factor of explosion types was compared in Figure 2 by indicating the peak pressure and impulse of each explosive type (Krauthammer, 2008).

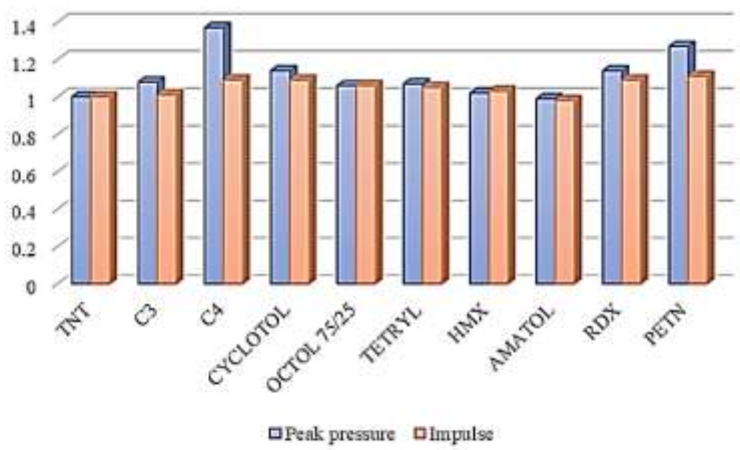

Figure 2. peak pressure and impulse of common explosives (Krauthammer, 2008)

Blast Effect on structures and the human body: The blast pressures experienced by a structure are generally related to the amount of explosive used, and the distance of the explosion depends on peak incident pressure, charge weight, and distance. Based on Department of Defense data from Gladstone and Dolan (1977) and Sartori (1983), the following Table 1 summarizes the effects on different structures and the human body of increasing blast pressure. This data is based on weapons testing and blast experiments to evaluate the effect of blast overpressure on structures and humans. These facts give information on probable explosive consequences.

Table 1. Effects of extended duration blast overpressures on structures and the human body.

Peak overpressure	Maximum wind speed	Effect on structures	Effect on the human body
1 psi	38 Mph	Glass window shatters	Light injuries sustained as a result of fragments
2 psi	70 Mph	Windows and doors blown off and serious roof damage	Glass and debris flying through the air cause injuries
3 psi	102 Mph	Residential structure collapse	Serious injuries are prevalent, death can happen
5 psi	163 Mph	Most buildings collapse	Injuries are universal, fatalities are widespread
10 psi	294 Mph	Strongly damaged or destroyed reinforced structures	The vast majority of individuals are killed
20 psi	502 Mph	Highly constructed concrete buildings are seriously damaged/destroyed	The number of fatalities is approaching 100 percent.

Review of studies

The evolution of materials and sophisticated design has piqued the interest of researchers and industries. Plate structures include metal and non-metal honeycomb cores, lattice structures, and foam. Since less research conducted on composite plate structures under blast loads.
Due to high costs and limited feasibility, full-scale studies on explosive behavior research are still intimidating. The findings of large-scale studies on steel plates produced by Jacinto et al (2001), are shown detonating loads with a range of equivalent mass (10 kg), ranging in distances from 30 to 60 m. This discovery strengthened the effect of limiting constraints on blast behavior (Xu, Liu, & Huang, 2019).

Kosiuczenko Krzysztof (2011), experiment involved a comparison of a steel plate with a thin stainless steel composite reinforcement plate which is consisting of five various S2/Glass texture-oriented layers. This experiment was performed with LS-Dyna software. The dimensions of the steel plate (25 to 25) cm 4-mm thick, covered by 5 high-resistance glass fibers S-2 layers, under 100g TNT blast wave load which it is located at a height of 10cm above the central plate. The arrangement of the composite layers was as [0, -45, 90, 45] as illustrated in Figure 3. Four boundary requirements to defined the restriction of mounting brackets in specific nodes are needed. This study demonstrates that the composite layers may increase the capacity of the whole system (Pach, Pyka, Jamroziak, & Mayer, 2017).

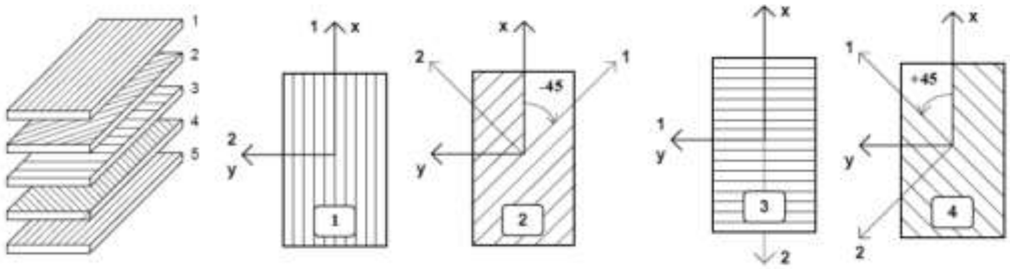

Figure 3. Layout of composite layers (Kosiuczenko, Niezgoda, Barnat, & Panowicz, 2011)

In addition, XiaodongCui et al (2012) carried out experiments on the deformation of square lattice sandwich plates with tetrahedral lattice cores under impulsive loading in order to anticipate the dynamic response based on a theoretical model developed by the authors. The significant deformation impact of the front face sheet is taken into account, and the structural deformation of the lattice core is well represented. Both the impulse transferred to the sandwich plates and the maximum deflection of the rear face sheet is found to be in good agreement with the anticipated and measured values (Cui, Zhao, Wang, Zhao, & Fang, 2012).

Models in three dimensions (3D) were investigated by the author YeYuan (2013). To predict the maximum central deflection and deformation mode of rectangular plates for different combinations of aspect ratios and impulses, numerical analyses were carried out using the non-linear finite element ABAQUS. The results were published in the journal Nonlinear Finite Element Analysis and Numerical Simulation (deformation and failure of rectangular plates subjected to impulsive loadings). However, the experimental results for square mild-steel and aluminum plates are justified where the load impact is found in good agreement, regardless of Model III (Yuan & Tan, 2013).

Fallah, et (2014). investigated the dynamic response of a blast-resistant lightweight fiber composite structure known as Dyneema, an alternative to armor steel for military uses. For the range of impulses examined, armor steel and Dyneema HB26 provide potential displacement reductions of almost 50% and 30%, respectively (Fallah et al., 2014).

A multi-layered aluminum alloy AA 7075 composite, inspired by the structure of nacre, was introduced by E.A. Flores-Johnson. (2015), and tested under blast load and compared to bulk plates, the thickness of both bulk plates and composite plates were 5.4mm and 3.3mm respectively. Although both composite and bulk plates were of the same thickness, the results of this investigation suggest that composite is more effective at absorbing blast loads than bulk plates. Composite plates required a larger load to reach the onset failure compared to the bulk plates. To sum up, nacre-like plates are a feasible alternative for shielding buildings against localized blast pressures (Flores-Johnson, Shen, Guiamatsia, & Nguyen, 2015).

Hazratiet et al (2016) investigated a numerical approach to predict failure in the reinforced V-shape plates subjected to blast loading of 50g TNT. V-shape plates are commonly used in the vehicle’s hull to mitigate the blast pressure effects and also to invest in the energy-absorbing by adding a honeycomb structure as a surface of the plate. Figure 4 shows a schematic diagram of a flat target and V-shape against a blast wave. Results demonstrate that the use of a V form plate with reinforcements of energy absorbers considerably reduces the blast load effects. It was noted that honeycomb reinforcement models absorb a substantial amount of the explosion energy and minimize the load sent into the chassis (Jing, Wang, & Zhao, 2013).

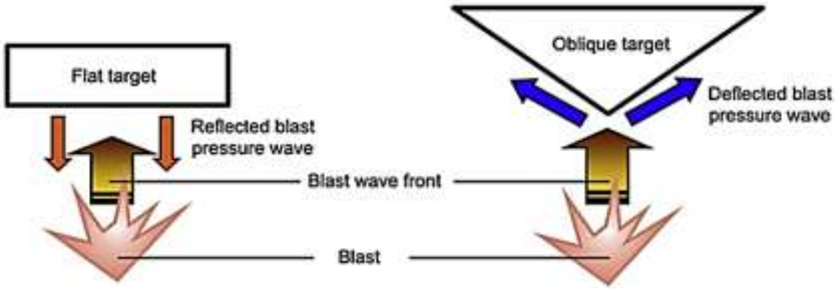

Figure 4. Schematic diagram occupant behavior to explosion (Jing et al., 2013)

Carry on polyurea coating effective studies by Alex Remennikov et al (2016) for enhancing blast protection therefore in this study he examined the response of three types of steel plates namely mild steel, high-strength steel, and stainless steel under a close-in blast loading while focusing on potential damage mitigation techniques through additional polyurea protective coatings. The test charge weights were (1kg) of NEQ TNT spherical charges used in a different standoff. On the other hand, all steel plate specimens have dimensions of 1000 mm x 1000 mm and 10 mm thickness coated with polyurea on both front and rear surfaces with two different coating thicknesses 6 mm, and 12 mm were used in order to absorb the effectiveness of the coating thickness. The highest residual plate deformation shows in the mild steel plates compared to high-strength and stainless steel as they achieved 60% and 26% respectively in the peak deformations compared to mild steel plates (Remennikov, Ngo, Mohotti, Uy, & Netherton, 2017).

Auora et al (2019) investigated the effect of stand-off distance on the dynamic response of thin ductile plates exposed to air blast loading using 0.8mm thick medium-strength (Docol 600DL) and high-strength (Docol 1400M) steels, respectively (Haghi, Behjat, & Yazdani, 2017). The overall response of the target plates showed a stiffer behavior for Docol 1400M than for Docol 600DL Table 2 shows the chemical utilized in this study.

Table 2. Chemical composition of Docol 600DL and Docol 1400M (Haghi et al., 2017)

Material	C (Max)	Si (Max)	Mn (Max)	P (Max)	S (Max)	Al (Max)	Nb + Ti (max)
Docol 600DL	0.10	0.40	1.50	0.010	0.002	0.040	——
Docol 600DL	0.20	0.40	1.60	0.020	0.010	0.015	0.10

Furthermore, Yuen et al. (2019) conducted a series of large-scale field experiments on clamped mild thin plates and therefore determined that the deformation of complicated loading could be roughly simplified as plates uniformly loaded in lab testing. It evaluates in this article the ultimate deflection of thin ductile plates (Rigby, Tyas, Curry, & Langdon, 2019).

As combined aluminum honeycomb has been considered a promising structure in the protection field due to its excellent energy absorption capacity Yi Meng et al (2020). Studied the mechanical behavior of combined honeycomb under explosion experimentally and through simulations and compared it with other conventional honeycomb structures. The results demonstrate that the normalized stresses of compression from the integrated honeycombs of Al5052 are stable for almost static and dynamic compression, therefore the findings indicate that energy absorption and pressure strain have been reduced with slider thickness and scaled distance (Meng, Lin, Zhang, & Li, 2020).

Tao Wang et al (2015) investigated the dynamic response of three (3) geometrically asymmetric sandwich plates with aluminum (3003H24) hexagonal honeycomb core as shown in Figure 5 density for each plate respectively (41.5 kg/m^3, 20.7 kg/m^3 and 69.1 kg/m^3) subjected to blast loading by applying cyclotri-methylene trinitramine (RDX) explosive charges at standoff distance e of 200-mm located at the center of the plate the study focusing on two main points of the design (i) different thicknesses of front and rear face sheets, (ii) different thicknesses and materials of front and rear face sheets. Studies demonstrate that sandwich plates with low core density sustain local breakage better than sandwich plates with high core density. The asymmetry factor affects the deformation and damage modes of sandwich plates with high core densities but again not low core densities. The honeycomb cores of sandwich plate specimens were also exposed to the same blast loading (Wang et al., 2017).

A broad variety of structural options are available. Various sorts of structures have been studied in the past as the studies above showed. Table 3 illustrates a different type of structure that has been/hasn't been invested against shockwave and determines their effect on energy absorption (Zhang, Lu, & You, 2020).

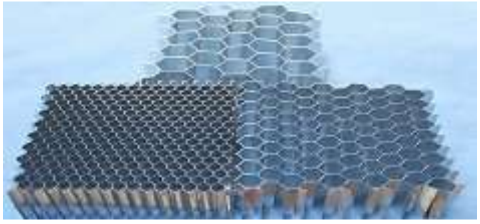

Figure 5. Hexagonal honeycomb Specimens (Wang et al., 2017)

Table 3. Type of plate structures (Zhang et al., 2020)

Honeycomb	Corrugated core	Foams
HEXAGONAL	I-CORE	CLOSED-CELL FOAM
SQUARE	V-CORE	OPEN-CELL FOAM
TRIANGULAR	O-CORE	
CIRCULAR	X-CORE	
CHIRAL		

Fabrication techniques

Many ways are known to manufacture composite components. The fabrication of composite materials requires two essential processes (Rao, 2021):

- stacking or lay-up of laminas made up of fiber and matrix components
- polymerization of the resin, which is accomplished by curing.

In addition, molding is used to shape the resin and reinforcement in most composite manufacturing techniques. Prior to and during cure, a mold tool is necessary to give the unformed resin/fiber combination its shape. Therefore, the choice of a technique for a certain component depends on the materials composite manufacturing methods some of the fabrication techniques are provided in Figure 6.

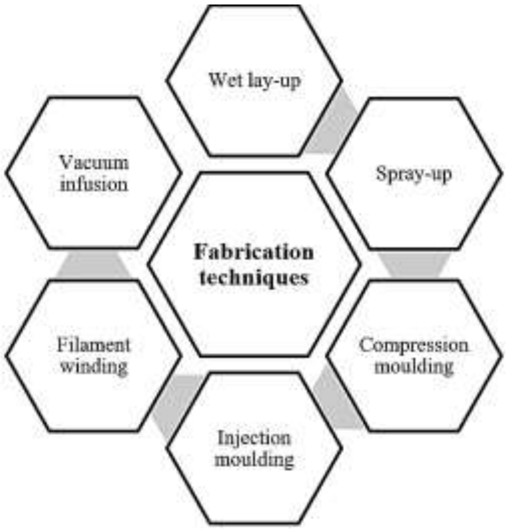

Figure 6. Fabrication techniques (Rao, 2021)

Core manufacturing process

Since there are a variety of core composite plate configurations, this part will specialize in the manufacturing process of a basic hexagonal honeycomb. Figure 7 shows five fundamental methods need to produce honeycomb. (Kılıçaslan, Güden, Odacı, & Taşdemirci, 2014):

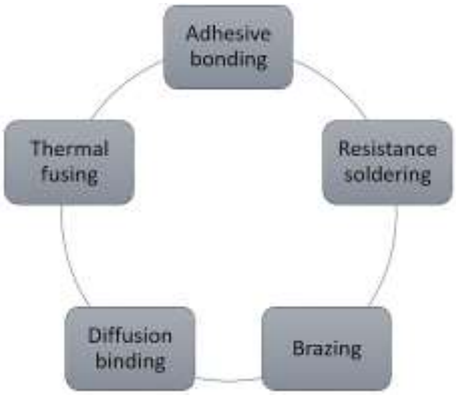

Figure 7. Production methods of honeycomb composite (Kılıçaslan et al., 2014)

However, there are two basic methods of manufacturing honeycomb core by applying adhesive bonding.

By expansion method

Figure 8 shows a schematic of the expansion process for core honeycomb production. The metallic sheet is cut to the required proportions, and sticky strips are printed on the surface of the sheet. Because of the way adhesive is applied, sticky the prints on consecutive sheets are displaced by half the distance between adjacent prints on the same sheet when they are placed next to each other. Following the solidification and curing of the adhesive, the HOBE block is cut into the appropriate thickness of the core, and then the HOBE slice is extended to produce honeycombs (Kılıçaslan et al., 2014).

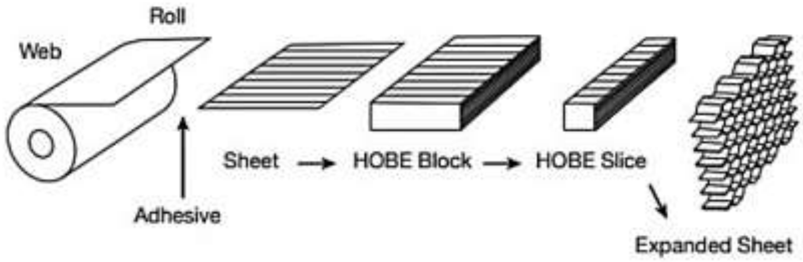

Figure 8. Schematic of the expansion process for core honeycomb production composite structure plate (Clarke, 2018)

Corrugation method

In this process, corrugations are created between toothed rollers by pressing metallic sheets. Then corrugated sheets are attached, brazed, or welded to form the core of the honeycomb. In general, this method is preferred for high-density cores that cannot be extended by thick and strong metal sheets. On the other hand, laminate plates typically are manufactured with a cure cycle range of 121°C to 77°C for 1 hour following heat-up rates of 1.1-2.2°C per minute with a pressure of around 0.48 MPa are utilized. Metallic plates can be treated in the same way as laminate; however, the amount of pressure that must be applied depends on the compressive strength of the core (Kılıçaslan et al., 2014).

Applications of composite structure plate

The following figure (Figure 9) demonstrates most of the uses of composite plates in both industrial and private sectors; thus, the application of the composite plate structure is extensive where is difficult to include all of them (Birman & Kardomateas, 2018).

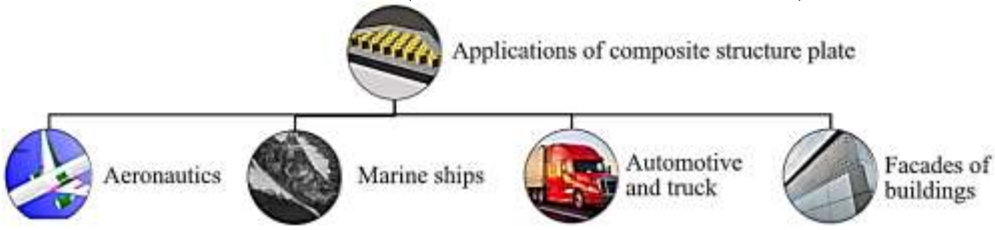

Figure 9. Application of composite structure plate (Kılıçaslan et al., 2014)

Materials selection

Over the last few decades, composite materials' production has impacted every area of human life, whether civilian or military. Almost composite material has been used in all aerospace structures, aircraft, tanks, and marine structures in the military arena, ships, tanks, and marine structures. However, composites in bridges, and sporting goods, and it has replaced existing steel and concrete building structures to be on the civilian side. Thus, choosing the right material can be a quite critical decision to relate to, due to the wide range of materials (Thomas & Tiwari, 2019). However, Figure 10 shows three main points that need to be taken into consideration to choosing suitable material.

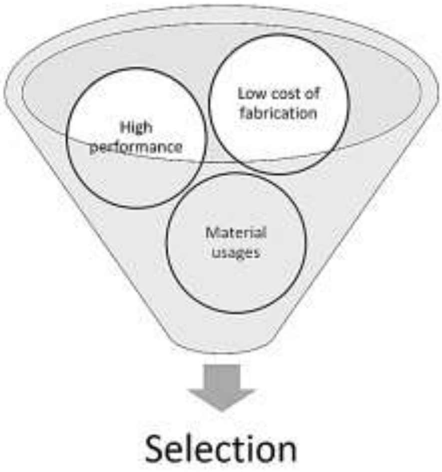

Figure 10. The main point to selecting a material

The following chart (Figure 11) summarizes the most prevalent composite materials in the industry based on manufacturing cost and Material performance however the material selection also depends on several factors, including the type of structure, thickness, type of usage, etc.

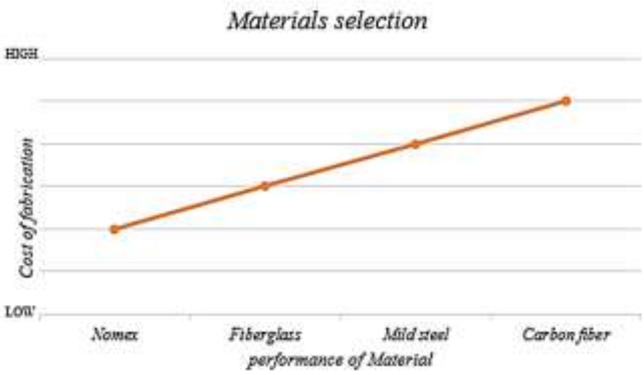

Figure 11. Performance of Material vs. Cost of fabrication

Conclusions

A study of diverse research accomplished in the present literature for deformation-fracture behavior, blast-loading, materials selection, and fabrication techniques of blast-proof composite plates have been introduced in this paper. It has been tried to highlight all the influential aspects in the investigation of blast-proof composite plate structures. The remarkable points of this study are as follows: Having reviewed a great sector of the blast composite plate research available it is apparent that nearly all the research conducted has been about metallic composite materials. Therefore, research in non-metallic composite materials seems very necessary; In most of study included the fabrication method of composite structures, as well as the costing and performance, but very limited studies are presented on comparison of two different composite; Composite materials which have now seemed to provide suitable mechanical behavior under blast loading as good as the metallic material. Also, they have priority based on cost and efficient manufacturing.

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