ENHANCEMENT OF BALLISTIC PROPERTIES BY HYBRIDIZATION METHOD OF MULTI-LAYERED COMPOSITE PANELS

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by
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ABSTRACT

ENHANCEMENT OF BALLISTIC PROPERTIES BY HYBRIDIZATION METHOD OF MULTI-LAYERED COMPOSITE PANELS

High performance fiber reinforced composite structures are used for ballistic applications in recent years due to several advantages lightweight, high strength and high energy absorbing capability. In this regard, it is aimed to enhance ballistic performance of fiber reinforced composites by hybridization method in this thesis.

Two of most used fiber types were selected as reinforcement which are E-Glass and Aramid fibers. As matrix epoxy resin was used. Homogeneous and hybrid structures were manufactured. In hybrid structures configuration was arranged as E-Glass layers are at the front and Aramid layers are at the back. Two different hybrid composites were manufactured with 50:50 and 70:30 Aramid and E-Glass layers. The effect of volume fraction of fabric layers on ballistic properties was investigated. Since there is a linear relationship between V_{50} and thickness, composite structures were manufactured with two different thicknesses and by the equation derived V_{50} values for different thicknesses could be determined.

Mechanical and ballistic tests were carried out in the study. Tensile, 3-Point bending and short beam strength tests were applied as mechanical tests and a V50 test was carried out as ballistic test. Composite structures were compared with each other based on test results.

Consequently, it was found that hybridization method increased mechanical and ballistic properties. Mass efficiency of hybrid structures were found to be higher than 1 (E-Glass composite was used as reference). It was also found that presence of E-Glass layers assists aramid structures to experience more delamination during impact and therefore increased energy absorbing capability.

ÖZET

ÇOK KATMANLI KOMPOZİT PLAKALARIN HİBRİDİZASYON İLE BALİSTİK ÖZELLİKLERİNİN GELİŞTİRİLMESİ

Fiber katkılı polimerik kompozit malzmeler balistik uygulamalarda düşük özkütle, yüksek mukavemet ve enerji sönümleme kabiliyeti gibi avantajlarından dolayı gün geçtikçe daha yaygın olarak kullanılmaktadır. Bu bağlamda, çalışmada fiber katkılı çok katmanlı kompozit malzemelerin hibritleme yöntemi ile balistik özelliklerinin geliştirilmesi amaçlanmaktadır.

Çalışmada, sıklıkla kullanılan fiber tiplerinden olan E-Cam ve aramid fiber tipleri kullanılmış olup reçine malzemesi olarak epoksi reçine sistemi tercih edilmiştir. Homojen ve hibrit fiber katkılı kompozit plakalar üretilmiş olup hibrit kompozit plakalarda konfigürasyon E-Cam fiber katmanı önde aramid fiber katmanı arkada olacak şekilde üretim gerçekleştirilmiştir. Aramid ve E-Cam fiber katmanların birbiri içinde hacimsel oranları 50:50 ve 70:30 olacak şekilde iki farklı tip hibrit kompozit plaka üretilmiştir. Bu sayede farklı fiber tiplerinin birbiri içinde hacimsel oranının balistik özelliklere etkisi de araştırılmıştır. Her kompozit plakadan iki farklı kalınlıkta üretim yapılmış ve test edilmiştir.

Kompozit plakalara mekanik ve balistik testler uygulanmış olup uygulanan mekanik ve balistik testler sırası ile çekme, üç nokta eğme ve kısa kiriş dayanımı ve V_{50} testleri şeklindedir. Test sonuçlarına göre homojen ve hibrit kompozitler arasında karşılaştırma yapılmıştır.

Sonuç olarak hibridizasyonun mekanik ve balistik özelliklerin artışında önemli rol oynadığı görülmüştür. E-Cam fiber katkılı kompozit plaka referans alınarak yapılan kütlesel verimlilik hesaplarında hibrit kompozitlerin 1’den büyük verimliliğe sahip olduğu görülmüş olup bu durum aynı seviye tehdide karşı daha düşük alansal ağırlık ile koruma sağlayabildiğini göstermektedir. Delaminasyon alanları incelendiğinde E-Cam katmanların aramid fiber katmanlarına delaminasyon ve enerji sönümleme için zaman kazandırdığı görülmüştür.

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CHAPTER 1

INTRODUCTION

Throughout the history humankind felt the need of protect themselves instinctively. This instinct started against wild animals and continued with production of several tools after the foundation of fire. With the passing of time, humans started competing each other and fighting for lands and raw materials. During this competition with the effect of improvement in technology new type of weapons were found such as spear, sword etc. and started to be used. Foundation of these new weapons brang new defense idea against them. In this regard, shields, body armors and helmets were manufactured and used. Samples of these armors can be seen in Figure 1 below.

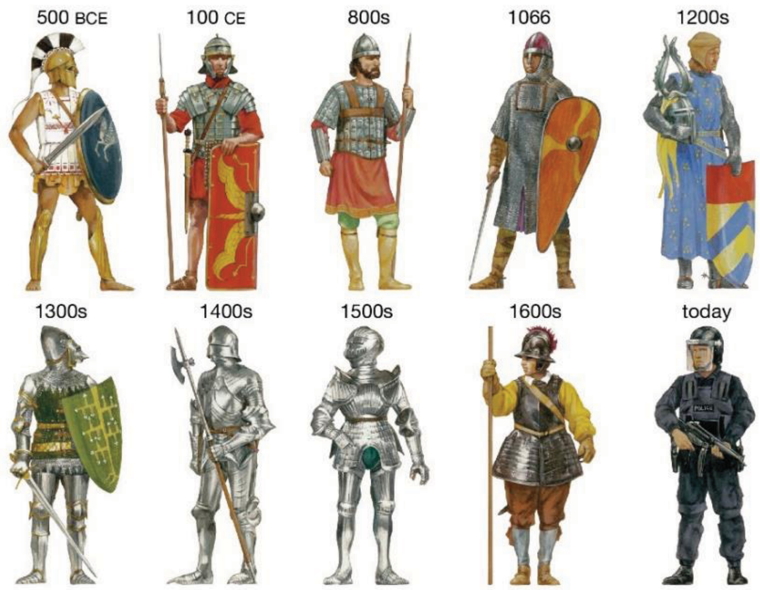


Figure 1. Body Armor Types Change in Time [1]

As it is seen in the figure above, body armors were used in ancient times were made of metal materials mostly. Among metal materials, steel was mostly preferred one due to the strength and impact advantages on other metals.

After the invention of vehicles, people started use this technology to get advantage at wars. In this regard, armored vehicles were found. As the vehicle technology developed, ammunitions also got more dangerous. Different types of threats were produced to defeat armored vehicles. Especially after the invention of explosive powder, the dynamics of the war was changed, and the need of more efficient protection solutions occurred. New requirements of armored plates were coming up as follows;

- Armor panels should not prevent the movement of the vehicle (mobility)
- For the high mobility of vehicles, armor panels should be lightweight.
- Manufacturing process of the materials should not be complicated (easy to manufacture)
- Armor materials should be cost effective.

Based on the first two requirement, tendency to the new and lighter materials were started. As the material technology improved, some alternatives for replacement with steel were found. One of these alternatives is ceramic materials.

Ballistic ceramics are very hard and brittle materials. By means of hardness, projectile is broken and by breaking the projectile, its energy might be dissipated. In this way ceramic materials can stop the threats. In some cases, ceramics may not be able to stop the projectile alone. In these cases, there are two main options, which are making the ceramic thicker and using another material with ceramic tiles. First option is efficient, but it also increases the total weight of the system. In the second option, a material, which has smaller density than the ceramic, may be used as a backing plate behind the ceramics. In that way, backing plate would be able to absorb the residual energy of the projectile that is broken and slowed down by the ceramic.

Fiber reinforced composites take the stage in ballistic applications at that point. They are used as a backing plate behind the ceramics and the whole system is called as *"Lightweight Composite Amor Systems"* (Figure 2). Fiber reinforced composites are able to stretch and due to the several deformation mechanisms they absorb the kinetic energy of projectiles.

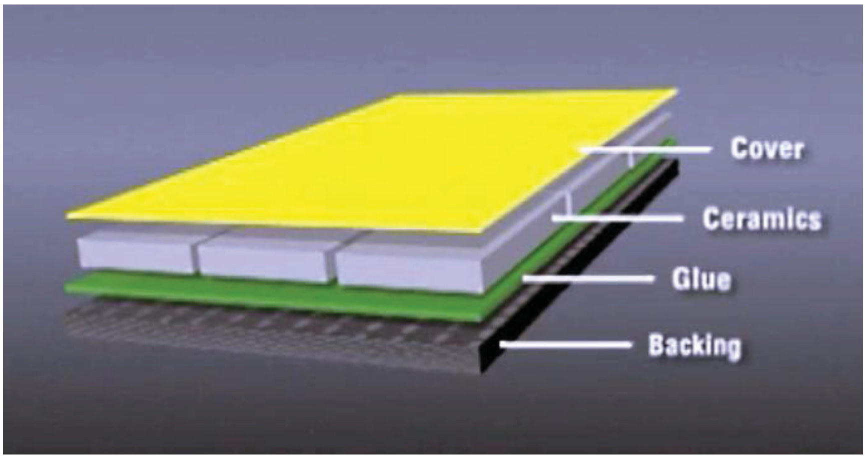


Figure 2. Example of Ceramic/Composite Lightweight Armor System [2]

Composite materials are combination of at least two different materials having different mechanical and chemical properties in a macroscopic level. As a result of combination of these two constituents a new material with unique properties is obtained. The constituents are generally called as fiber and the matrix. Fiber type has a significant effect on the ballistic properties of composites. In addition to fiber type, matrix type, thickness, fiber/matrix ratio are some other parameters that affect the ballistic impact properties of composite plates.

The ballistic impact characteristics of fiber reinforced composite materials are investigated in the literature in many studies. In these studies, researchers are also looking for the ways to improve the properties of composites. One of the most effective methods is the hybridization of the fibers in which at least two different fiber types are used for manufacturing of the composite plates. In this way, the positive effect of different fiber types may be exploited.

The aim of this study is to improve the ballistic impact characteristics of fiber reinforced composite plates by using two most common fiber types which are Aramid and E-Glass fibers and to investigate the behavior of ballistic limit velocity with the thickness of the plates. In this way alternative cost-effective solutions which are easy to supply will be found.

CHAPTER 2

COMPOSITE STRUCTURES AND MANUFACTURING TECHNIQUES

2.1. Introduction to Composite Materials

Composite structures are the combination in macro-level of at least two materials having different mechanical and chemical properties with unique and better properties. Researchers started to develop new materials for applications in which high strength and low density are required. Especially during the last decade composite structures are preferred for structural applications in the industry as the material technology develops [3]. When compared with the traditional engineering materials as aluminum, steel etc. composites have several advantages as listed below.

- Composite materials have low density compared to metals and ceramics
- High mechanical properties (strength, elastic modulus) put composite structures forward.
- Composites have high resistance against environmental conditions (elevated temperatures, oxidation etc.)
- According to the application they may be used as conductive or insulator.

Composite materials are generally composed of two phases which are called as reinforcement and matrix phase. Basically, reinforcement is responsible for bearing the load applied on composite structure. Matrix phase is used for covering and load transmission between reinforcements. Also, matrix material protects reinforcement against environmental issues.

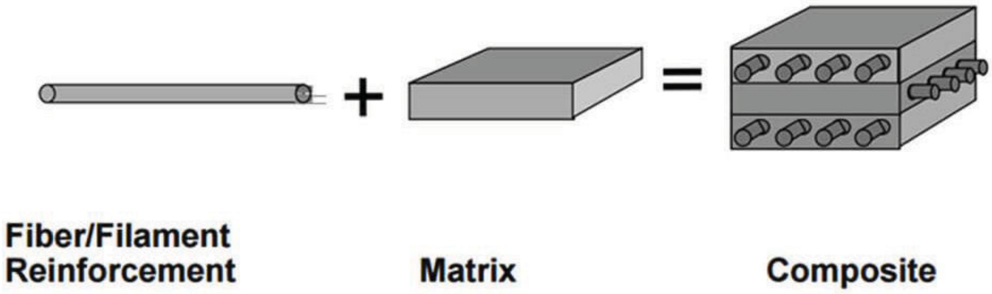


Figure 3. Formation of Composite Structure [4]

As mentioned, and showed in Figure 1 above, composite structures are composed of constituents and composites can be classified by reinforcement geometry and matrix type.

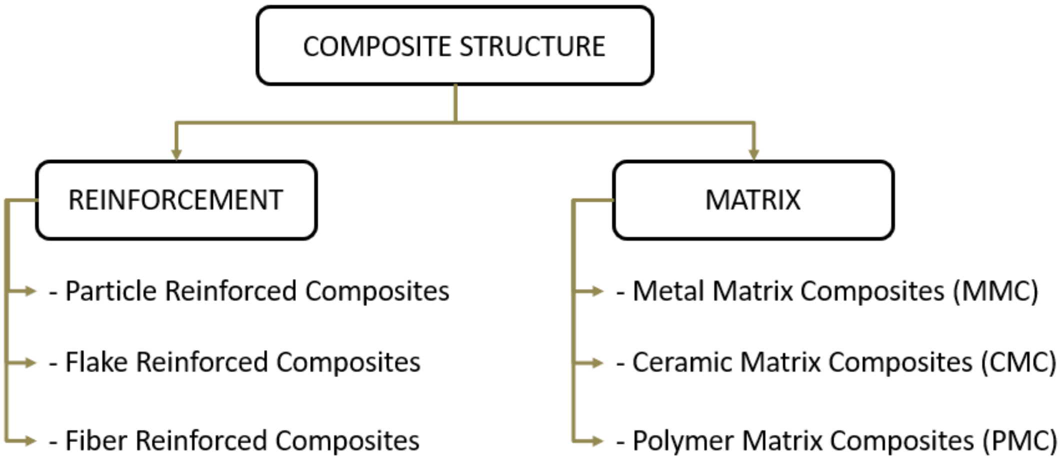


Figure 4. Classification of Composite Structures

As a reinforcement, fibers are generally preferred for the applications in which high strength is required. Due to their long and continuous structures, fiber reinforcements have higher strength and modulus when compared with particle and flake reinforcements.

Metal matrix composites are more ductile than other types. On the other hand, in the cases resistance against elevated temperatures and lightweight are required metal matrix composites become less efficient. Ceramic matrix composites are used to improve the fracture toughness of the system. Also composites with ceramic matrix are able to resist elevated temperatures and they have lower density compared to metal matrix composites. However, due to the requirement of high temperatures for production of ceramic matrix composites and complexity of the process, the cost of manufacturing become higher. Polymer matrix materials are ideal by means of their lightweight and easy to manufacture properties. Also, polymer matrices have high resistance against environmental conditions as elevated temperatures. Based on these characteristics, polymer matrix is the most used type with the fiber reinforcements in the industrial applications. The combination of polymer matrix and fiber reinforcement is called as *“Fiber Reinforced Polymer (FRP)”*. In fiber reinforced polymers there are different types of fiber and matrix materials that may be used.

2.2. Fiber Phase

Fibers are one of the constituents in composite materials responsible for carrying the load that is applied on the system. Fibers may be in the form of continuous (long) or discontinuous (short). Continuous fibers have higher strength and modulus than short fibers. Both types are being used in industry based on the application.

Fibers are generally classified as natural and synthetic. In the figure below the classification of fiber is shown.

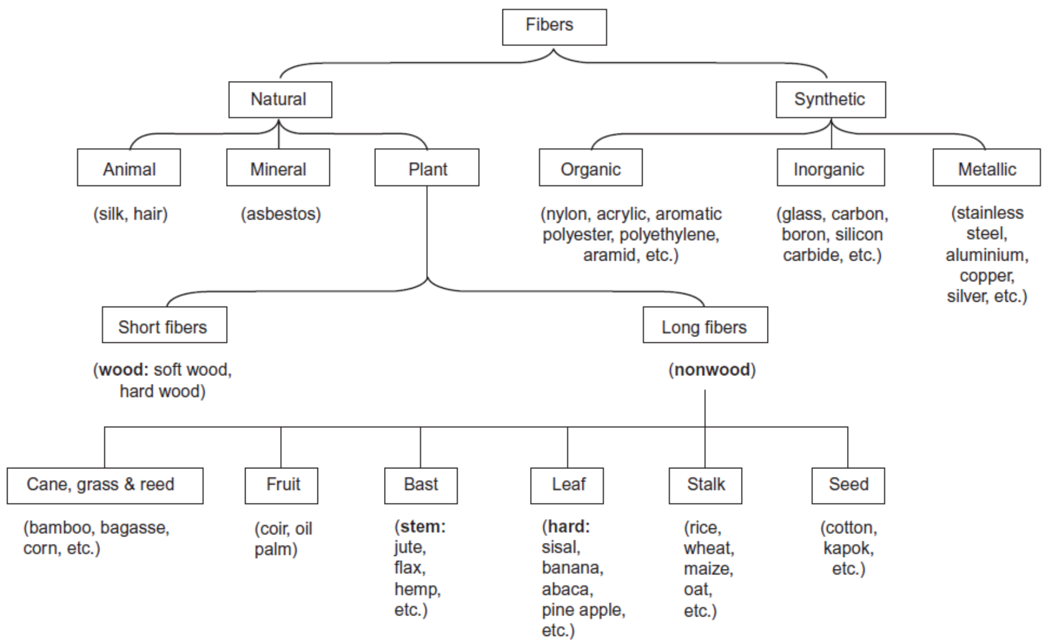


Figure 5. Classification of Fiber Types [5]

As seen in Figure 3 above many natural and synthetic fibers types exists. Some of the synthetic fibers are widely used for composite manufacturing. These fiber types are;

- Glass Fibers

- Carbon Fibers
- Aramid Fibers
- Polyethylene Fibers

2.2.1. Glass Fibers

Glass fiber reinforcements are almost the most used fiber type for industrial applications. Functional properties of glass fiber are similar to the steel and has higher stiffness when compared to aluminum. Reasons of use of glass fibers are listed below.

- Glass fibers are easy to manufacture.
- They have high resistance against corrosion.
- E-Glass is the most used type of glass fibers and it is suitable for cost sensitive applications.
- As a reinforcement they have high strength and resistance against chemicals [6].

Glass fibers have their own classification, and the types of glass reinforcement is given in the figure below;

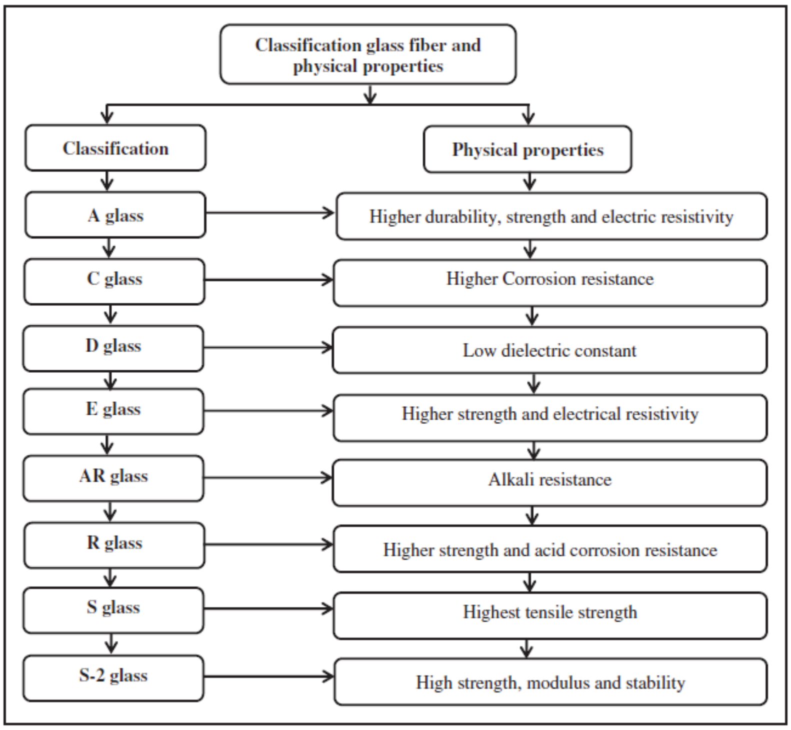


Figure 6. Classification of Glass Fiber Reinforcements [7]

As seen above, there are several types of glass fibers and each type has different mechanical properties. Differences between mechanical properties of glass fibers can be seen in the table below.

Fiber	Density (g/cm^3)	Tensile strength GPa	Young's modulus (GPa)	Elongation (%)
E-glass	2.58	3.445	72.3	4.8
C-glass	2.52	3.310	68.9	4.8
S_2-glass	2.46	4.890	86.9	5.7
A-glass	2.44	3.310	68.9	4.8
D-glass	2.11–2.14	2.415	51.7	4.6
R-glass	2.54	4.135	85.5	4.8
EGR-glass	2.72	3.445	80.3	4.8
AR glass	2.70	3.241	73.1	4.4

Figure 7. Physical and Mechanical Properties of Different Glass Fiber Reinforcement Types [7]

When the mechanical properties above are analyzed, it is clear that S2-Glass fiber type has the highest strength, modulus, and elongation values. These advantages make S2-Glass suitable for ballistic applications and it is generally used with phenolic resin for ballistics. S2-Glass fiber reinforced composites may be used as backing plate with ceramic tiles and also, they are used as spall liner behind the main body of the armored vehicles.

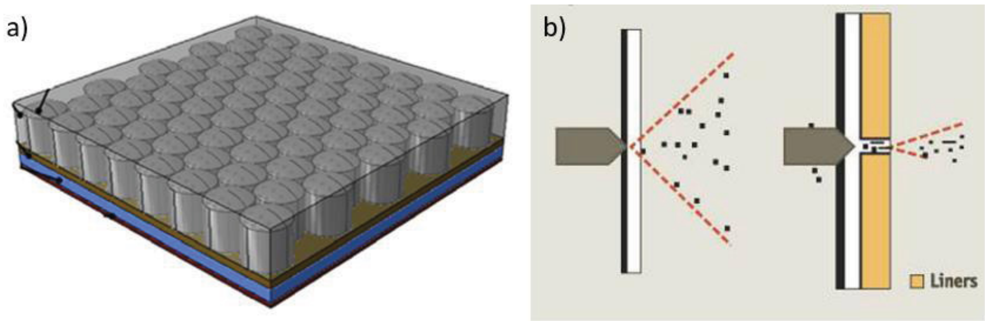


Figure 8. Composite Structures a) Backing Layer b) Spall Liner [8]

Another widely used type of glass fibers is E-Glass fiber. They are found basically for the applications in which electrical resistance is required. However, when the strength and modulus of E-Glass are measured it is seen that they are also suitable for structural applications. Due to the cost advantage, E-Glass fiber reinforcement is one of the most suitable reinforcement type for cost sensitive industries as automotive and marine.

2.2.2. Carbon Fibers

Carbon fibers are lightweight advanced fiber types with high strength and elastic modulus properties. They are thin and lighter fiber types when compared to glass fibers and also, they have higher mechanical properties than glass fibers. In addition to high mechanical properties carbon fibers have some other advantages as follows.

- Carbon fibers have high specific strength at room temperature, and they can keep their mechanical properties at elevated temperatures.
- At room temperature, carbon fibers have high resistance against moisture and chemicals.
- Carbon fibers have variety of mechanical properties of specific engineering applications [6]

Carbon fibers are generally used for aerospace applications due to their high load bearing capacity and they are suitable for high pressure vessels. In the last decade carbon fibers are started to be used for sporting goods as bicycles due to the need of lightweight in this industry.

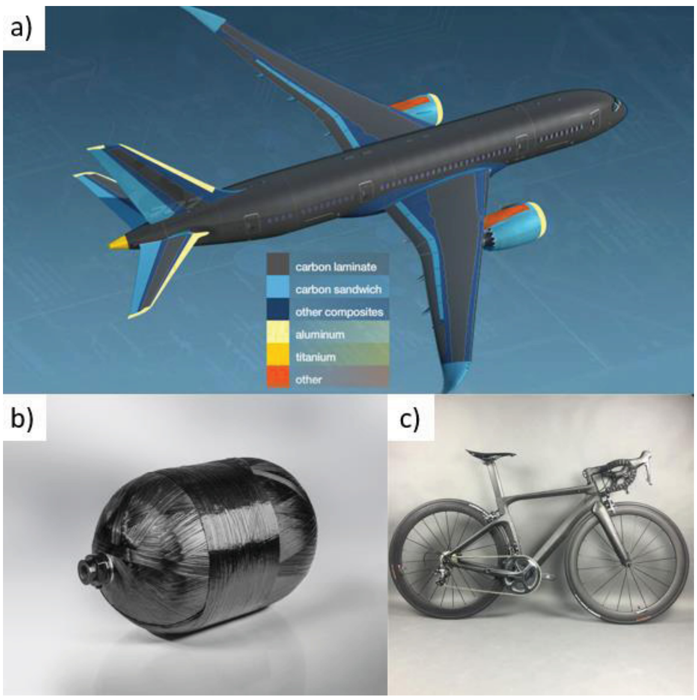


Figure 9. Carbon Fiber Reinforcement a) Airplane Parts b) Pressure Vessels c) Sporting Goods

2.2.3. Aramid Fibers

Aramid fibers are one of the most used type of reinforcements with high modulus and strength. Aramid fibers are organic fibers and due to the existence of amide groups in their chemical structures, they are named as high strength fibers. Aramids provide several advantages for the applications in which they are used [6].

- Aramid fibers have lower density compared to glass and carbon fibers
- By means of high fracture toughness and elasticity properties, aramid fibers have high resistance against impact loads.
- Aramid fibers are flame retardant.

In the industry due to their high strength and modulus properties, aramid fibers are generally used for rope and net manufacturing. Besides, having high fracture toughness provides aramids to have high energy absorbing capacity. This makes aramid fibers suitable for ballistic applications. As S2-Glass fibers they are used as backing plate in ceramic composite lightweight armor systems and spall liner behind the main body of armored vehicles (Figure 10). Since aramids have lower density, they provide high mobility for armor systems. So, they are also used for personal protection (helmets, body armor).

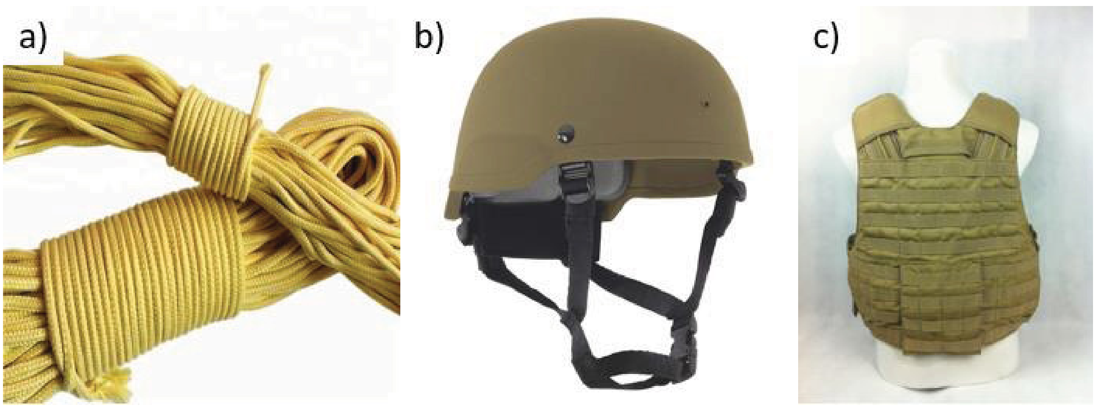


Figure 10. Aramid Fibers as a) Rope b) Helmet c) Personal Body Armor

2.2.4. Polyethylene Fibers

Similar to the aramid fibers, polyethylene is also an organic fiber type and polyethylene fiber is famous with its lightweight property. Its density is even smaller than water (0,88 g/cm³). Besides polyethylene is widely used due to its high strength [3]. The most known type is ultra-high molecular weight polyethylene fiber (UHMWPE) which is popular for ballistic applications. In addition to its lightweight some other advantages of polyethylene fibers are;

- By means of its elasticity, polyethylene has high resistance against impact loading.
- Mechanical properties of polyethylene are barely affected by erosion and abrasion.
- They have high resistance against chemicals.
- At room temperatures, polyethylene has high strength and modulus.
- Energy absorbing capacity is the highest one among other synthetic fibers.

The most known drawback of polyethylene fiber is that the mechanical properties are significantly affected by temperature. As the temperature increases, mechanical properties of polyethylene decreases since the melting and glass transition temperature of the material is low. Also, polyethylene fiber is not suitable for cost sensitive applications due to its high cost.

The resistance against abrasion and high strength make them suitable for rope and net manufacturing as aramid fibers. They are also suitable for ballistic applications by means of their high energy absorbing capability. With the difference of aramid fibers polyethylene is mostly preferred for personal body armors and is used as spall liner in helicopters.

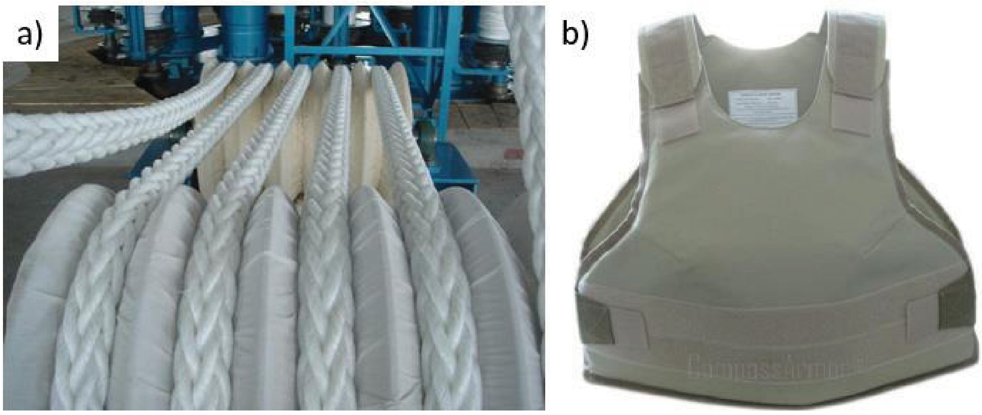


Figure 11. UHMWPE as a) Rope b) Personal Body Armor

2.3. Matrix Phase

In fiber reinforced polymer composites, matrix phase has several responsibilities. First, matrix (resin) covers the reinforcement and provides the transmission of the load applied between fibers. Meanwhile small portion of the load is carried by resin. Another task of resin is to protect fibers against factors as abrasion, friction, or corrosion. This type of interactions may cause micro or macro cracks on fibers and eventually failure before expected. Matrices also fill blanks between fibers and prevent the motion of brittle cracks between fibers. As a result, they increase the toughness of the composite system [6].

Adhesion bonding between fiber and resin is vital for mechanical properties of composite structure. In structural applications to prevent the failure caused by fiber pull-out, interface between fiber and resin should be strong. This adhesion is related with surface energy of fiber and resin. There are different types of polymer matrix materials for different types of fibers.

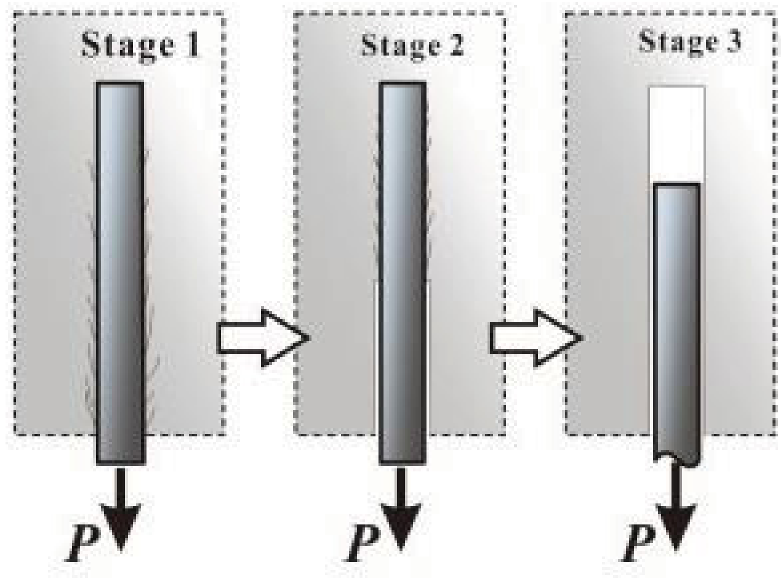


Figure 12. Fiber Pull-Out Deformation

2.3.1. Thermoplastic Polymers

Polymers are the combination of constituents named as monomers. When monomers are bonded by an electrical bonding type "Van Der Waals" thermoplastic polymer is formed. Van der Waals is a weak bonding type and allows the thermoplastic softens when heated and be reshaped [6]. This is the most popular characteristics of thermoplastics.

The most known thermoplastic materials and their basic properties are given below.

- *Polyurethane:* PU matrices have high resistance against chemicals and impact strength at room temperature. They are mostly preferred for automotive industry and used for gear knob and instrument panel manufacturing. They are also may be used as matrix for polyethylene fiber in ballistic applications due to their high impact strength.
- *Polyethylene:* PE is one of the most manufactured plastic types in a year. There are different types of polyethylene with low and high density and by means of its variety it is ideal for wide range of applications. While low density polyethylene is used for low strength applications, high density polyethylene may be used as fiber in ballistic applications.
- *Polypropylene:* PP is composed of propylene monomers and it is widely used for composite manufacturing. It is used for textile industry and for manufacturing of specific structures as living hinge. In composite manufacturing PP is generally used with aramid fabrics for ballistic applications.

2.3.2. Thermoset Polymers

Thermosets are also polymer materials as thermoplastics. The difference between these two types of polymers is the bonding type of monomers. In thermoset polymers, monomers are bonded each other with a chemical bonding type called as “cross-linking”. Since it is chemical bonding it is much stronger than electrical Van der Waals bonding. Fraction of cross-linking is harder so that is why thermoset polymers are not able to be reshaped by heating after curing is completed. Thermoset polymers have more brittle structure and much higher strength than thermoplastic polymers. Due to their high strength they are mostly preferred for composite manufacturing [6].

- *Epoxy:* Epoxy is the most known type of thermoset polymers. In the industry epoxy-based adhesives are used often. Epoxies can also be used as resin for composite manufacturing. They are preferred with carbon fibers for aerospace applications by means of high strength and high resistance against elevated temperatures.

- *Polyester:* Automotive is cost-sensitive industry and since polyester is much cheaper than epoxy it becomes and ideal resin type for the industry. Since the surface energy is suitable with polyester resins, glass fibers are generally used for manufacturing of vehicle parts.
- *Phenolic:* For some applications toughness is an important parameter. Phenolic is tougher resin type when compared to epoxy and polyester resins. The high toughness and cost advantages make phenolic resin ideal for ballistic applications. They are generally used with S2-Glass and Aramid fiber types. The only disadvantage of phenolic resin is to release toxic gas during curing process at high temperatures. This necessitate extra precautions for composite manufacturing.

2.4. Composite Manufacturing Techniques

As mentioned above, there are different suitable matrix types for each different fiber types. For manufacturing with these fibers and resin materials, several techniques are available to be used. Techniques are preferred according to the strength, surface quality, fiber/resin ratio etc. requirements in the application. The process that is followed is generally based on the resin curing cycle in these manufacturing methods.

2.4.1. Hand Lay-Up Method

Hand lay-up is mostly used type of techniques for thermoset resin composite manufacturing. In this method dry fabrics or layers are laid down one by one and after stacking is finished resin is applied to the dry fabrics. Resin application may be done with the aid of vacuum. After stacking, dry fabrics are covered by vacuum bag and there are two pipes in the system. One of them is connected to the machine which takes the air of the system and the other one relates to the resin so meanwhile resin is applied to the fabrics. After the application is done, curing process takes place. This type of hand lay-up method is called as *"Vacuum Infusion Method"*. Vacuum is also used for the pressure applied on the fabrics.

Another hand lay-up method is done by resin impregnation to the dry fabric layers one by one during stacking. Layers are cut to a desired dimensions and resin is impregnated by a roll to the fabrics and then wet layers are stacked on each other. After the process, the system is covered by vacuum bag and after a while resin curing completes.

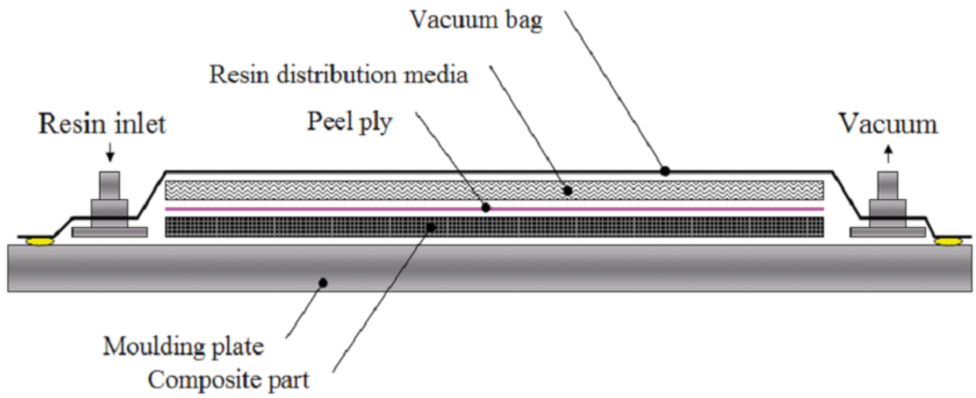


Figure 13. Vacuum Infusion Method [9]

Curing may be done by pressing the fabric layers instead of vacuum. This hand lay-up technique is named as *"Wet Lay-Up Method"*.

2.4.2. Open Molding Method

Open molding method is a cheap and fast manufacturing technique that is done in one side mold. In automotive industry for the vehicle parts (mostly outer parts) this method is used often. The most known type of open mold method is *"Spray-Up Method"*.

In spray-up technique resin and fibers are taken from different containers and combined at the tip of spray gun. Before the application, a separator is applied to inside of the mold. According to the requirement before fibers and resin, gelcoat may be applied and after gel-coat is cured resin and additives are sprayed inside the mold. After the curing of resin, the part is separated from the mold and manufacturing is completed. As reinforcement chopped glass fibers and as matrix polyester resin is preferred mostly for this type of application. The technique is preferred for many applications in which high strength is not required due to the cost and time advantages [10].

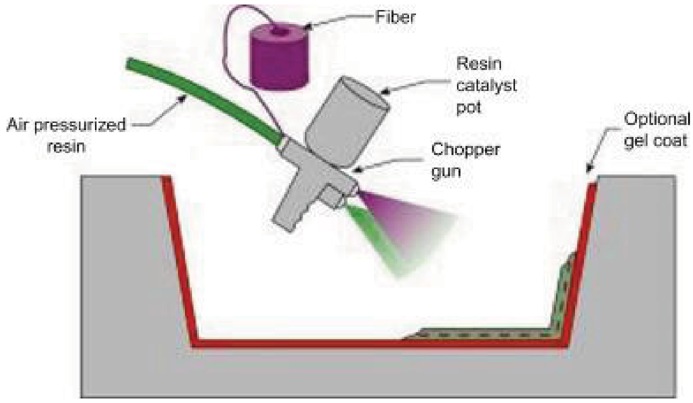


Figure 14. Spray-Up Method [10]

2.4.3. Resin Transfer Molding (RTM)

To produce relatively complex geometries with continuous fibers, resin transfer molding (RTM) method may be used. The difference between open molding and RTM methods, in RTM closed mold with two sides is used. Inside of the mold is machined to the desired geometry of the composite part. Since machining process is needed for the mold, metals are generally preferred as a mold material. Dry fabrics are placed in the mold and two sides are closed on the dry fabric layers. Resin is transferred by pipes placed on the top and bottom sides of mold parts and the curing process takes place after the pressure is arranged [11]. In this method, since the resin flow is vital, resin materials with low viscosity are generally used. High viscosity resins may not be sufficient to obtain desired adhesion bonding between fibers and resin. This would cause significant drop in mechanical properties of composite material.

Parts with high strength and surface quality may be obtained and since high pressure and temperatures are not required, the method is cheaper than autoclave method.

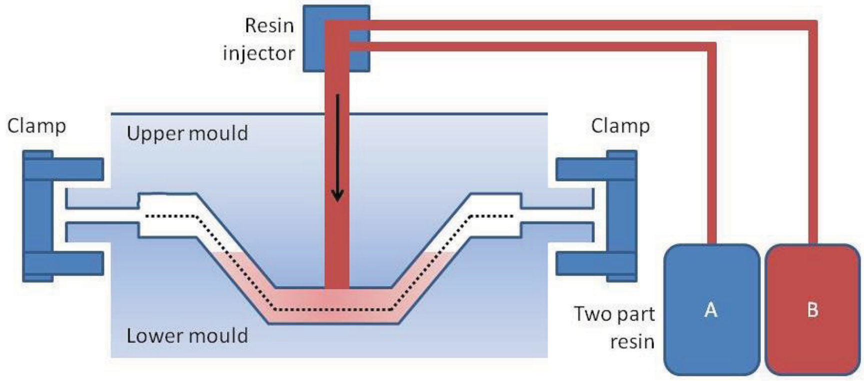


Figure 15. Resin Transfer Molding Method (RTM)

2.4.4. Prepreg Method

Prepreg name is derived from pre-impregnated term and as it is deduced from the term, manufacturing is carried out by using the fabrics on which resin is already impregnated. As a result, high strength, surface quality and fiber volume content composite structures may be obtained. Resin impregnated fabrics are stacked on each other and curing process is applied under high pressure and temperature. For the high pressure and temperature basically, there are two options. One of them is *"hot press"*. Stacked fabrics are pressed in a machine and heat is applied at the same time in this method. In *"autoclave"* method as in hot press high temperature and pressure are applied but besides fabrics are covered by vacuum bag. In this method surface quality is better and fiber volume ratio may be approximately 3-4% higher than hot press. Compared to hot press, autoclave becomes more expensive solution due to the special equipment is needed like autoclave oven and vacuum system.

Prepreg method is not suitable for cost sensitive applications because compared to other methods, composite fabrics should be stored at special conditions. Refrigerators are used for storage to prevent the curing of resin at room temperature. This increases the cost of the technique with the manufacturing equipment.

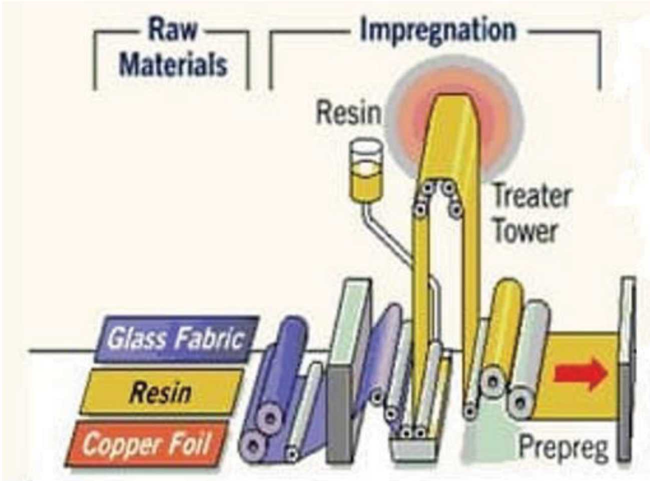


Figure 16. Prepreg Forming Process

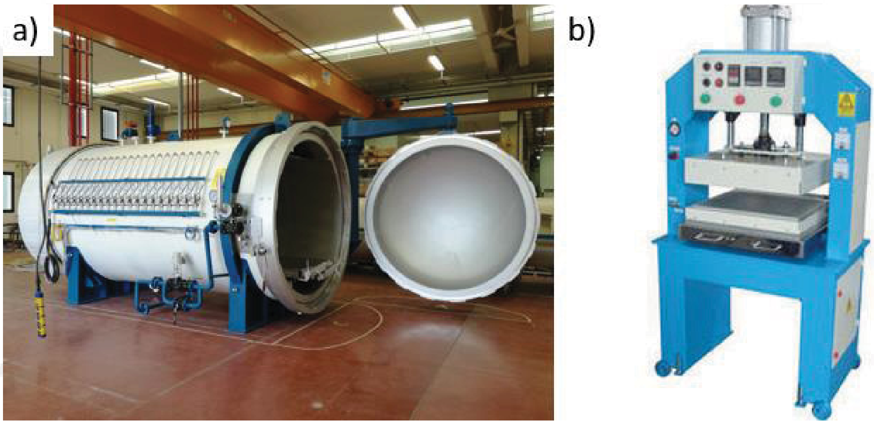


Figure 17. Prepreg Manufacturing a) Autoclave b) Hot Press

2.4.5. Filament Winding Technique

Filament winding method is used to manufacture continuous fiber reinforced cylindrical composite structures. It is used for composite pipes and high-pressure vessel manufacturing in the industry. In manufacturing process, a mandrel which is placed horizontally is rotating. During this rotation filaments (reinforcement) that is impregnated by resin in resin bath is wrapped on the mandrel by the apparatus at the end of the machine. This apparatus is also able to rotate. In this way winding angle may be arranged based on the requirements. During the last decade due to corrosion problem of metal pipes for gas and liquid carrying, composite pipes become more popular since they have higher resistance against corrosion and they are durable. Manufacturing of these pipes are generally done by using glass fiber reinforcements by means of their cost advantage. For the aerospace applications high strength carbon fiber reinforced high-pressure vessels are being manufactured by this technique.

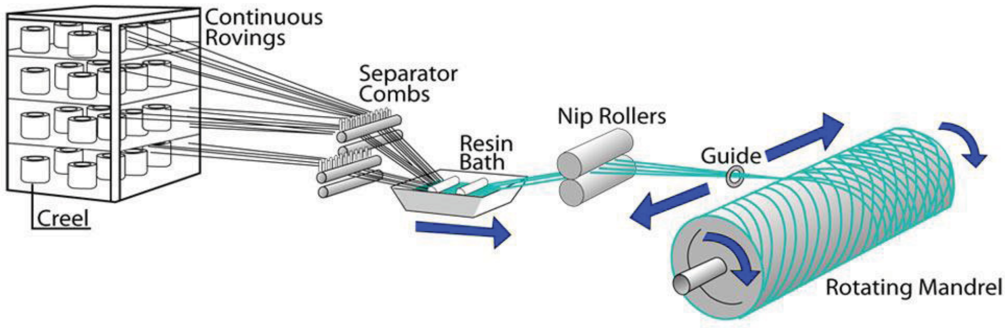


Figure 18. Filament Winding Manufacturing Process [12]

2.4.6. Pultrusion and Extrusion Methods

For the manufacturing of composites having constant cross section, pultrusion and extrusion techniques are generally used [6]. In pultrusion method, continuous fibers are taken by a tension from the source to the resin bath. After resin impregnation fibers are pulled to a die whose inside is machined to the desired geometry. Heat is applied to the resin impregnated fibers to provide resin curing. After curing composite structure exists from the die and by the cutting device outside, composites may be cut to the desired dimension.

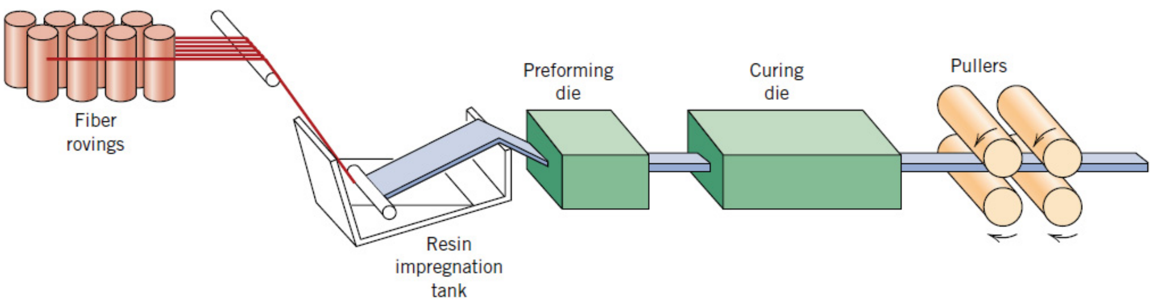


Figure 19. Pultrusion Process Flow Chart [6]

In extrusion method, different from pultrusion, materials are not pulled but pushed. There is a big screw inside the mold and the mold is connected with the die. There is a tank on the mold in which composite components are stored and components are taken to the mold. Inside the mold heat is applied to the thermoplastic materials. By the help of screw rotation materials move forward to the die. Due to the heat thermoplastic materials are softened and inside the die cooling process takes place. After curing thermoplastic composites exists from the die and by cutting device composites are cut to the desired dimension.

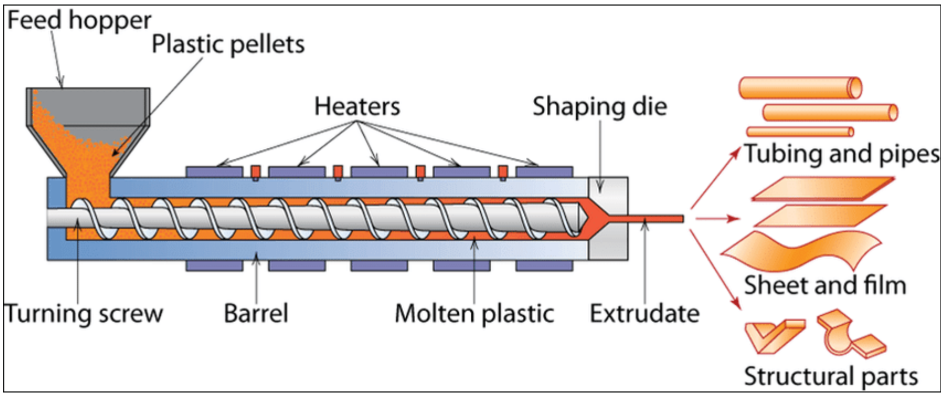


Figure 20. Extrusion Process Flow Chart [13]

CHAPTER 3

BALLISTIC SCIENCE AND BALLISTIC BEHAVIOR OF MATERIALS

Ballistic is one of the fields of science which studies the behavior of a thread/bullet inside the barrel, in the air after getting out the barrel and on the target during the impact event. The name “Ballistic” is derived from a catapult system which was used during the middle age wars, for soldiers to get inside the castle and to harm the structures. The system is called as “Ballista” (Figure 21). Rocks, huge arrows and such objects were thrown to the counter side with Ballista systems and to strike aimed region behavior of the object had to be calculated. Based on these calculations, position of catapults was arranged. These calculations are the keystone for modern ballistic applications.

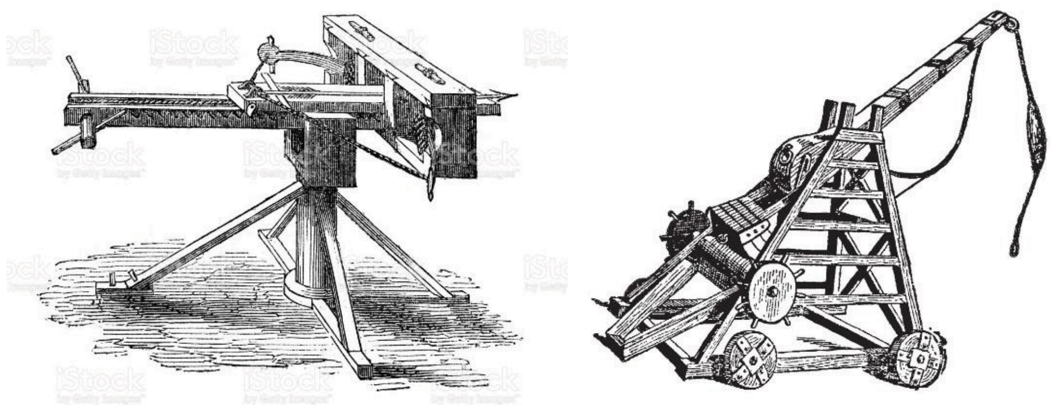


Figure 21. Ballista Systems

As stated above ballistic studies the bullet inside the barrel, in the air and on the target. On this basis ballistic is divided into three groups which are;

- Interior Ballistic
- Exterior Ballistic
- Terminal Ballistic

3.1. Interior Ballistic

Interior ballistic investigates the parameters as the propellant pressure, acceleration and the exit velocity of the bullet and backlash of the gun from the firing pin hits the fuse to the bullet exit from the barrel [14]

When the firing pin hits the fuse, a component placed in the fuse generates an explosion which causes elevated temperatures. Flames occurred as a result of this explosion reaches the powder and due to the high temperatures powder starts burning. During this burning issue, high pressure gas is occurred. Since the gas with high pressure is not able to get out from the side walls of the barrel, it pushes the bullet forward and causes the bullet exit from the barrel (Figure 22).

Normally, powder burns slowly and kindly. However as stated above, in kinetic energy threats the core of the bullet is confined by a cartridge and the cartridge is surrounded by the barrel. These obstacles make the gas stuck in the cartridge and as a result the temperature and the pressure increase exponentially. When the energy of the gas reaches the inertia of the bullet, the bullet starts to move and finally it exits the barrel with high velocities. The exit of the bullet causes the backlash of the gun. The more weight of the bullet would cause harder backlash of the gun.

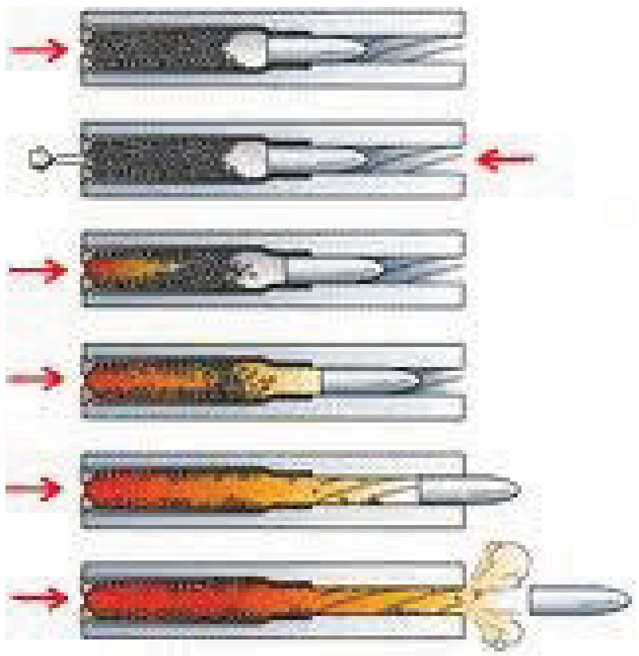


Figure 22. Firing System of a Bullet

3.2. Exterior Ballistic

Exterior ballistic is a field of ballistic which investigates the behavior of the bullet inside the air from the barrel to the target. During the fly, bullet is not affected by the side effects as in the barrel and behaves like a free body. Because of this, the behavior of the bullet is much more complicated than the behavior inside the barred and detailed mathematical calculations are required to measure the approximate route of the bullet.

Basically, there are two main factors that affects the bullet behavior during the fly. The air resistance at the tip of the bullet is one these parameters and the other one is the gravity. These two parameters cause the bullet to slow down and move downward during the fly [14]. Assuming the bullet as a point in a vacuumed environment is the simplest case for the exterior ballistic calculations. In this case the only factor that could affect the behavior of the bullet in the air is gravity. When the bullet is taken account with its own geometry instead of as a point mass of the bullet and the air resistance which depends on the geometry of the bullet become parameters that should be taken in consideration.

Consequently, parameters listed below are needed to calculate the bullet motion in the air.

- Influence of gravity
- Muzzle velocity
- Angle of the barrel
- Bullet geometry
- Sectional density (Ratio of core diameter to the weight)

Figure 23. Exterior Ballistic (Bullet Path in the Air) [15]

3.3. Terminal Ballistic

Terminal ballistic is the study of the penetration behavior of a bullet on the solid or liquid target [14]. This field of ballistic science studies the behavior of the bullet at the moment that it hits the target and how energy of the bullet is transferred to the target. Terminal ballistic is divided into two categories as penetration potential and wound ballistic. While the penetration potential studies the penetration ability of the bullet on different types of target materials, wound ballistic studies the effect of the bullet on the living tissue.

3.3.1. Wound Ballistic

Wound ballistic investigates impact and effects of a bullet on a living tissue. During wounding of a living tissue, three mechanisms takes place to absorb the kinetic energy of the bullet which are laceration and crushing, shock waves and cavitation [16]. Threshold velocity for penetration of a living tissue is around 40-60 m/s. When the muzzle velocity of a bullet is considered (700-800 m/s) penetration of the tissue would not be a challenge for the bullet. When penetration starts to proceed, kinetic energy of the bullet is transferred to the adjacent tissues by the shock waves and due to the movement of these tissues a hole named temporary cavity is occurred. Since shock waves push adjacent tissues away, diameter of the temporary cavity is larger than bullet core diameter. The reason why the cavity is temporary is elastic characteristics of the tissues. Due to the elasticity, the cavity reverts back, and the hole is going to be healed after a while. Length of temporary cavity is short. It starts from the region where penetration begins and gradually diameter of the cavity tightens. After a while diameter of the cavity become stable since the kinetic energy of the bullet decreases. In addition to temporary cavity, permanent cavity is also occurred due to the bullet's own destruction during penetration incident [14]. Generally, diameter of permanent cavity is close to bullet core diameter. In some cases, it might be larger than bullet core diameter but it always smaller than temporary cavity diameter (Figure 24)

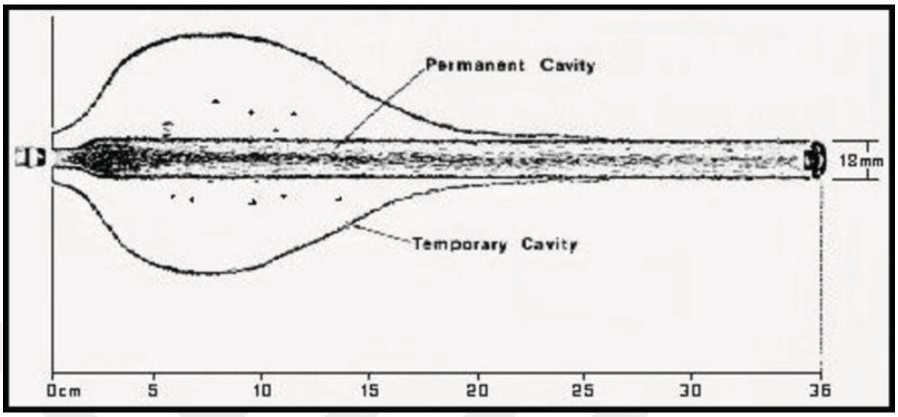


Figure 24. Temporary and Permanent Cavity [17]

Diameter of the cavities explained above depend on the geometry, weight and width of the bullet. In cases of bullets with hypervelocity, tissues show explosive motion towards adjacent tissues and gigantic temporary cavities are occurred. Since the diameter of the cavities are large, in such cases, vital tissues or bones might be damaged. In addition, when the penetration starts and the kinetic energy is transferred, adjacent tissues at the entrance tend to spread to the gap. This is called as back-leaping where the impact takes place.

3.3.2. Penetration Potential

Penetration characteristics of different types of materials contribute substantially to the investigation of shooting incidents. In the past, shooting on pine boards with different thicknesses were used to measure the penetration performance of a bullet. However, there were many factors that might affect the results to deviate from accuracy. Moisture, knot content, age of wood are some examples for these factors, and these might cause also low precision results [14].

Nowadays, different methods are used to calculate the performance of a bullet. One of them is the comparison of penetration speeds on living tissue and the other one is the depth of penetration of bullets on steel materials. Based on the caliber, bullets have different effects on target materials. Energy absorbing mechanisms of target materials change with the type of the material. Since in armor systems, steel, ceramic and fiber reinforced polymers are generally preferred, penetration mechanisms of these materials are explained in the following section.

3.4. Impact Behavior of Materials

3.4.1. Steel

Steel is one of the most used metal types for ballistic applications. In case of a threat shaped like rod hits a steel plate if target is softer than threat penetration occurs by homogeneous plastic flow. After penetration, there might be a little or no deformation is observed on the rod (threat). When hardened steel (armor steel) is used as target there will be shear zone at the impact region. At the back face of the target bulge is observed and due to the shear plug, piece of steel is broken off and penetration takes place. During the penetration incident, due to the tension load which transferred from the impact point to the adjacent regions, spalls are occurred and spread to the surrounding. This provides target to spread the kinetic energy of threat.

As a result, there are three main deformation mechanisms during penetration of steel. These are plastic deformation, shear plug and tensile fracture.

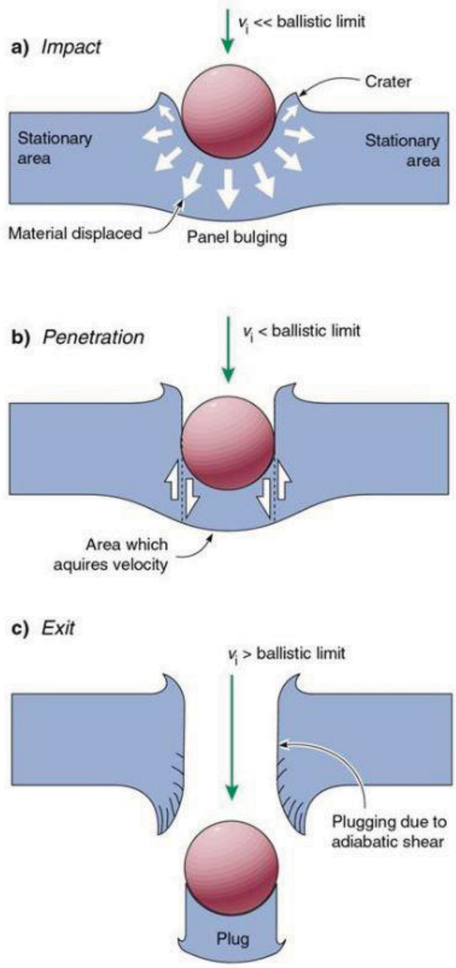


Figure 25. Steel Penetration Mechanisms [18]

3.4.2. Ceramic

Ceramics are harder and more brittle materials compared to other ballistic materials. Ceramic material penetration is basically based on fracture at the impact region and spread of ceramic particles. In researches of ceramic penetration mechanisms, it is observed that after the fracture takes place it proceeds in radial and thickness direction. This is called as Hertzian Cone Cracks. When deformed ceramics are analyzed, intergranular/intragranular micro and macrocracks, shear zones, dislocations and phase transformations are observed as penetration mechanisms. During the penetration due to the high hardness characteristics of ceramics during the penetration event, fracture and other deformations are observed on the threat also.

There are several factors that affect the impact behavior of ceramics. Porosity, manufacturing technique and ceramic type are some examples of these factors. One of the most important factors is confinement of ceramic blocks. Charles et. al. [19] studied the effect of confinement of ceramics on ballistic impact properties. Three different types of confinement were used for the study. In one of tests, bare ceramic tile was used. RHA steel was used behind ceramics to measure the depth of penetration for comparison of confinements. First confinement was applied to ceramic tile radially. In second one ceramic tile was confined radially and there was a steel plate on the ceramic also. In the third and the last one there were two steel plates on the ceramic tile (Figure 26)

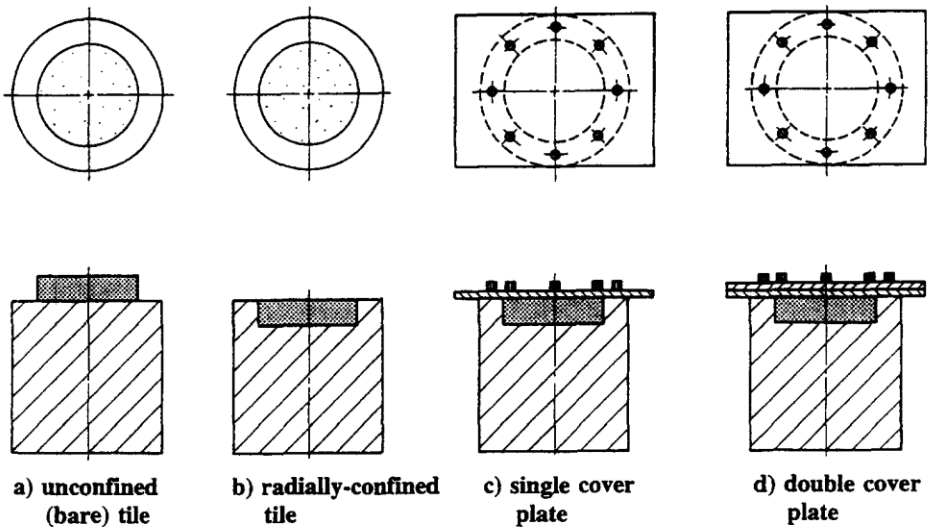


Figure 26. Confinement of Ceramic Tiles [19]

Before ballistic tests on ceramic tiles, depth of penetration (DOP) was measured on RHA steel as reference value. After reference DOP measurements confined ceramics were placed in front of RHA steel and ballistic tests were carried out. Residual DOP values were measured to analyze which confinement method is better for ceramic tiles. As a result, it was observed that confinement of ceramic tiles increases their ballistic performance when compared to bare ceramic tile. It was found that ballistic performance of ceramic tile depends on the cover plate thickness. From the analysis it was said that after an optimum thickness of cover plate performance of ceramics decreases.

The reason of confined ceramic shows better ballistic performance than bare ceramic might be as the ceramic becomes powder its compression properties increases. In confinement, ceramics are not able to spread to the surrounding as much as bare ceramics, so resistance of ceramic tile to the threat increases.

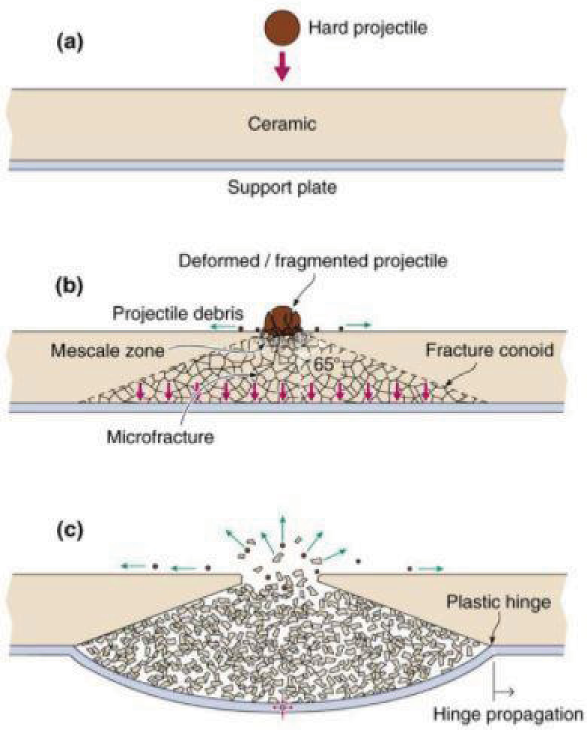


Figure 27. Ceramic Penetration Mechanisms [18]

3.4.3. Fiber Reinforced Polymer Composites

Material response of composite structures during an impact event can be analyzed in two main titles which are global and local response. Distribution of local and global response during impact depends on several factors like geometry and impact speed of threat. Among these factors impact speed of threat is the most important parameter for the distribution of two material responses. The main difference between two responses is global response depends on parameters as target geometry and dimensions while local response does not depend on such kind of factors (Figure 28) [20].

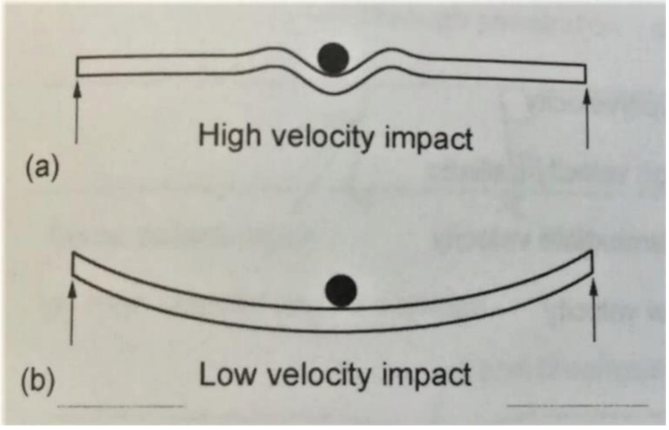


Figure 28. Material Responses a) Local Response b) Global Response [20]

In low speed impacts it is more likely to observe global response. As the impact speed increases global response gives its place to local response. As it is seen in Figure 8 in global response, composite structure bends as quasi-static load is applied on it while in local response more complicated deformation mechanisms like shear plugging, delamination, fiber/matrix cracking might be observed. In local response dominant deformation mechanism depends on the fiber/matrix type, panel thickness and threat type.

3.4.3.1. Global Response

Global energy absorbing mechanism is generally observed in low speed impact events. In such cases, there is enough time for kinetic energy to spread to large area in composite structure. During impact, elastic waves occurred by shear and flexural loads and expand to the borders inside the material. Elastic waves are combination of longitudinal and transverse strain waves. Longitudinal strain waves move in plane direction by stretching the yarns. Meanwhile transverse strain waves move along the thickness direction and a cone formation occurs which would cause bulge in the back face of composite in further steps. However, since the longitudinal waves are faster than transverse waves, cone formation is smaller than the deformation occurred in plane direction and bending is observed as a resulting response. These strain waves continue until the kinetic energy of threat is fully absorbed or perforation occurs. Global response is generally observed under 100 m/s impact events [20].

3.4.3.2. Local Response

As the impact speed of the threat increases local material response takes place instead of global response. Unlike global response, local response consists of several different deformation mechanisms. Deformation mechanisms of fiber reinforced polymer composites in local response are more complicated than steel and ceramic materials. The reason is fiber reinforced composites do not have same properties in every direction, in other words they are no isotropic materials. Composite structures would absorb the kinetic energy of a threat by bending due to the presence of fibers instead of spreading the kinetic energy by fracture like ceramics. With regards to this characteristic, fiber reinforced composites are generally used as a backing plate with ceramic tiles or as a spall liner behind the hull structure of armored vehicles.

During the impact event of composite structures fibers are divided into two groups: primary and secondary yarns. The region which is equal to the diameter of the threat is called region 1 and the rest is called region 2 (Figure 29) [21].

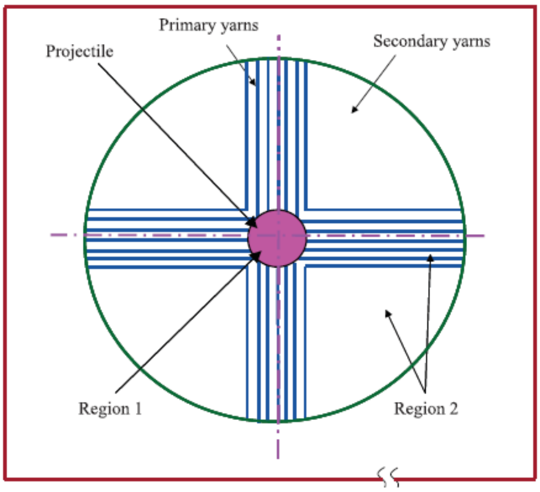


Figure 29. Fiber Groups and Regions During Impact of Composites [21]

As the penetration starts, compression load is applied to the primary yarns first. This compression load is transferred to the layers until it reaches to the back face of composite plate, then the load turns back as tension. When the tension and compression loads encounter shear force occurs. That kind of shear load causes fiber breakage. This fiber breakage will cause shear plug in further steps of impact. Meantime the load is transferred to the secondary yarns by matrix cracking. Matrix cracking can be occurred by three ways. One of them is due to transverse shear loads. Transverse shear load provides matrix cracking by moves along the fiber direction. Second one is matrix cracking by bending load. This type of load is formed at back side of composite structure and caused by in-plane tension loads. The last one is load transfer from primary yarns to secondary yarns layer by layer. Regardless of source, matrix cracking leads to delamination. Delamination is failure of bonding between fiber and matrix and provides the yarns to transmit the kinetic energy to adjacent yarns. Transfer of load from primary yarns to secondary yarns in one layer continues until the primary yarns in this layer fail. Due to the loads applied on composites during impact, mechanical properties of fibers are important for ballistic performance.

Delamination, consequently, matrix cracking, is the most important deformation mechanism of fiber reinforced composite structures. It provides the kinetic energy to be transferred to the secondary yarns and stretching of fibers. As a result of stretching, bulge is occurred at the back face of composite plate. In addition to the deformation mechanisms mentioned above, fiber friction is another mechanism. It takes place when the yarns fail and threat moves forward in hole occurred. Hence deformation/penetration mechanisms of fiber reinforced composites might be listed and shown as below [6].

- Compression
- Tension
- Fiber Breakage / Shear Plug
- Matrix Cracking / Delamination
- Fiber Friction

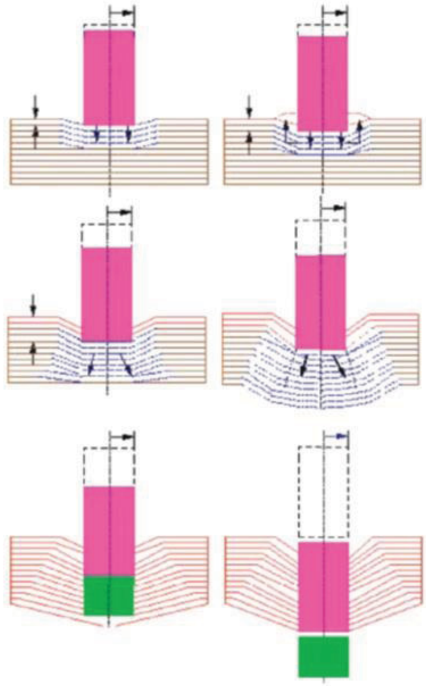


Figure 30. Fiber Reinforced Composites Penetration [21]

Sorting of deformation mechanisms during impact depends on fiber type and threat geometry. Normally shear plug is observed at last however, if brittle fibers are used in composite structure delamination takes place for a short time and shear plug is observed as a main deformation mechanism. For tougher fiber and matrix types kinetic energy of the threat is transmitted more easily. As a result, delamination takes place as a main deformation mechanism. When the delamination is the main mechanism, deformation area at the back face of composite plate would be large and bulge can be seen clearly.

3.5. Ballistic Performance of Composite Structures

Ballistic performance of fiber reinforced composite structures is affected by multiple factors.

3.5.1. Fiber/Resin Type

In ballistic applications, fibers with low density and high energy absorbing capacity are preferred. As stated above, delamination is the most important energy absorbing mechanism in composite structures. Delamination is directly affected by fiber and resin type.

The most used fiber types for ballistic applications are S-Glass, aramid and polyethylene fibers. S-Glass is one of types of glass fiber and the letter “S” means strength. Advantage of S-Glass on other glass fiber types is higher strength and elastic modulus characteristics. When compared with other ballistic fibers aramid and polyethylene, its density is higher, and it has more brittle structure. Compression and tension loads, fiber breakage and shear plug are the main deformation mechanisms for S-Glass fiber reinforced composites during impact. S-Glass fibers are generally used with thermoset resin materials. The other fiber type used with thermoset resins is aramid fiber. Aramid fibers are much lighter when compared to S-Glass fibers. Due to their elasticity, the main deformation mechanism of aramid fibers is matrix cracking, bending and delamination. Aramids are also known with their high friction characteristics between yarns. Due to their low density, aramids are preferred for personal protection as body armor and helmets. In addition to S-Glass and aramid fibers, polyethylene is also used for ballistics. Polyethylene fibers have lowest density among them, and they are generally used with thermoplastic resins like polyurethane and rubber. Highly elastic polyethylene fibers have much better ballistic performance than S-Glass and aramid fibers, however, polyethylene is the most expensive one. In ballistic applications ultra-high molecular weight polyethylene (UHMWPE) fibers are preferred. Since it has low density with high ballistic performance, polyethylene is also used for personal protection with aramids. The only disadvantage of UHMWPE fibers for personal protection is having a large bulge at the back face. This bulge might cause back face trauma and to prevent this hybridization with carbon fibers is used. Carbon fibers are used to provide more rigidity to the structure. In this way bulge might be reduced and back face trauma is prevented.

Resin type is also important for ballistic performance of composite structures. Thermoplastic resins are tougher than thermoset resins. More delamination might be observed in composites manufactured with thermoplastics. Among thermoset resins epoxy and phenolic are the most used types. Epoxy has higher strength and elastic modulus than phenolic, however, phenolic is tougher than epoxy. In impact events, toughness is more important than strength and therefore composite structures with phenolic resin show better ballistic performance. Phenolic resin has one disadvantage which is releasing a toxic gas under high temperatures. In autoclave and hot press manufacturing techniques if phenolic resin is about to be used, extra precautions are needed. Phenolic is mostly used with S-Glass and aramid fibers. Thermoplastic polymers are preferred for increasing delamination in composite structure. Delamination occurs by failure of bonding between fiber and matrix. If in-plane shear properties of composite is high then, failure of the bonding becomes harder. Thermoplastic resins are not able to bond fibers as good as thermoset resins. So, the bonding between them might fail easily and this will provide kinetic energy is transferred to the secondary yarns easier. Therefore, studies of composite structures with thermoplastic resin are also carried out.

3.5.2. Fiber Texture

In addition to fiber and resin type, in some cases texture also affects the ballistic properties of composites. The most basic texture types are unidirectional (UD) and woven (Figure 31).

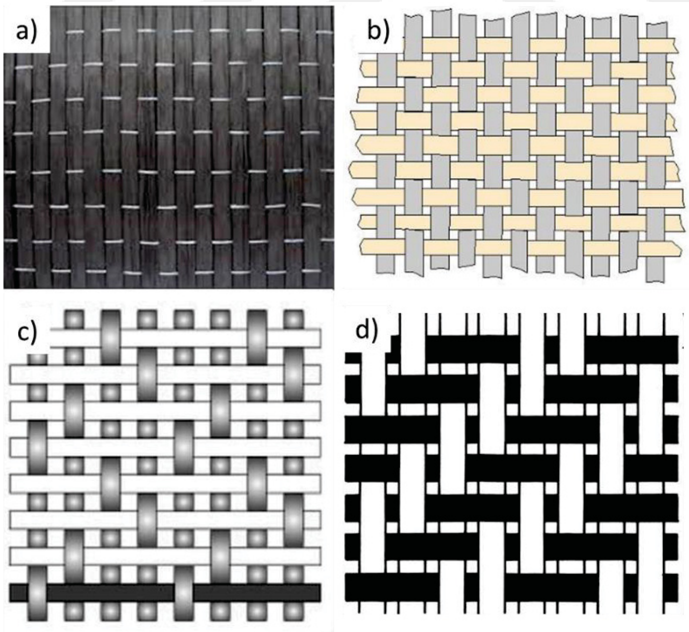


Figure 31. Knit Types a) UD b) Plain Weave c) Satin Weave d) Twill Weave

In some studies, unidirectional fiber reinforced composites are found to have better ballistic performance than woven fabric reinforced composites. As a reason it is said that UD composite structures have more capability to transmit kinetic energy to the secondary yarns. In woven composites knitting points might prevent the energy transfer and some part of energy turns back from these points [22]. However, there are studies in which woven composites have better ballistic performance due to the friction between fibers.

3.5.3. Threat Geometry and Impact Velocity

Geometry and impact speed of the threat are other factors that determine the ballistic impact behavior of fiber reinforced composite structures. In a study carried out with Kevlar composites, it is observed that kinetic energy of sharp tip threats is easier to be absorbed at low velocities [23]. At high impact velocities penetration performance of sharp tip threats increases. Sharp tip threats cause global response at low impact velocities, therefore it is easier to absorb kinetic energy for composite structure. However, blunt tip threats have a reverse situation. At low velocities, this type of threats is more effective.

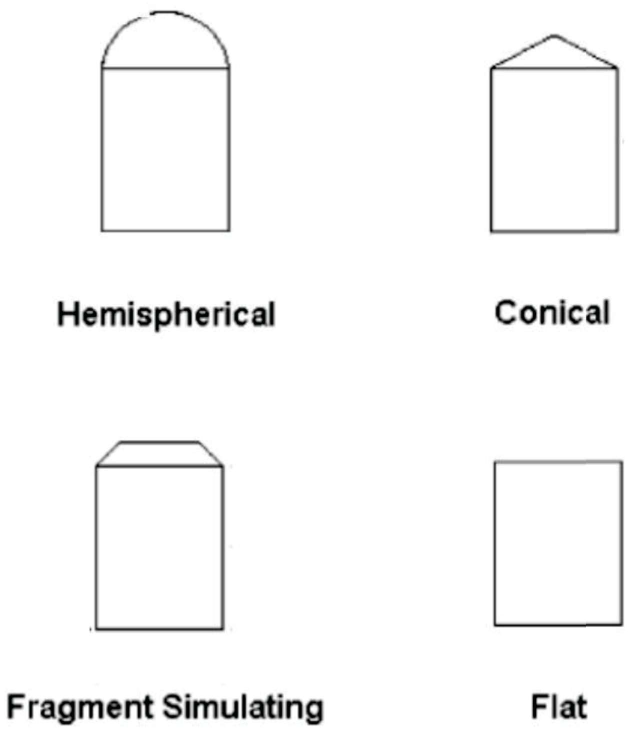


Figure 32. Threats with Different Geometries [24]

3.5.4. Target Thickness

Thickness affects the deformation mechanisms during impact event. For thin composite structures there is not enough time for kinetic energy to be transferred from primary yarns to secondary yarns, therefore delamination is not main deformation mechanism. In this case shear plug and fiber breakage are the main deformation mechanisms. As the composite plate become thicker, yarns have enough time to transfer kinetic energy to secondary yarns by matrix cracking and delamination. Hence more kinetic energy can be absorbed, and more bulge and delamination can be observed. Shear plug and fiber breakage become deformation mechanisms in background. In Figure 33 difference of deformation mechanisms between thin and thick composite plates are seen below.

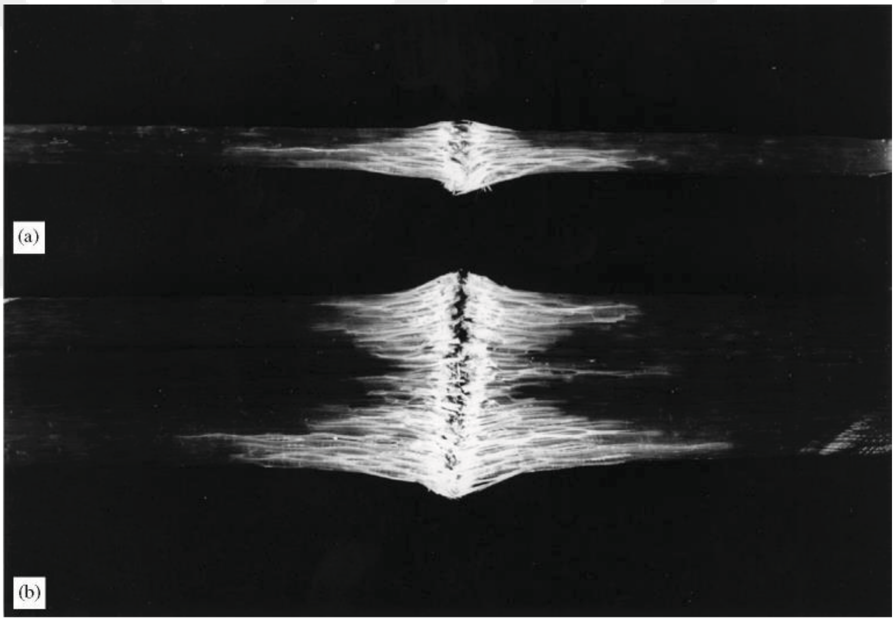


Figure 33. Thin and Thick Composites Deformation Mechanisms [25]

As stated above there are several factors which affect ballistic performance and deformation mechanisms of composite structures. For thin composite plates since deformation mechanisms are similar for all types, there would not a big difference in ballistic performance of composites. As an example, figure shown below is taken from a study in which effect of matrix material on ballistic performance is studied [26]. It is clear from the graph ballistic performance of epoxy resin aramid composites and polypropylene matrix aramid composites are similar. As the thickness increases, since the main deformation mechanisms change, the difference become clearer.

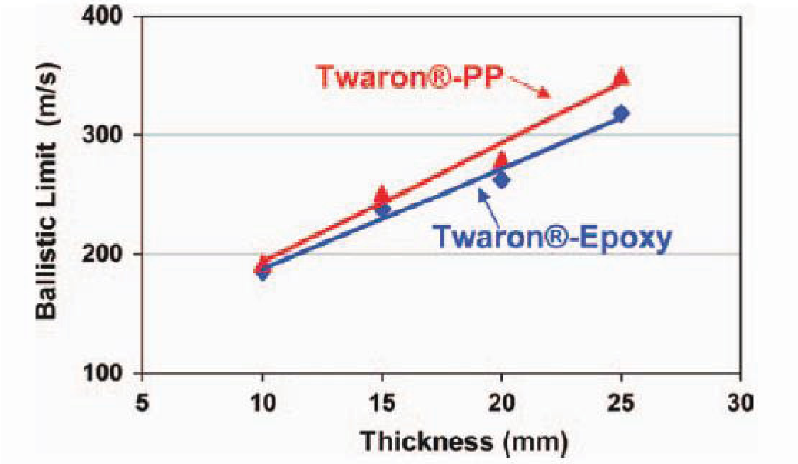


Figure 34. Effect of Matrix and Thickness on Ballistic Performance of Composite Structures [26]

Consequently, due to their low density, high energy absorbing capability and elasticity, composite structures become a suitable option for lightweight armor structures in ballistic applications.

3.6. Lightweight Armor Systems

For protection against low caliber threats metal, ceramic and fiber reinforced composites might be enough without any support. The hull structure of armored vehicles is generally steel or aluminum which provide protection against 7.62 mm or 5.56 mm caliber threats. For personal protection (body armor, helmets) ceramics or composite structures are preferred. However, for higher caliber threats these materials are generally used together. Ceramic and metal or ceramic and composite armor systems are the most known examples for lightweight armors.

In lightweight armor systems every component has its own task. Ceramics are used as a front layer due to their hardness. In this way when the bullet hits the armor, first it is faced with ceramic layer and bullet core is broken by ceramics and kinetic energy is spread to the surrounding. Then after bullet passes through ceramic structure, residual kinetic energy is absorbed by metal of fiber reinforced composite which is used as a backing layer. Composites are generally preferred as a backing layer since they have lower density than metals. This would decrease the areal density of total armor system and increase the mobility of armored vehicle. However, if the project is cost sensitive metals might be used instead of composites (Figure 35)

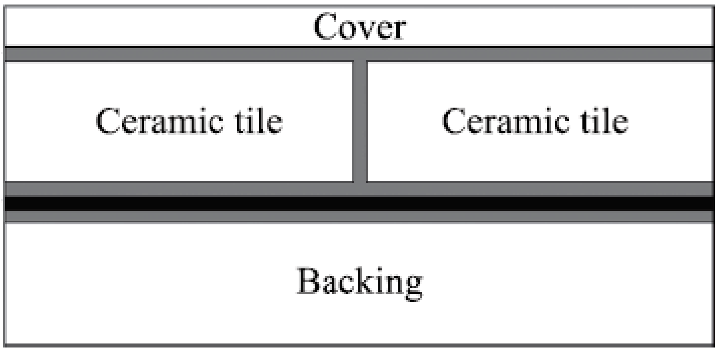


Figure 35. Ceramic Faced Lightweight Armor System [21]

As fiber reinforced composites aramid, glass and polyethylene fiber reinforced composites are mostly used. For ceramic layers, alumina (Al_2O_3) or silicon carbide (SiC) are the most popular types. Ceramic materials might be used as monolithic plate and tiles. Monolithic plates are better for kinetic energy absorbing however, when a bullet hits the plate micro and macro cracks are spread to the other sides of plate. So monolithic ceramic plates are not suitable for multi-hit applications. Ceramic tiles are smaller and can be manufactured in different geometries. In this case, there will be many ceramic tiles in whole armor system and if one them is hit by a bullet, fracture is transferred to the adjacent tiles. However other ceramic tiles do not take damage so the whole system becomes suitable for multi-hit applications. Disadvantage of ceramic tiles is having worse energy absorbing capability than monolithic ceramics. For the same type of bullet thicker ceramic tiles should be used. This makes the armor system to be heavier. Square and hexagonal geometries are mostly preferred geometries for ceramic tiles (Figure 36) [14].

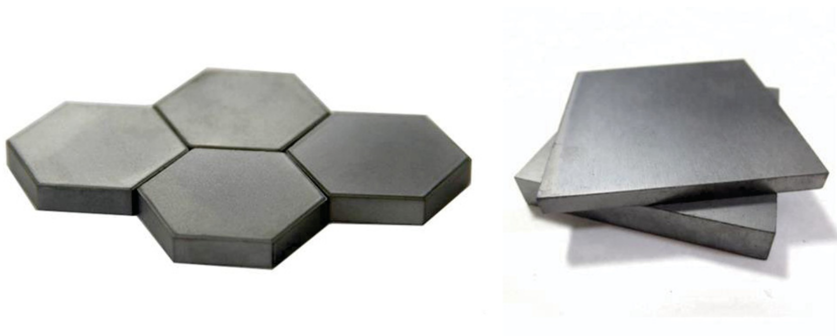


Figure 36. Hexagonal and Square Ceramic Tiles

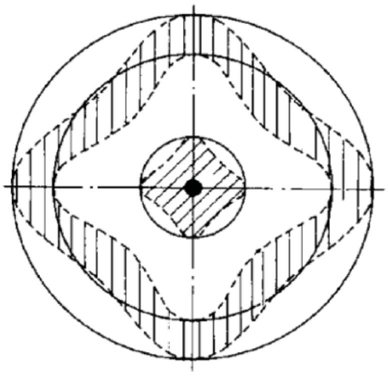
CHAPTER 4

LITERATURE SURVEY

High energy absorption performance and lightweight are the main requirements for ballistic applications [27]. Due to their fibrous structure and low density, fiber reinforced composite structures become more popular for vehicle and personal armor applications. As stated in Chapter 2 different types of fibers as glass, carbon, aramid or polyethylene are used with thermoset or thermoplastic matrix materials like epoxy, phenolic, vinyl ester, polyurethane or polyethylene.

4.1. Glass Fiber Studies

Fiber reinforced composite structures are used for ballistic applications to achieve requirements as lightweight and high strength which can not be achieved by traditional engineering materials like steel [28]. Deformation mechanisms of composite materials are more complicated than metals or ceramics and investigated in many studies as in Naik et. al.[28]. It is stated that impact loads can be classified as low velocity, high velocity, and hyper velocity impacts. Penetration mechanisms of composites depends on the velocity during impact incident. In the study tensile and shear failure delamination and matrix cracking were found to be main deformation mechanisms for E-Glass fiber/epoxy composites hit by flat ended projectile. When the impact started, compression loads were occurred and reflected from the back face as tension load. The combination of tension and compression loads caused shear cutting and flat tip of projectile makes shear cutting easier. During shear cutting energy was transferred to the secondary yarns until primary yarns were failed by tension loads. This transfer leads delamination and cone formation (Figure 37).



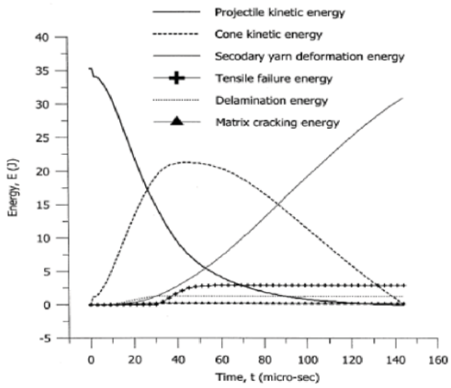


Figure 37. Experimentally Measured Delamination Area and Deformation Mechanisms [28]

It was observed delamination and cone formation were main deformation mechanisms for composite structures. Since aramid and polyethylene have more bending capability more delamination would be observed in aramid or polyethylene composites. In addition to impact velocity thickness also effects the deformation mechanisms take place and ballistic performance of composites. Reddy et. al. [29] studied ballistic performance of E-Glass fiber reinforced phenolic composites with varied thicknesses against 7.62 mm x 39 mild steel core ammunition. Impact velocity was varied from 500 m/s to 700 m/s in the study. It was found that more cone formation and delamination was observed in thick composite panels when compared to thin panels (Figure 38).

Figure 38. Cone Formation and Delamination in Thick and Thin Composite Panels [29]

It was seen that thick panels have more energy absorption capability than thin panels. To find out the critical thickness value, residual velocity of bullet was measured during impact tests and after 15 mm thickness it was observed that residual velocity dramatically decreased (Figure 39).

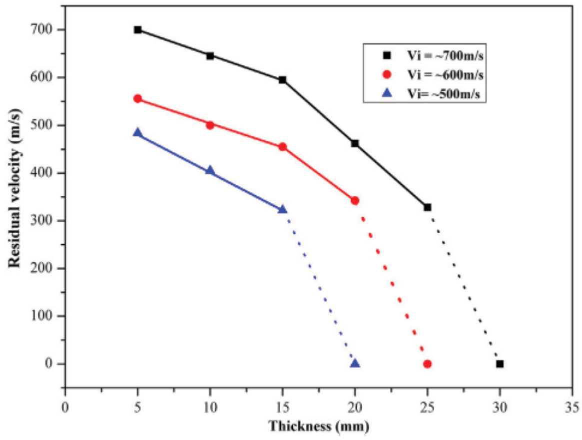


Figure 39. Residual Velocity vs. Thickness [29]

Cross sections of composite structures at impact points hit by varied velocities were investigated. It was seen that at points hit by lower velocities there was more delamination than points hit by high velocities. Researchers states that at lower velocities there was more interaction time between composite and the bullet, and this is why there was enough time for delamination unlike high velocity impact in which fiber breakage and shear cutting were observed as main deformation mechanisms.

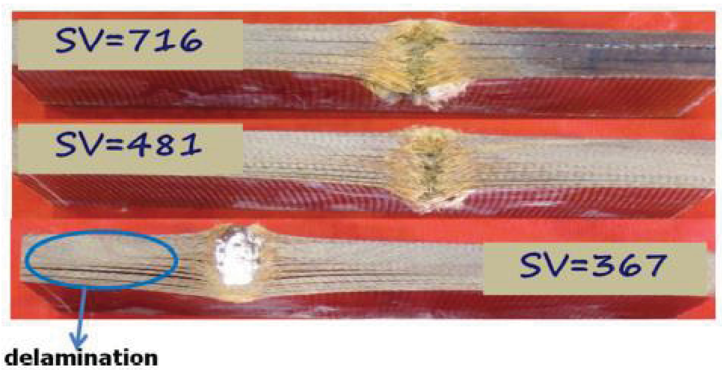


Figure 40. Deformation Mechanisms at Varied Impact Velocities [29]

Another study in which effect of thickness on ballistic performance of glass fiber composites was carried out by Bodepati et. al. [30]. In the study E-Glass/epoxy composite panels with 3 mm, 5 mm and 7 mm thicknesses are tested at 0°, 30° and 60° impact angles. As a result of tests, it was found that 3 mm composite panels could stop the bullet at 60° impact angle while 5 mm panels stopped the bullet at 30° and 7 mm panels provided protection against the projectile at same velocity at 0° (normal angle). The reason is explained, as the impact angle increases the path length of projectile at impact also increases and ballistic performance of composite panel gets better. In this way for the same projectile at same speed, thinner composite panels would be enough for protection.

Matrix provides protection for fibers against environmental issues in composites. Matrix is also important for energy transferring from primary yarns to secondary yarns in composite structures during impact. Wong et. al. [31] studied the effect of matrix type of ballistic limit of glass fiber reinforced composite panels. E-Glass fibers were used with two types resin materials which are epoxy and phenolic. Phenolic resin was used as neat and with 10% and 50% PVB additive. Ballistic limit velocity tests were carried out by using 7.62 mm (.30 cal.) fragment simulating projectile (FSP). Delamination area in epoxy composites was lower than phenolic composites (Figure 41) however composites with neat epoxy showed higher ballistic limit velocity than composites with neat phenolic resin (Figure 42).

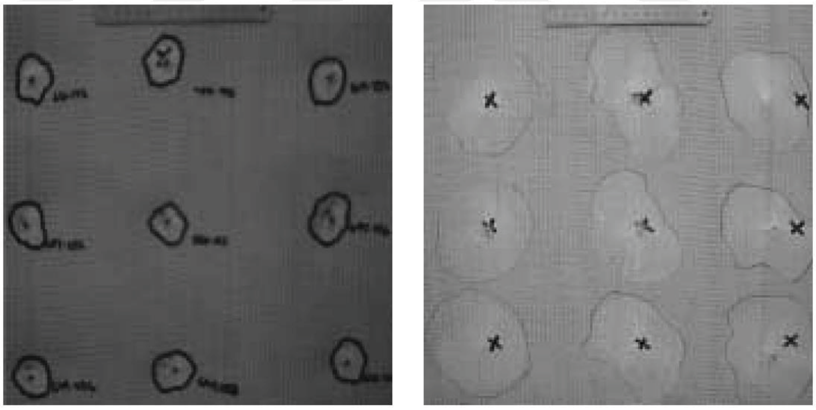


Figure 41. Back Face of Phenolic and Epoxy Resin Composites Respectively

Material	V_{50} (m/s)
Phenolic resin+PVB 50:50	581.3
Phenolic resin+10% PVB	670.9
Epoxy mix 57	651.2
Phenolic resin	601.2
Phenolic resin+Amino Silane	589.6

Figure 42. Ballistic Limit Velocity of E-Glass Fiber Reinforced Composites with Different Resin Materials [31]

As it can be seen from Figure 41 when PVB was added to phenolic resin, ballistic performance of composite panel increases since PVB increases the fracture toughness of phenolic resin. However, there is an optimum value and for higher fraction of PVB would cause decrease in impact performance.

S-Glass also known as strength glass is another type of glass fiber usually used in ballistic applications. DeLuca et. al. [32] investigated the ballistic performance of S2-Glass fiber reinforced composite structures against 12.7 (207 grain) mm and 20 mm (830 grain) fragment simulating projectiles (FSPs). Impact velocities were arranged below the ballistic limit velocity and after impact compressive strength of composite panels were measured by compression test technique (Figure 43). It was seen that after compressive properties of composite panels decreases dramatically as the strike velocity increases. As the increase in strike velocity increases compressive strength becomes more stable (Figure 44).

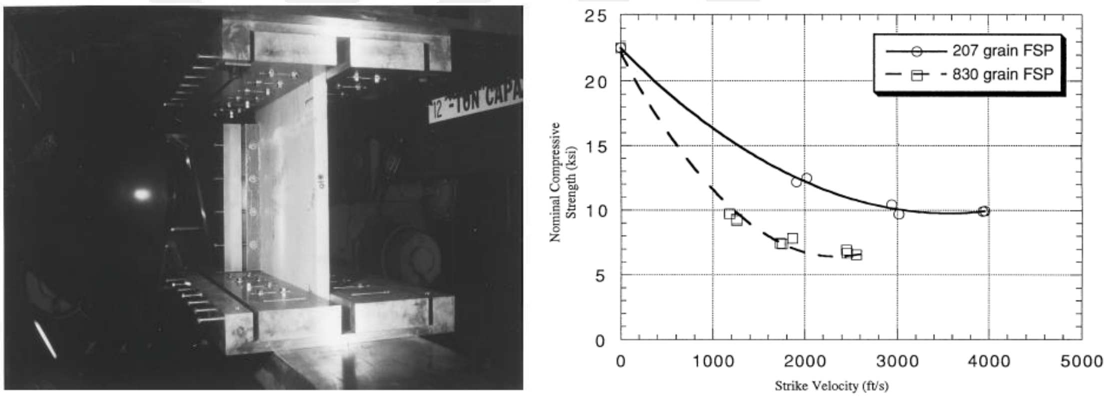


Figure 43. After Impact Compressive Strength Test Setup and Results [32]

As a result of ballistic and mechanical tests, it was found that composites hit by 12.7 mm FSP had higher after impact compressive strength than composites hit by 20 mm FSP. It can be seen from the Figure 43. It is also seen from Figure 44 damage volume in composites hit by 20 mm FSP is larger than others.

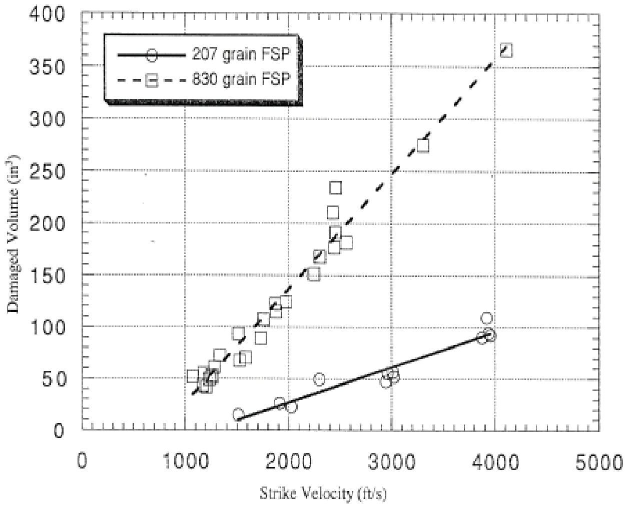


Figure 44. Damage Volume of Composites Hit by Different Types of Fragment Simulating Projectiles [32]

4.2. Aramid Fiber Studies

Aramid fiber reinforced composites are generally used for personal protection as body armor and helmet. Like glass fiber composites, thickness, matrix type, impact velocity parameters effect the impact performance of aramid structures. Park et. al. [33] studied the effect of thickness on the ballistic performance of Kevlar 29 reinforced vinyl ester composite structures. In the study dart drop test method was used to investigate the behavior of Kevlar composites. Delamination area, energy absorption with respect to number of layers were analyzed. Drop test was carried out by 4 m/s (160 J) impact. As a result, more bending and delamination area was observed in thin composite panels than thick panels. This is because impact type was low velocity impact and as stated in [20], during low velocity impact global response could be seen. For thick panels, impactor did not have enough time to create delamination. However, in thin panels more bending and delamination occurred (Figure 45).

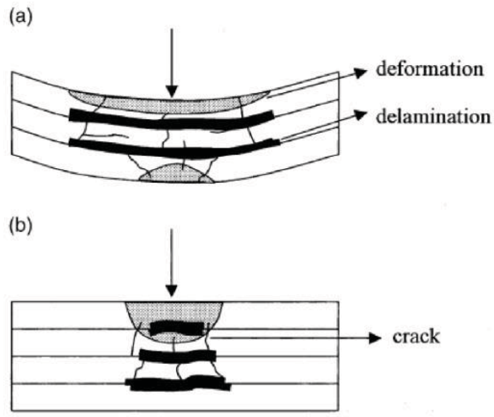


Figure 45. Low Velocity Impact Response of a) Thin and b) Thick Panels [33]

Braga et. al. [34] studied the effect of thickness on ballistic performance also. In their study minimum thickness required to stop 7.62 mm Lv.III ammunition from NIJ Standard [35] was found. In their previous studies multilayered armor structure (MAS) was developed to provide protection against threat used in this study. Kevlar fiber reinforced composite structures with 8 mm (16 layers), 25 mm (48 layers), 37.5 mm (72 layers) and 50 mm (96 layers) were manufactured for ballistic tests. When energy absorption of composite panels was analyzed it was seen that after 20 mm thickness energy absorption capability increased dramatically while delamination area increased after 37.5 mm thickness (Figure 46).

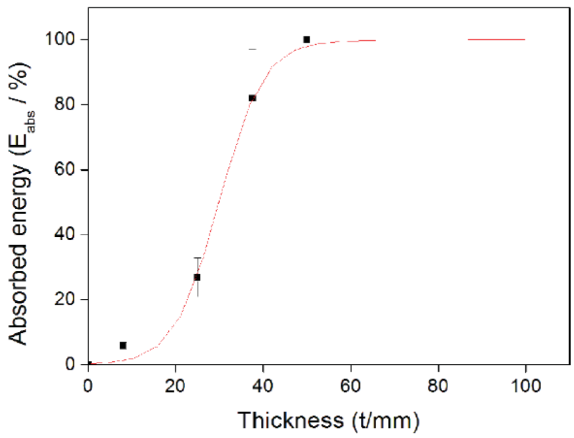


Figure 46. Energy Absorption wrt Panel Thickness [34]

Among panels with varied thickness only 50 mm (96 layers) thick Kevlar composite provide protection against 7.62 mm bullet (Figure 47). When it was compared with MAS which was found to be 25 mm for protection from previous work, Kevlar composite is thicker. Also, there was more bulge observed at the back face of

Kevlar composite. Since there was a ceramic layer in MAS, bullet core was broken by ceramic and residual velocity was absorbed by composite layer. Therefore, there was less bulge than Kevlar composite. As a result, it is stated that for higher levels of threats armor structures with ceramic layer are more efficient than composite structures alone.

Laminate thickness (mm)	Number of layers	V_i(m/s)	V_r(m/s)
8.00	16	861 ± 7	835 ± 10
25.0	48	859 ± 6	732 ± 30
38.0	72	843 ± 6	194 ± 310
50.0	96	857 ± 3	0

Figure 47. Impact and Residual Velocities of Composite Panels with Varied Thickness [34]

Carrillo et. al. [36] investigated the effect of presence of matrix in composite panels in their study. Ballistic performance dry aramid fabrics and composite panels with thermoplastic polypropylene (PP) matrix were compared. PP resin was used to make delamination easier for composite panels. As a result of ballistic tests, it was found that composite panels with PP matrix provided protection with less number of layers than dry aramid fabrics (Figure 48).

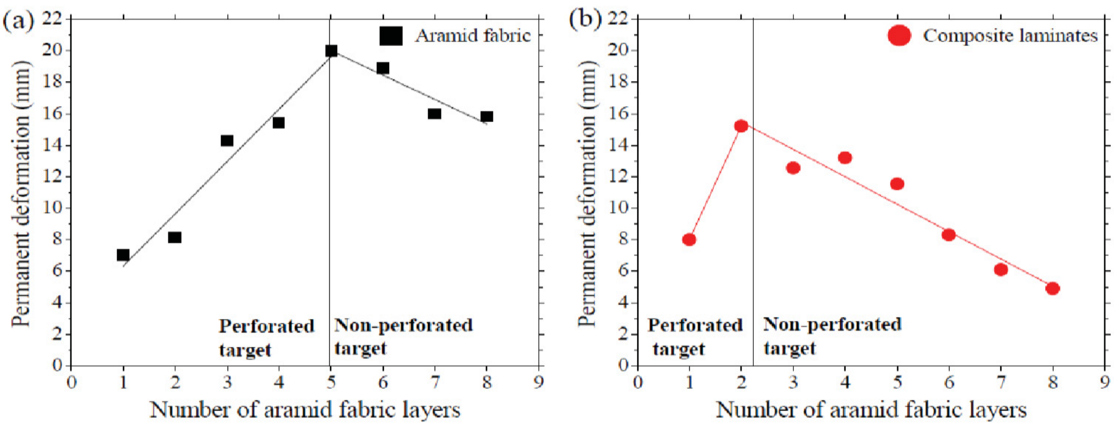


Figure 48. Ballistic Performance of a) Dry Aramid Fabric b) Composite Panels with PP resin [36]

It is stated that since there was no matrix in dry fabrics energy could not be transferred to the secondary yarns while it could be transferred easily in composite panels. In figure 49, it is clear that delamination area in composite panels with PP matrix is larger than dry fabrics. In dry fabrics kinetic energy was stuck in first region and penetration occurred by fiber breakage and shear cutting.

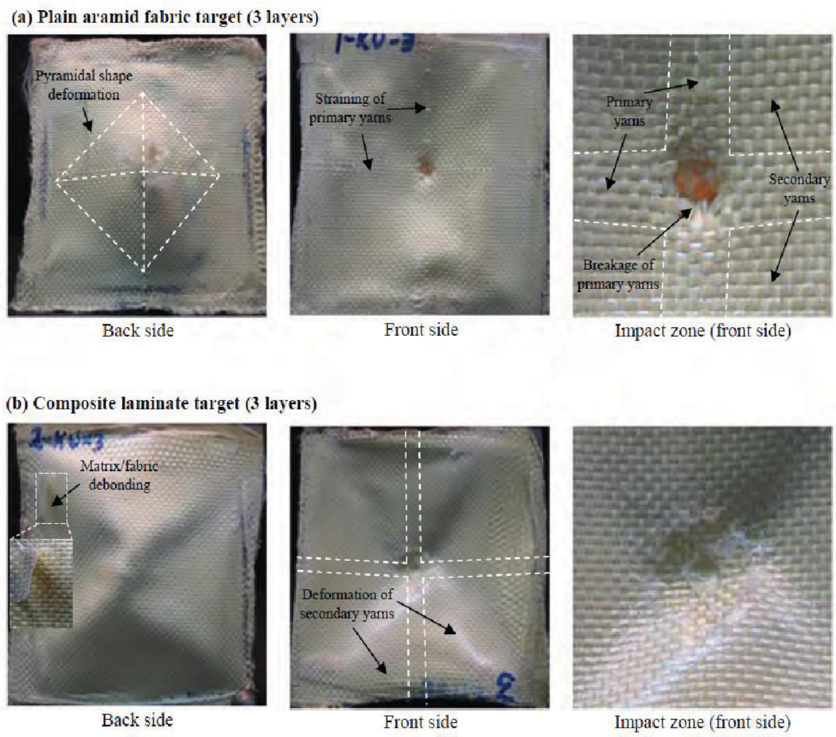


Figure 49. Delamination Area and Deformation of Secondary Yarns of a) Dry Fabric and b) Composite Panel with PP Matrix [36]

It was proved that presence of matrix is important for composite panels in this study. Type of matrix is also an important parameter for aramid fiber reinforced composites. In the study of Nayak et. al. [26] effect of matrix type on ballistic performance of aramid composites against armor piercing (AP) projectile (7.62 mm / 0.30 caliber) was studied. Thermoset and thermoplastic matrix types were compared by using epoxy and polypropylene (PP). In addition to matrix type thickness effect on performance was also investigated. After ballistic tests were carried out, it was found that ballistic properties of thin panels were close to each other and as panel thickness increases the difference between two types of panels became clearer (Figure 50). This is because during the impact of thin panels, fabrics could not find enough time for energy transfer to the secondary yarns and, deformation mechanisms were mostly fiber breakage and shear plug. Matrix type did not have significant effect on deformation mechanism and ballistic performance (Figure 50).

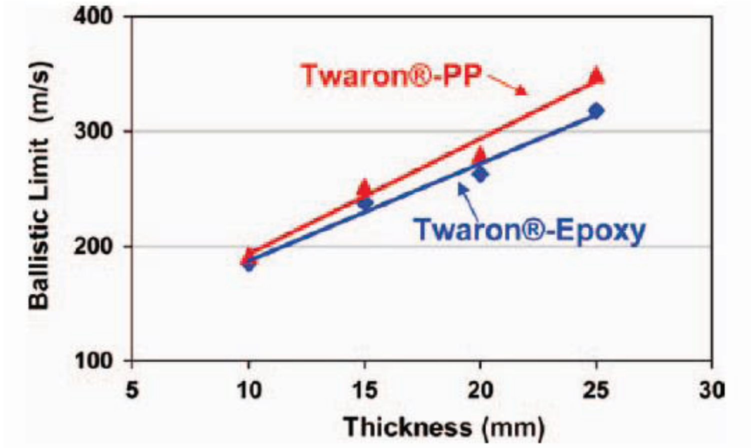


Figure 50. Ballistic Limit Velocity of Aramid Fiber Composites with PP and Epoxy Matrix [26]

From Figure 50 it is seen that composite panels with PP matrix showed better ballistic limit than epoxy matrix composites. Due to higher toughness and elasticity of thermoplastic matrix than thermosets, PP matrix composites experiences more delamination than epoxy composites (Figure 51).

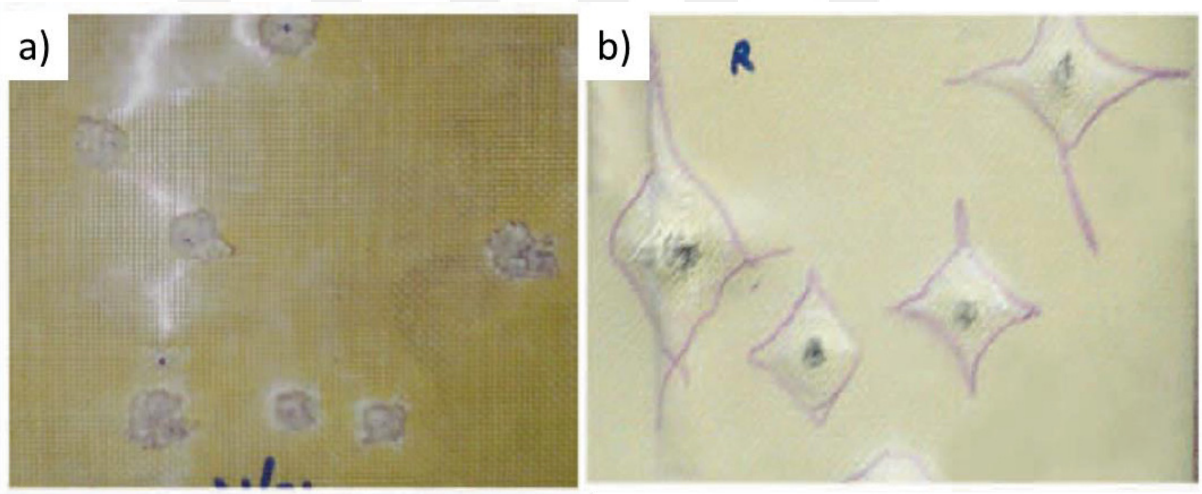


Figure 51. Rear Face of a) Aramid/Epoxy and b) Aramid/PP Composite Panels After Impact [26]

As stated before, aramid and polyethylene fiber types are generally used for personal protection (body armor and helmets). During operations, these armor structures would be exposed to varied environmental conditions as high/low temperatures, moisture etc. In this regard Soykasap et. al. [37] studied the effect of varied temperatures on ballistic performance of Kevlar-29 composite panels. Experimental and numerical tests on 20 layers (8 mm) thick Kevlar/phenolic composites were carried out at varied temperatures from -30ºC to 60ºC. At lowest and highest temperatures highest deformation area was observed at rear face of composite panels. That showed ballistic properties of Kevlar composite panels were not dramatically affected by temperature (Figure 52a). However, when the mechanical properties were analyzed it was found that temperature has considerable influence on mechanical properties (Figure 52b).

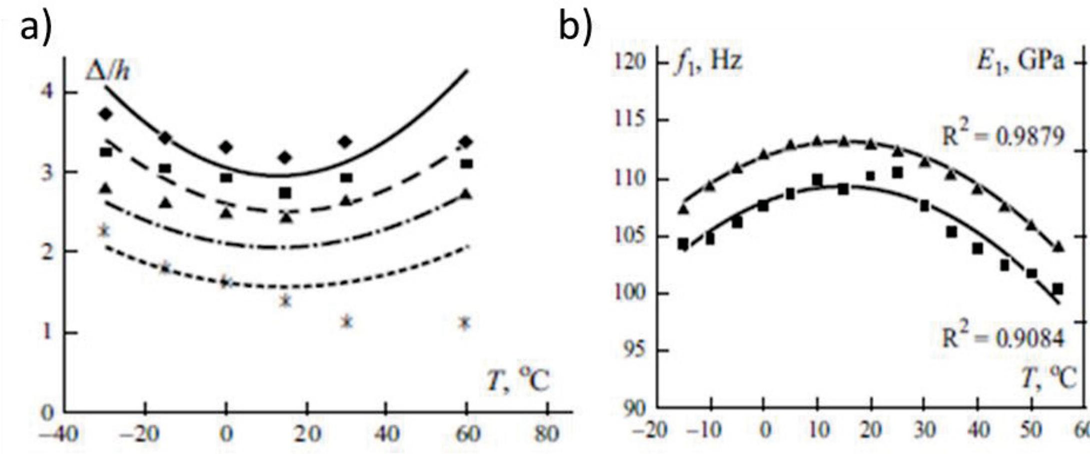


Figure 52. Ballistic Performance a) Deformation Area vs. Temperature b) Elastic Modulus vs. Temperature [37]

In addition to aramid fabric, in some of studies effect of environmental conditions on other types of ballistic fabrics are observed and compared with aramid fabric [38, 39]. Merriman et. al. [38] studied ballistic performance of composite structures reinforced with four different types of fibers which are aramid, ultra-high molecular weight polyethylene (UHMWPE), S-Glass and E-Glass fibers. To observe the effect of resin material two types of matrix were chosen as phenolic and polyester resin. 1.1 gr fragment simulating projectile was used for V50 ballistic tests and results showed that aramid fabrics showed better results with phenolic resin while glass fiber composites showed higher ballistic limit with polyester resin. For the same areal density of composite panels, aramid and polyethylene fiber composites have higher ballistic limit than glass fiber (S-Glass, E-Glass). When glass fiber composites were compared with each other it was seen that S-Glass showed better ballistic performance than E-Glass. Up to approximately 20 kg/m² polyethylene fiber reinforced panels showed higher ballistic limit velocity. As the areal density was increased aramid fiber composites took the lead.

Effect of environmental conditions were also investigated. It was seen that polyethylene fiber was the type which was mostly affected by temperature and moisture. When aramid fabrics were exposed to moisture and high temperatures it was found that ballistic limit increased. Under different temperature and moisture conditions aramid fabric composites was seem to be better than other types of fiber reinforced composites [38]. Another study in which aramid and polyethylene fiber composites were compared was carried out by Karahan et. al.[39]. Effect of fiber type/structure and thickness on the ballistic performance of composite panels were investigated. Aramid fiber composites were manufactured by three different types of fabric structure which are plain weave, biaxial UD (+45º/-45º), cross-plied UD (0º/90º). Results showed that for the same number of layers (24) aramid fiber composites (LP1, LP2, LP3) had higher ballistic limit than polyethylene fiber since aramid fabrics were thicker and 24 layers aramid composites were thicker than 24 layers UHMWPE composites (LP4, LP5). However, when mass efficiencies were compared UHMWPE composites had an advantage on aramid fabrics (Figure 53). For aramid fabric composites,

Label	Reinforcement	Fabric orientation	Panel thickness, mm	Areal density, kg/m^2	V_f, %	V_{50}, m/s	Ea, J	V_{50}/AD, m^3/kg s	Ea/AD, Jm^2/kg
LP_1	R_1	0°/90°	12.4	9.840	55.1	579.00	491.13	58.80	49.91
LP_2	R_2	45°/−45°	9.20	11.040	53.3	650.00	618.96	58.90	56.07
LP_3	R_3	0°/90°	12.1	12.240	64.2	707.00	732.28	57.80	59.83
LP_4	R_4	0°/90°	6.20	6.312	68.7	540.00	427.19	85.60	67.68
LP_5	R_5	0°/90°	4.25	4.776	70.1	530.00	411.52	111.00	86.16

Figure 53. Ballistic Limit and Energy Absorption of 24 layers Aramid and Polyethylene Composites [39]

4.3. Polyethylene Fiber Studies

Polyethylene fibers are basically divided into two categories based on their density which are low density (LDPE) and high-density polyethylene (HDPE) fibers. HDPE fibers are also called as ultra-high molecular weight polyethylene and they are commonly preferred for personal protection in ballistic applications. The most known advantage of UHMWPE fibers on traditional engineering materials as steel, aluminum and other types of fibers is low density. Nguyen et. al. [40] compared ballistic performance UHMWPE composites with metals and other fiber type composites. V50 ballistic tests were carried out by 12.7 mm and 20 mm FSPs. When RHA was taken as reference material, UHMWPE composite had mass efficiency more than 1 which means UHMWPE could provide protection for the same projectile at lower areal density (Figure 54).

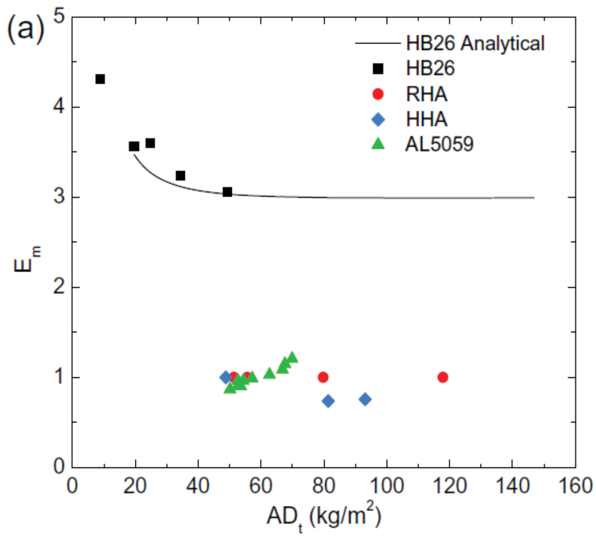


Figure 54. Mass Efficiency of UHMWPE on Metals [40]

Researchers also compared UHMWPE composites with other types of fiber composites which are aramid, glass, and carbon fibers. It was seen that other type of fibers had mass efficiency lower than 1. As a result polyethylene was seen to be more efficient than metals and other fiber types for ballistic applications (Figure 55).

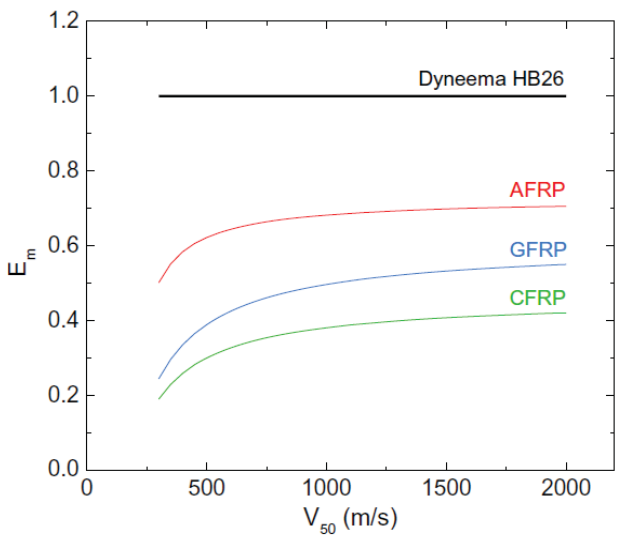


Figure 55. Mass Efficiency of Different Fiber Type Reinforced Composites [40]

Ballistic performance of polyethylene fibers is affected by several factors as temperature, resin type and fiber structure. As for aramid fabric, polyethylene composites reinforced with UD fiber structure has better ballistic limit than woven fiber structure composites [41]. Ballistic limit of cross-plied and woven polyethylene fiber composites was studied by Dimeski et. al [22]. 1.1 gr FSP was used for ballistic tests and composite panels with four different areal densities which are 3, 5, 7 and 9 kg/m² were tested. As a result, it was found that UD composites showed higher ballistic limit than plain woven composites. Researchers stated that the existence of knitting points in woven structures caused energy to be reflected and prevented the kinetic energy to be transferred to the secondary yarns. Since there was no knitting point in UD structures, energy transfer from primary to secondary yarns was easier so was delamination (Table 1).

Table 1. Ballistic Limit Velocities of UD and Woven Composite Panels [22]

Fiber Structure	3 kg/m²	5 kg/m²	7 kg/m²	9 kg/m²
Plain Woven	319.1	412.9	498.2	557.3
UD	401.1	517.4	601.9	682.1

As it can be seen from Table 1, UD composites had higher ballistic limit than woven composites for all areal densities which were tested in the study. Lee et. al. [41] also proved that UD composites are better than panels reinforced with woven fabric structure. Effect of matrix type was also investigated in their study by polyurethane and vinyl ester resin materials. As in previous study, V50 ballistic tests were carried out by using 1.1 gr FSP threat. UD composites had higher ballistic limit than woven composites (Figure 56a) and when delamination area at rear face of composite panels were compared it was seen, composites manufactured with vinyl ester resin had larger delamination area than polyurethane resin (Figure 56b).

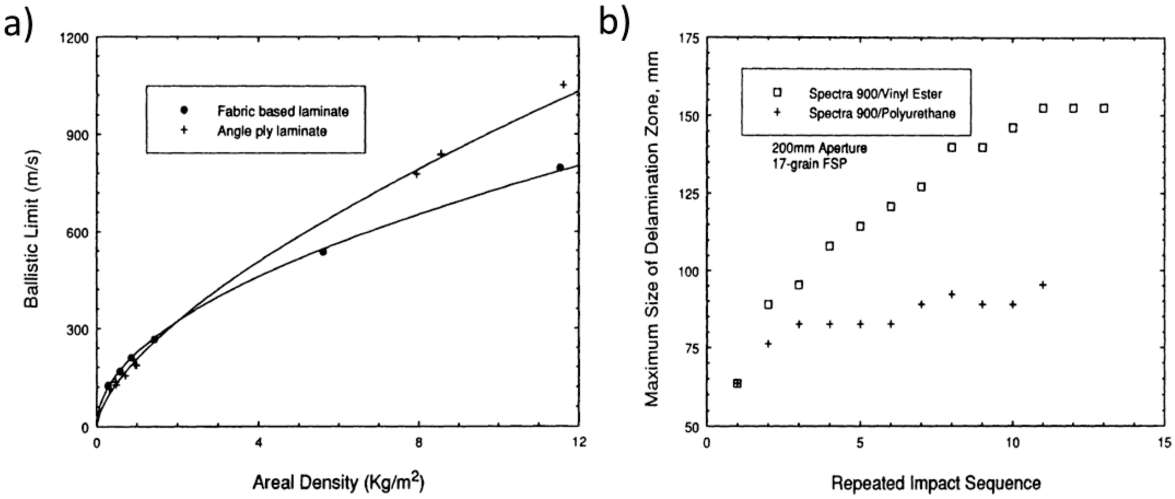


Figure 56. Ballistic Performance Comparison of a) Fabric Structure b) Resin Type [41]

4.4. Other Types of Fiber Studies

In addition to glass, aramid and polyethylene fibers, other types of natural and synthetic fibers have also being studied. Generally elastic fiber types are used for ballistic applications and in the study of Iremonger et. al. [42] ballistic limit of Nylon 6.6 fiber composites against 1.1 gr FSP threat was studied. 12 and 22 layers of composite panels were manufactured by hot press method and two different pressure values were applied for the proses which were 0.56 (1A, 2A) and 3.20 MPa (3A, 4A). Panels manufactured with 3.20 MPa had lower thickness and areal density for the same number of layers. The effect of manufacturing parameters on ballistic performance was investigated in this way. As a result for thin plates higher pressure was seem to be better for impact performance while for thick panels manufacturing with high pressure resulted in better results (Figure 57).

Sample	V_l ($m\,s^{-1}$)	Areal density, A ($kg\,m^{-2}$)
1A	315.3	3.99
2A	426.7	7.08
3A	355.8	3.85
4A	418.4	6.83

Figure 57. Ballistic Limit for Nylon 6.6 Fiber Composites [42]

Deformation mechanisms were also analyzed after impact and it was stated that since they are all elastic fibers penetration mechanisms were very similar with aramid and polyethylene fiber composites and delamination was the dominant mechanism while for brittle fiber types as carbon fiber, shear plug and fiber breakage are main deformation mechanisms. Carbon fiber composites are preferred for aerospace applications due to their high mechanical properties and lightweight. Impact performance of carbon fiber is lower than other types and Ulven et. al. [24] studied the effect of projectile shape on the ballistic performance of carbon fiber composite panels. Tests were carried out for 3.2 and 6.5 mm thick composites with four different projectile tips which were flat, conical, fragment simulating and hemi-spherical (Figure 58).

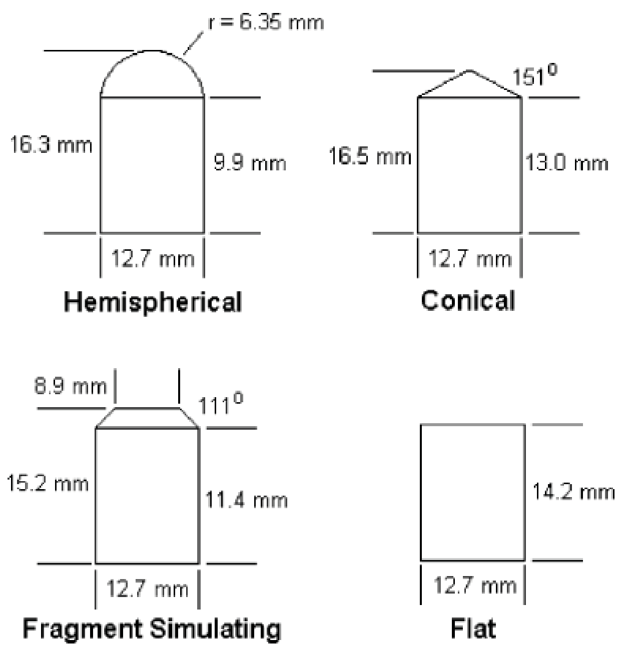


Figure 58. Projectile Geometries [24]

Carbon fiber composites showed better results when impacted by conical projectiles for thick panels. Thinner panels had similar results due to the deformation mechanism occurred. Thin panels experienced global response and as panel gets thicker response becomes local (Figure 59).

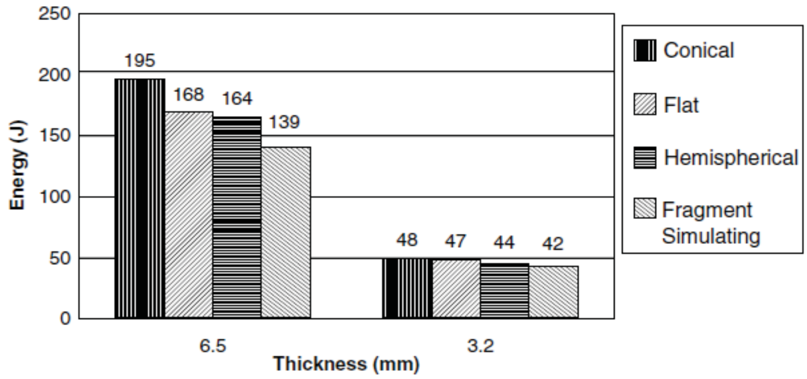


Figure 59. Ballistic Performance of Carbon Fiber Composites Against Different Projectile Geometries [24]

4.5. Hybrid Composite Studies

4.5.1. Hybrid Fiber Reinforced Composites

Hybridization is one of the most used method to improve the ballistic properties of fiber reinforced composites. It might also be used to obtain cost effective solutions. Aramid and glass fibers might be given as example for hybrid composites. Balakrishna et. al. [43] studied the effect of volume fraction of aramid and glass fiber layers in composite panel on the ballistic performance against armor piercing (AP) and non-AP (ball) threats. As a result, it was found that composite panels in which glass fiber layers were dominant showed better performance against ball ammunition. The reason was said to be glass fibers are more brittle than aramid fibers and ball threats could be deformed by hard and brittle fiber types. However, AP threats could not be deformed, and the kinetic energy of the projectile should be absorbed. In this case aramid layer dominant composite panels were better option for AP threat protection (Figure 60).

Fibre reinforcement glass-aramid weight ratio	Bullet	
	Armour piercing	Ball
100:0	1.00	1.00
80:20	1.03	0.74
50:50	1.20	0.82
34:66	1.32	
0:100	1.41	0.66

Figure 60. Ballistic Performance of Glass-Aramid Fiber Composites Against Armor Piercing and Ball Threats [43]

Park et. al. [44] carried out a similar study in which Kevlar and S2/Glass fiber reinforcement were used for hybridization and effect of stacking sequence on ballistic behavior was investigated. It was found that when the glass fiber layer was used in the back and aramid layer was used in front, composite panel showed higher ballistic performance.

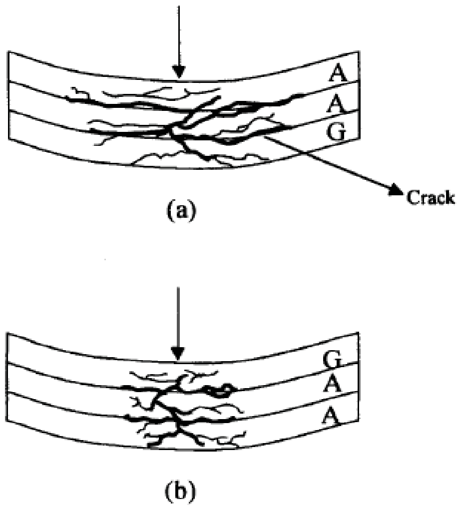


Figure 61. Delamination of Hybrid Composites with Different Stacking Sequences [44]

In Figure 61 it is seen that more delamination area was observed when glass fiber layers were placed in the back side. As a result, more kinetic energy absorbed than other stacking sequence. In addition to glass fiber layers, carbon fiber is also preferred for hybridization. Bandaru et. al. [45] studied the effect of hybridization and stacking sequence of Kevlar, glass and carbon fiber layers. After ballistic tests were carried out it was observed that when Kevlar layer was used in 4th position which is as backing layer in glass and carbon composite panels (Figure 62).

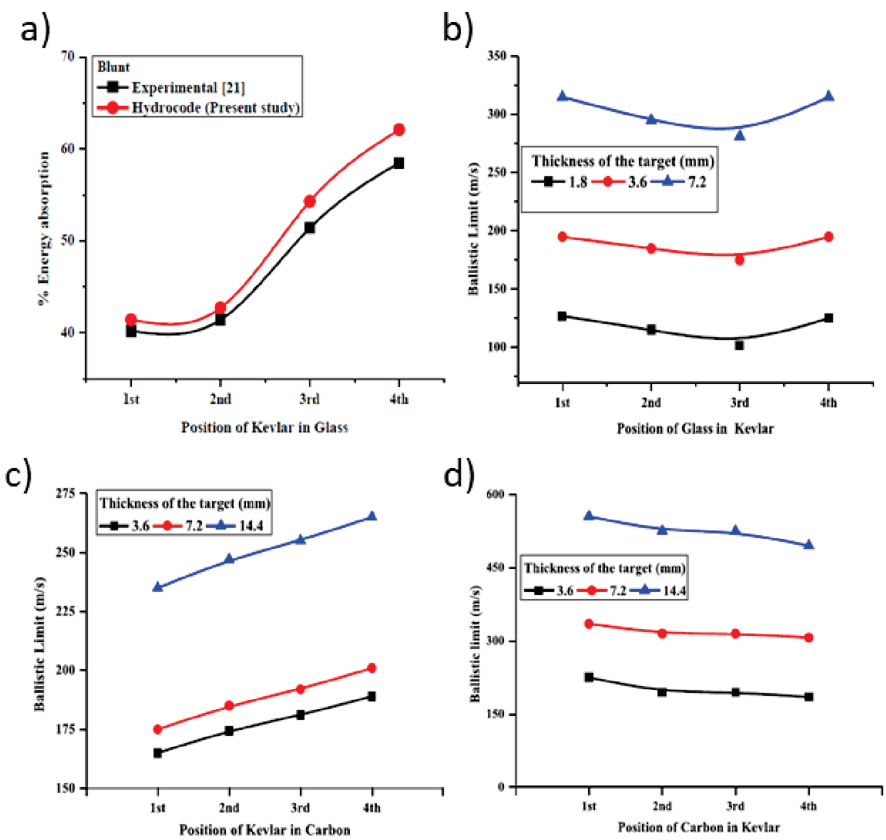


Figure 62. Effect of Stacking Sequence of Kevlar, Glass and Carbon Fiber Layers a) Kevlar in Glass (K/G) b) Glass in Kevlar (G/K) c) Kevlar in Carbon (K/C) d) Carbon in Kevlar (C/K) [45]

For personal protection ultra-high molecular weight polyethylene (UHMWPE) fiber composites are mostly preferred due to their high elasticity and energy absorption capabilities. During impact, delamination causes bulge creation at the back face of composite panel. However, this bulging might harm the person who carries the armor. Also mechanical properties of polyethylene composites might limit their usage for structural applications. To reduce the bulge, prevent trauma and increase strength it is aimed to increase rigidity of composite panel as in the study of Zulkifli et. al. [27]. Effect of position of carbon fiber layers in UHMWPE composite on ballistic performance against 9 mm FMJ bullet was studied. It was observed that when the carbon layer was placed in front, bulge was minimum and showed optimum test results among other hybrid structures. In this way ballistic properties of UHMWPE composite were enhanced while back face signature (bulge) was reduced (Figure 63).

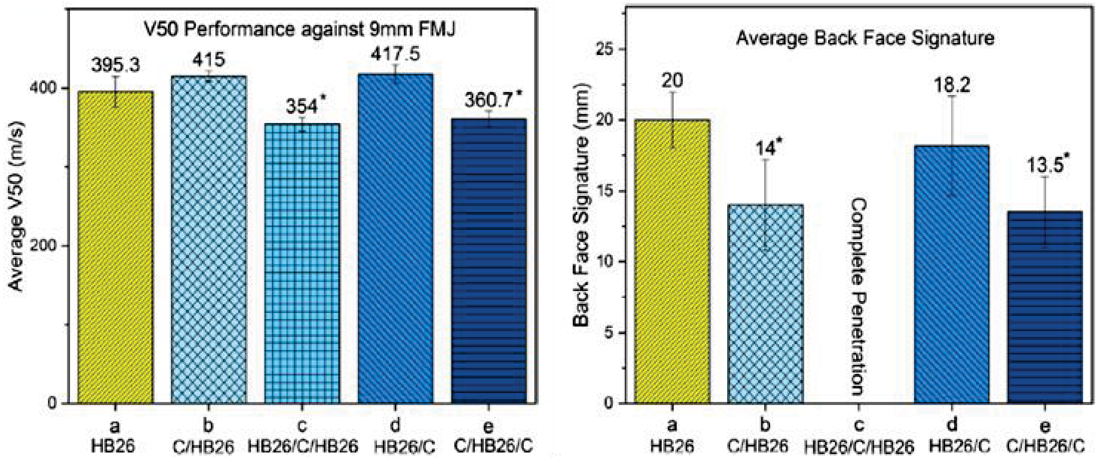


Figure 63. Ballistic Performance and Back Face Signature of UHMWPE and Hybrid Composites [27]

Lu et. al. [46] carried out a similar study in which it was aimed to investigate mechanical and impact properties of UHMWPE/Carbon hybrid composites. Volume fraction of carbon fiber in UHMWPE composite was increased and the change in ballistic and mechanical properties were analyzed. It was observed mechanical properties of hybrid structures were increased continuously with increase of carbon fraction in composite panel. However, for impact performance a certain value was found. Impact properties increased until 57% of carbon fiber layer. After that value impact performance of composite panels was seemed to be decreased due to composite panel became more brittle as the fraction of carbon fiber layer increased (Figure 64).

For some applications which is cost effective, high performance ballistic fabrics might not be preferred. Based on these applications Reddy et. al. [47] studied the hybridization of carbon and E-Glass fibers with each other. Homogeneous carbon and glass fiber composites and three hybrid structures with different carbon:glass weight fractions were manufactured which are 75:25, 50:50 and 25:75. Homogenous fiber reinforced composites were used as reference. It was found that carbon fiber reinforced composite panels showed better results and among hybrid structures 50:50 weight fraction hybrid panel had higher energy absorption capability than others. After the best configuration specified, effect of thickness on energy absorption was observed. It was found as thickness of the panel increased delamination area and energy absorption capability of composite panel also increased. Since threat had more interaction time with composite panel through thickness direction, there was enough time for energy to be transferred to the secondary yarns (Figure 65).

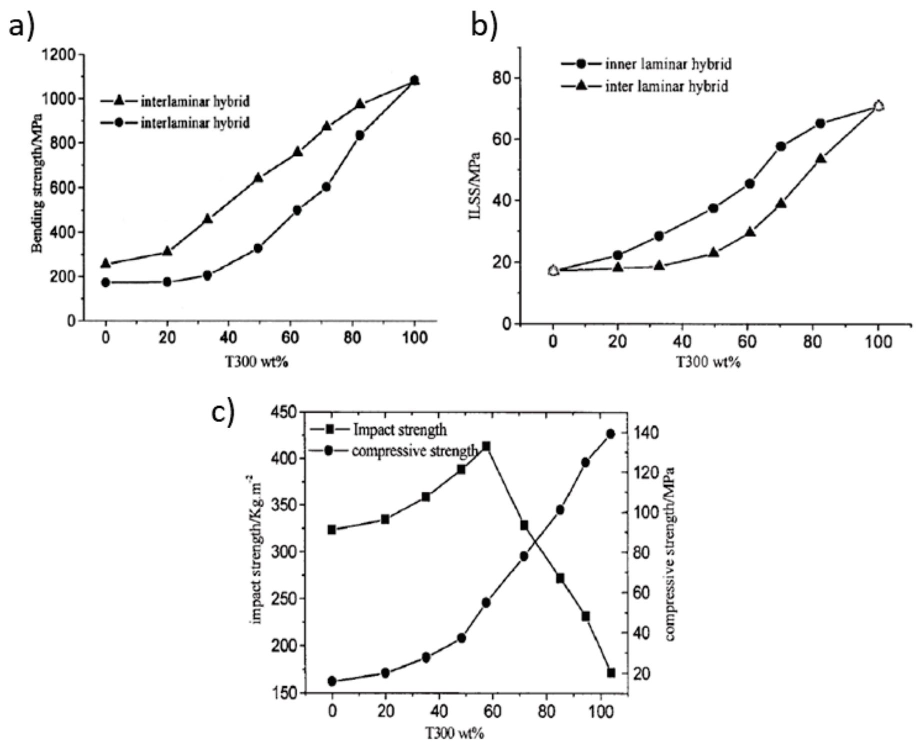


Figure 64. a) Bending Strength b) ILSS c) Impact and Compressive Strength Properties of Hybrid Structures with Different Carbon Fiber Layer Fraction [46]

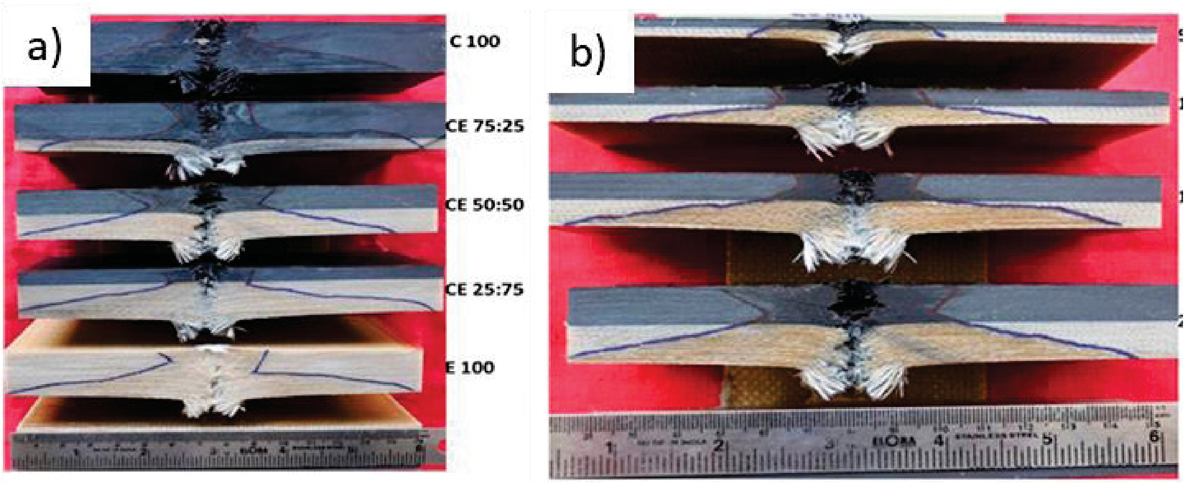


Figure 65. Effect of a) Weight Fraction b) Thickness on Energy Absorption Capability of Composite Panels [47]

Aramid, glass, carbon, and polyethylene fibers are synthetic fiber types and mostly preferred for structural and ballistic applications due to their high mechanical properties. However, there are natural fibers which also can be used for ballistic applications. They are generally used by hybridization with synthetic fiber types. In this way composite panel has high strength and modulus due to the presence of synthetic fiber layers and become more cost effective and environmentally friendly due to the presence of natural fiber layers. Based on that Salman et. al. [48] studied the ballistic performance of hybrid structures manufactured by kenaf and aramid fibers. Ballistic tests were carried out against 9 mm FMJ bullet and it was found that as the aramid layer increased in composite panel, ballistic limit also increased. As an optimum fraction of fiber layer 50:50 was decided to be used.

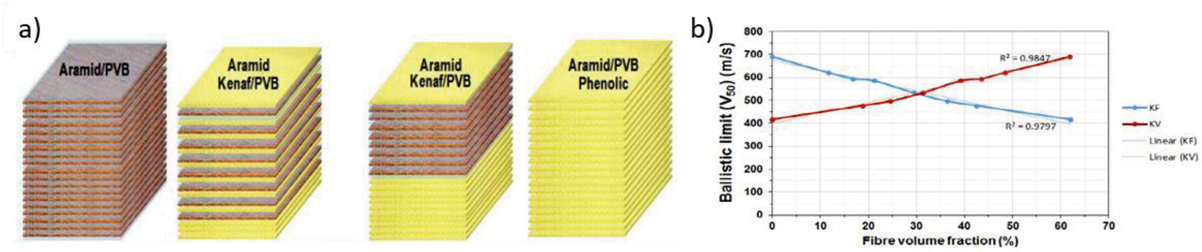


Figure 66. a) Stacking Sequences of Hybrid Structures b) Ballistic Performance wrt Fiber Layer Fractions [48]

4.5.2. Lightweight Armor Systems

In addition to hybrid fiber reinforced composites, hybrid structures might also be formed by combination of two different type of materials. In lightweight armor systems ceramic tiles are used as front layer and fiber reinforced composites are placed as backing plate. Ceramic tiles dissipate kinetic energy of projectile by shattering and composite structure absorbs residual kinetic energy of projectile. As stated in Chapter 3 there are several types of ceramics that might be used in armor structures which are alumina, silicon carbide and boron carbide. Shokrieh et. al. [49] studied the ballistic performance of lightweight armor structure consists of boron carbide (B_4C) and Kevlar composite. In the study total thickness of armor system was constant while thickness of ceramic and composite layers was changed. Optimum thickness of ceramic and composite layers was calculated by Heterington equation first. Three different armor structures were manufactured and tested. After ballistic tests it was observed that for the configuration in which ceramic layer was thinner than optimum thickness, ceramic layer did not have enough time to fully break the projectile and in the configuration in which ceramic layer was thicker than optimum one, composite layer did not have enough time to absorb residual kinetic energy of the projectile and hence, highest residual velocity was observed (Figure 67). It was also seen energy absorption capability of armor structure increased until its ballistic limit and after the limit even slight changes in velocity caused dramatic decrease in energy absorption of total system.

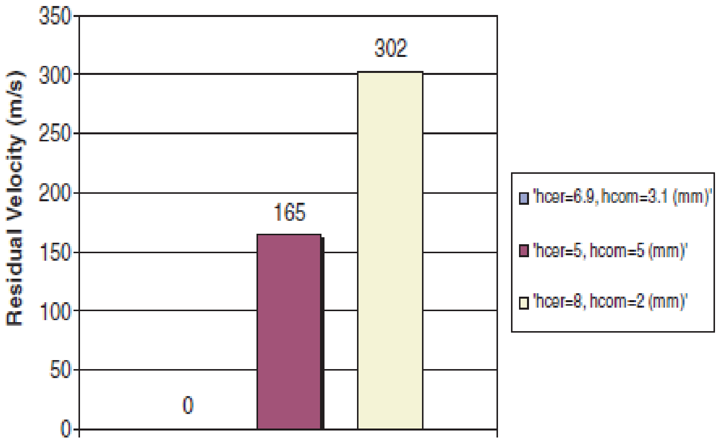


Figure 67. Residual velocity of Three Different Armor Structure Configuration [49]

Another study in which all ceramic tiles with the same backing layer was tested was carried out by Dateraksa et. al. [50]. Same thickness of S2 Glass reinforced composite was used as backing layer for all ceramic types which were Al_2O_3, SiC, B_4C. Ceramic layer thickness was also held constant which was 7 mm. V50 ballistic tests were carried out by 7.62 mm ammunition and ceramic performances were compared. As a result, armor structure with alumina ceramic layer showed better performance than others. Since B_4C ceramics have lower fracture toughness they have brittle structure and during impact dwell and interaction time was shorter than other ceramics. Therefore, armor structure with boron carbide ceramics showed lower ballistic limit than with alumina or silicon carbide. It was also stated that as the areal density of total armor system increases, ballistic performance also increases.

Fracture toughness determines the energy absorption capability of ceramic tiles while dwell is important for interaction time of ceramic and threat. In the total system, interface between ceramic and composite layers is an important parameter for ballistic performance of lightweight armor. In this regard Tasdemirci et. al. [51] studied the effect of interlayer between ceramic and composite layer on ballistic performance of total system. 4 different structures which were without interlayer (WO), with rubber (WR), with Teflon (WT) and, with aluminum foam interlayer (WF) were manufactured. For the ballistic tests 7.62 x 51 mm M61 ammunition was used and it was observed that all configuration stopped the bullet at the same speed. However, as a result of numerical analysis it was seen that armor structure without an interlayer showed better performance than others. Among rubber, Teflon and aluminum foam, rubber was seemed to be more efficient. Researchers stated that Teflon and aluminum foam delayed the energy transfer from ceramic to composite layer and this caused more load was applied to the ceramic layer and less energy was transferred to composite layer.

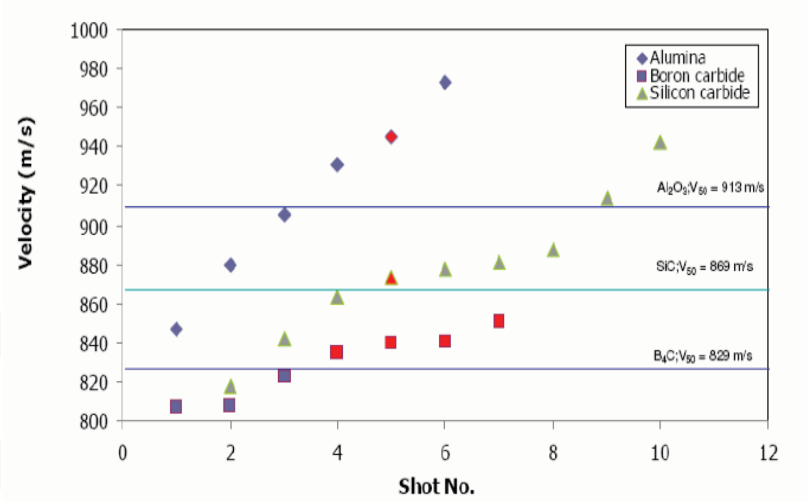


Figure 68. Ballistic Limit Performance of Armor Structures with Different Types of Ceramic Layers [50]

For ballistic applications and hybridization aramid, glass, carbon and polyethylene fibers are popular options however aramid and glass fibers might be more efficient for cost effective applications. In this regard, hybridization method by using aramid and glass fibers for ballistic performance enhancement was used in this study.

CHAPTER 5

EXPERIMENTAL

5.1. Materials

In this study, for composite structure manufacturing plain woven aramid and E-Glass fibers were used as reinforcement and epoxy resin system was used as matrix material. ARP 170T RC40 aramid fabrics with 170 gr/m² areal density from SPM Kompozit and GW280P glass fabrics with 280 gr/m² areal density from METYX were impregnated by VTP H300 epoxy resin systems in SPM Kompozit.

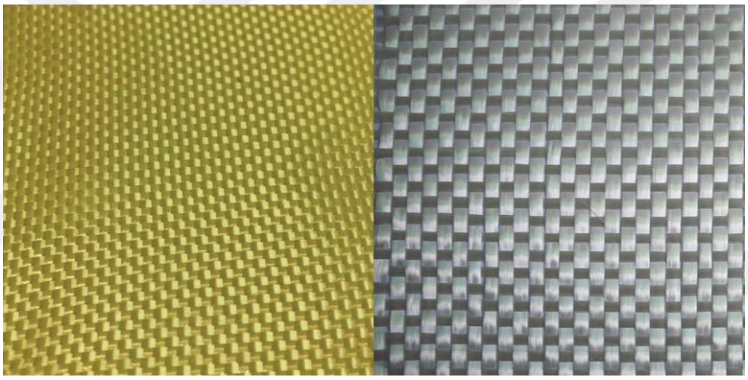


Figure 69. Plain Woven Aramid and Glass Fiber Reinforcements

5.2. Manufacturing of Multi-Layered Composite Structures

Aramid and E-Glass fabrics were impregnated by epoxy resin and prepreg curing in autoclave method was used for composite manufacturing in the study. After impregnation layers were cut and stacked in desired configuration. Then fabrics were covered by vacuum bag. Under high pressure and temperature in autoclave, cured composite panels were obtained. Vacuum bagged fabric layers and curing period are given in Figure 70 and 71.

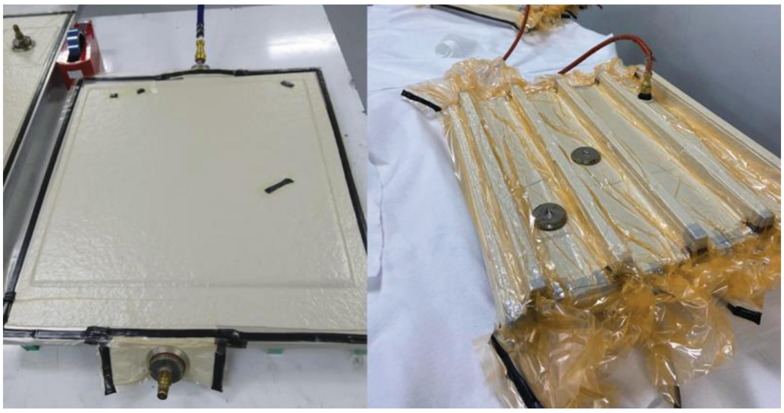


Figure 70. Layers Covered by Vacuum Bag Before Autoclave Process

Homogeneous and hybrid fiber reinforced composites were manufactured for mechanical and ballistic tests. In hybrid composite structures E-Glass layers were used in front and aramid fiber layers were used in the back. Hybrid structures with the same stacking sequence and two different volume fractions of E-Glass and aramid layers were manufactured. Homogenous E-Glass and aramid fiber reinforced panels and hybrid panels are remarked as E, A, H1 and H2 respectively. Number of layers and configuration of composite panels are given in table below.

Table 2. Stacking Sequence and Fraction of Fabric Layers

Panel No	Number of Layers	Stacking Sequence	Volume Fraction (%)
E1	38	38 Layers E-Glass	100:0
E2	50	50 Layers E-Glass	100:0
H1.1	40	21 Layers Aramid + 19 Layers E-Glass	50:50
H1.2	53	28 Layers Aramid + 25 Layers E-Glass	50:50
H2.1	41	30 Layers Aramid + 11 Layers E-Glass	30:70
H2.2	55	40 Layers Aramid + 15 Layers E-Glass	30:70
A1	40	40 Layers Aramid	0:100
A2	53	53 Layers Aramid	0:100

After manufacturing of composite panels, thickness and areal densities were measured. Information is given in Table 3.

Table 3. Thickness and Areal Densities of Composite Panels

Panel No	Thickness (mm)	Areal Density (kg/m²)
E1	8.70	15.60
E2	11.7	20.54
H1.1	8.80	13.38
H1.2	11.7	17.86
H2.1	8.80	12.64
H2.2	11.7	17.10
A1	8.70	10.96
A2	10.3	14.18

Since aramid fibers have lower density than E-Glass fibers, aramid fiber reinforced composites are lighter than glass composites at the same thickness. Manufactured composite panels and stacking sequences can be seen in Figure 72 below.

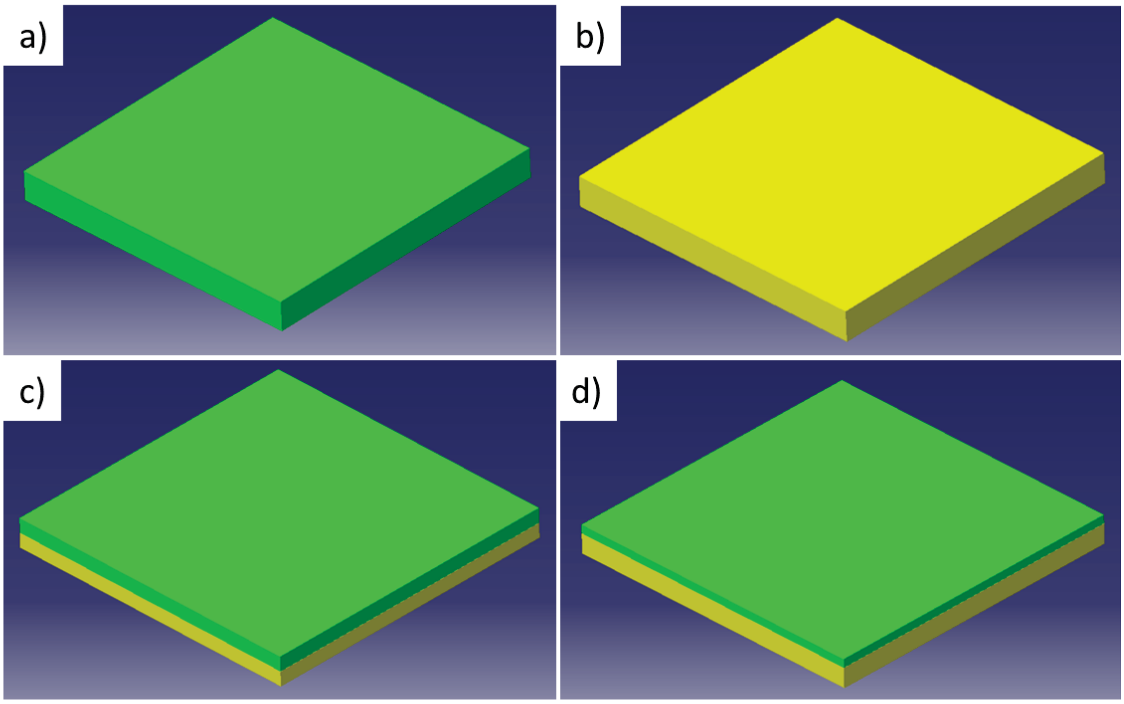


Figure 71. Stacking Sequence of Composite Panels a) E-Glass (E) b) Aramid (A) c) Hybrid 1 50:50 (H1) d) Hybrid 2 30:70 (H2)

5.3. Characterization of Composite Structures

5.3.1. Mechanical Tests

In the study mechanical properties of homogenous and hybrid fiber reinforced composites were investigated according to ISO and ASTM standards. Three mechanical tests which are tensile, bending and charpy impact tests were applied to composite structures.

5.3.1.1. Tensile Test

During an impact event several loads are applied to the fibers at the same time which are tension compression and shear. Among them tension has greatest effect on energy absorbing capability of composite laminates. In this regard tensile strength test was applied to the composite structures to observe the effect of hybridization on tensile properties.

Tensile test was carried out according to the ISO 527-4 standard [52]. Five test specimens for each composite panel were cut from composite panels by water jet and tested. Geometry of test samples are given in Figure 72.

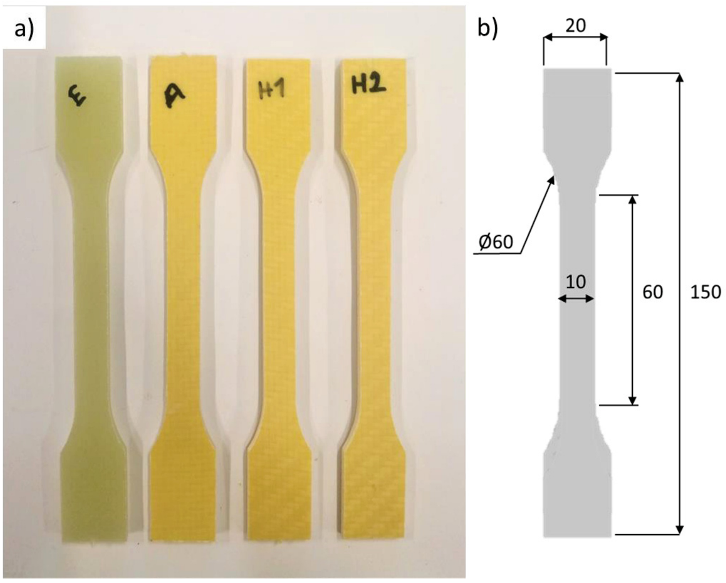


Figure 72. a) Tensile Test Specimens t:4 mm b) Test Specimen Dimensions ISO 527-4 Type 1B (Dimensions are in mm)

For tensile tests, test machine with maximum capacity of 100 kN was utilized and crosshead speed was arranged as 2 mm/min. Tensile strength was calculated by the following equation.

$$\sigma_{UTS} = {}^{F_{max}}/_{A_{cross}}$$

where σ_{UTS}, F_{max} and A_{cross} are tensile strength, maximum force observed and cross-sectional area of composite test sample, respectively. Elastic modulus was calculated by slope of elastic region in stress vs. strain graph as shown below.

$$E = {}^{\sigma}/_{\varepsilon}$$

where E and ε are elastic modulus and strain values.

5.3.1.2. Bending Test

For low speed impacts, global response can be observed in fiber reinforced composite structures. As the impact speed increases, global response gives its place to local response but does not disappear. In global response bending characteristic of composite structures has importance. In this regard, three point bending test was carried out according to ASTM D790 standard [53]. Test specimens were prepared based on standard. Dimensions and geometry of specimens are given below.

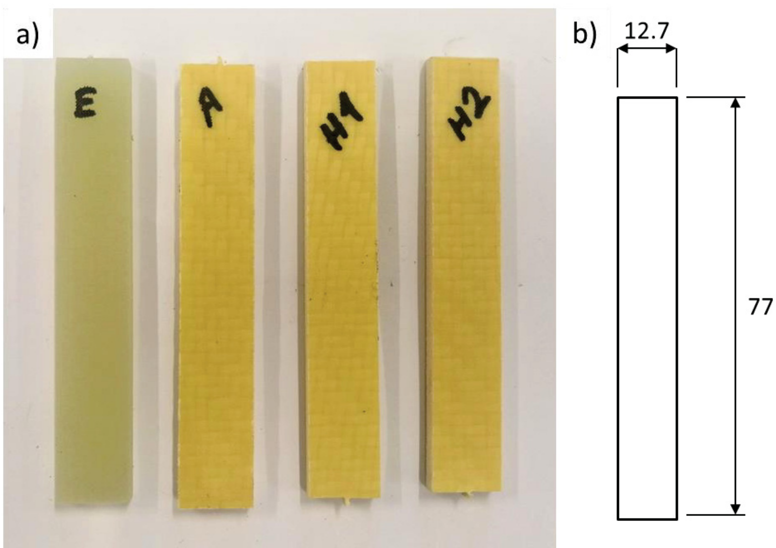


Figure 73. a) Bending Test Specimens b) Specimen Dimensions (mm)

Bending tests in which span length was arranged as 64 mm were carried out with 1.7 mm/min crosshead speed. Flexural strength was calculated by the formula below.

$$\sigma_f = {}^{3 \text{ x } P \text{ x } L}\!/_{2 \text{ x } b \text{ x } d^2}$$

where P is the maximum load observed in the tests, L is support span length, which was 64 mm, b is width and lastly d is the thickness of specimen.

5.3.1.3. Short Beam Strength Test

Kinetic energy absorption of threat is achieved by energy transfer from primary yarns to secondary yarns. This transfer is occurred due to failure of fiber matrix bonding in other words delamination. Delamination properties of composite structures can be analyzed by short beam strength test method according to ASTM D2344 standard [54]. In this regard short beam strength test was applied to composite test specimens to observe fiber matrix bonding strength. Test specimen geometry and dimensions are given in Figure 74 below.

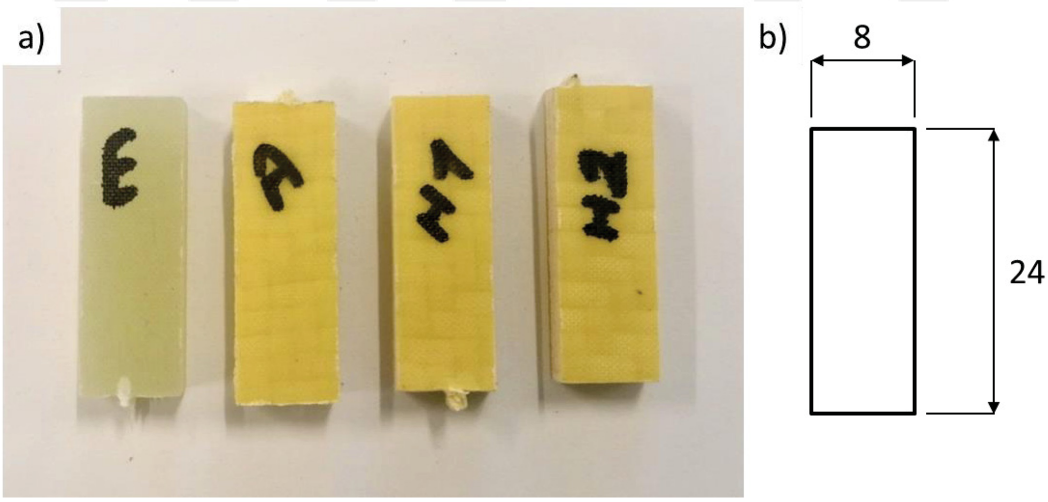


Figure 74. a) Short Beam Strength Test Specimens b) Specimen Dimensions (mm)

Short beam strength of composite specimens was calculated as a result of tests in which support span length was arranged as 16 mm and 1 mm/min crosshead speed was used by the following formula below.

$$F^{sbs} = 0.75 \text{ x } \frac{P_m}{b \text{ x } h}$$

where F^{sbs}, P_m, b and h represent short beam strength, maximum load observed, width and thickness of specimen respectively.

5.3.2. Ballistic Tests

For investigation of ballistic performance of different materials, V50 test method is the most used one. In this regard V50 tests were applied to homogenous and hybrid composite panels by using 1.1 gr (5.56 mm caliber) fragment simulating projectile (FSP) (Figure 75) according to MIL-STD-662F standard [55]. V50 values were calculated by taking average of at least 2 complete penetration and 2 partial penetration velocities in the range of 30 m/s.

FSP threat was used with 7.62 mm sabot and cartridge. 5.56 mm FSP threat was first placed in 7.62 mm sabot. Then, sabot was fixed on top of the barrel in which gunpowder was put to obtain desired impact velocity (Figure 76).

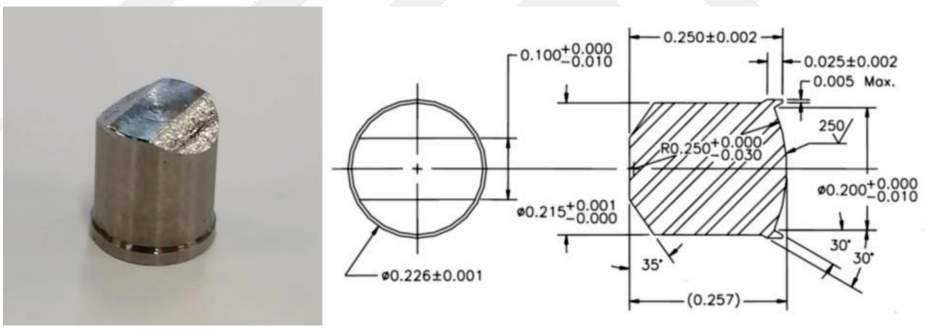


Figure 75. 0.22 Caliber (5.56 mm) Fragment Simulating Projectile and Dimensions [56]

Figure 76. Projectile Preparation

A barrel which was suitable for 7.62 mm cartridge was used for firing 17 meters from target. Ballistic tests were carried out in ROKETSAN Ballistic Protection Center Ballistic Test Laboratory.

CHAPTER 6

RESULTS AND DISCUSSION

6.1. Tensile Test Results

When tensile test results are analyzed it is seen that aramid fiber reinforced composites have higher tensile strength and elastic modulus than hybrid and glass fiber reinforced composite structures.

Table 4. Tensile Test Results

Sample	σ (MPa)	E (GPa)	ε (%)
A	467.4	32.5	1.50
E	435.1	26.1	2.20
H1	451.2	29.7	1.84
H2	437.3	28.8	1.56

However, although glass and hybrid structures have strength and modulus, they have higher elongation than aramid. Since there is tension load during impact event, higher tensile strength is desired for ballistic applications. However, elongation is also an important parameter since it provides delamination and bulging during impact. Lower elongation causes composite structure to be more brittle and therefore main deformation mechanism would be fiber breakage and shear cutting instead of delamination. Based on this it is expected E-Glass and hybrid composites would have more delamination area than aramid composites.

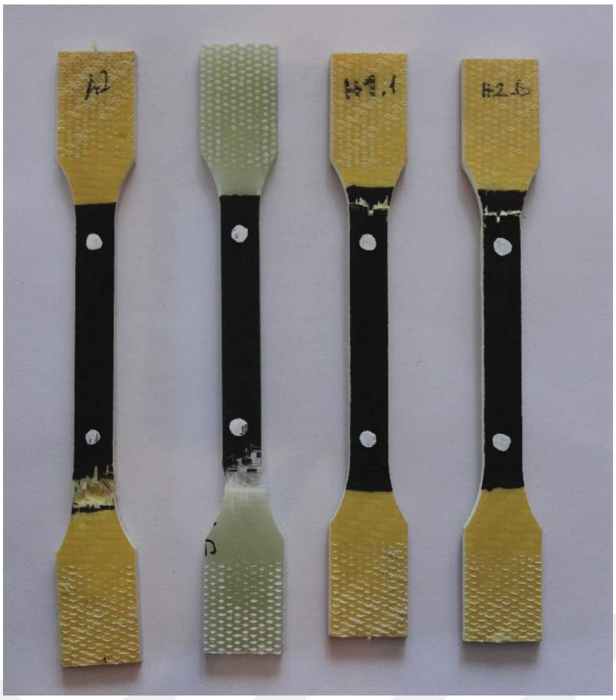


Figure 77. Samples After Tensile Test

6.2. Bending Test Results

Bending characteristic of composites is an important parameter for global response during low velocity impact. Test results show that E-Glass composites have higher bending strength than aramid and hybrid composites showed better performance than aramid and glass fiber composites.

Table 5. Three Point Bending Test Results

Sample	σ_F (MPa)
A	377.9
E	530.2
H1	567.9
H2	566.8

Having higher bending strength provides advantage to composites for low velocity impact. However, for high velocity impact local response takes place and local deformation mechanisms as delamination, bulge, stretching, fiber breakage become more important. Since E-Glass composites have more elongation, although hybrid structures have higher bending strength, E-Glass composites would have better ballistic performance among other composites for the same thickness. Aramid fabrics are generally used with phenolic or polypropylene (PP) resin. These resin types assist aramid fabrics to be stretched and delaminate easily. However, epoxy resin makes aramid structures more brittle and rigid. Therefore, glass and hybrid composites could bend more than aramid composites (Figure 78).

Figure 78. Bending Test Samples

6.3. Short Beam Strength Test Results

During impact event, compressive load that occurs on primary yarns are reflected from back face of composite structure as tension. These compressive and tension loads cause shear formation together. Delamination (energy transfer from primary to secondary yarns) continues until primary yarns fail due to the presence of shear and tension loads. Therefore, shear characteristic of composites affects ballistic properties. Based on this short beam strength test was carried out and it is seen that E-Glass fiber reinforced composite samples showed higher strength among all samples.

Table 6. Short Beam Strength Test Results

Sample	σ_{SB} (MPa)
A	318.8

E	455.0
H1	408.9
H2	396.4

Therefore, E-Glass composites could resist shear load during impact event and transfer more kinetic energy to the secondary yarns from primary yarns. In the Figure 79 below failure mechanisms of composite samples after short beam strength test are seen. More delamination could be observed in E-Glass sample.

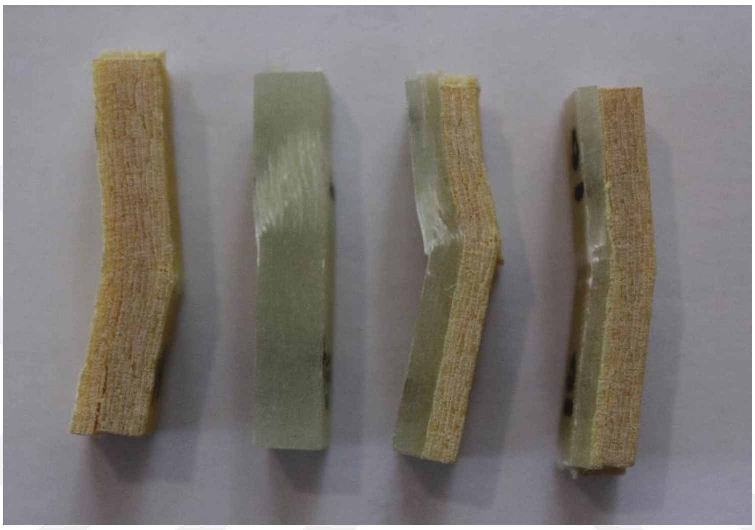


Figure 79. Short Beam Strength Test Samples

6.4. Ballistic Test Results

Ballistic tests were carried out according to MIL-STD-662F standard by measuring V_{50} values of composite panels. Comparison between test samples and fiber types that are mostly used in ballistic applications is made and deformation mechanisms are analyzed.

6.4.1. Deformation Mechanisms

After ballistic tests, test samples were cut by water jet at the impact point and deformation mechanisms are analyzed from cross section of composite panels.

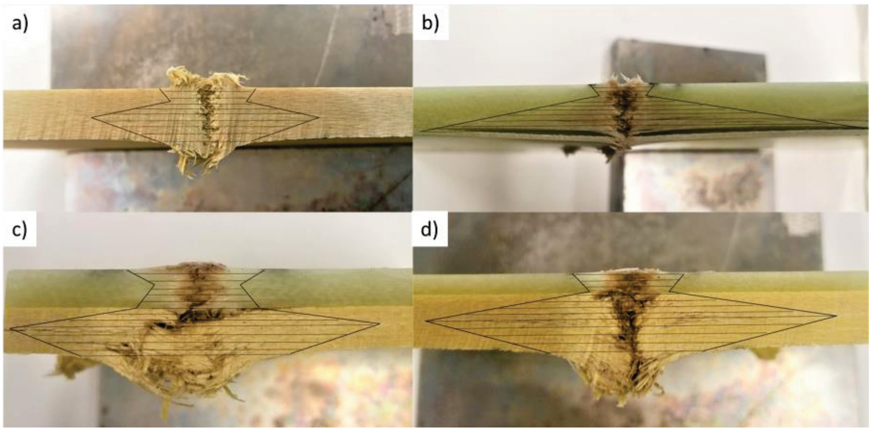


Figure 80. Delamination Area of Composite Test Samples a) Aramid b) E-Glass c) H1 d) H2

According to the Figure above, E-Glass composite structures experienced larger delamination area and at the back-face delamination could be observed. However, for aramid composites delamination is larger in the middle of structures but still it is narrower than E-Glass composites. Delamination area shows energy absorbing capability.

In hybrid structures, it is seen that aramid layers had more delamination area than homogenous aramid composites. The reason can be said to be E-glass assist aramid layers and provide enough time to experience delamination. However, delamination in aramid layers could not continue to grow and became narrow at the exit point of bullet.

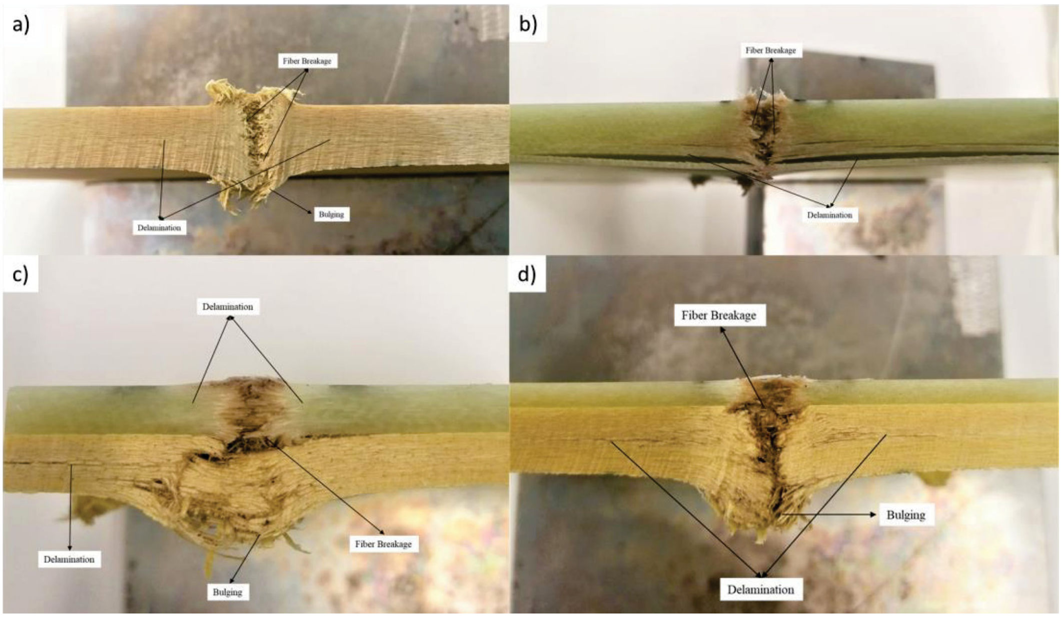


Figure 81. Deformation Mechanisms of Composite Structures a) Aramid b) E-Glass c) H1 d) H2

When the deformation mechanisms are analyzed it is clearly seen that delamination and fiber breakage due to shear cutting are the main deformation mechanisms during impact. Aramid layers experienced also bulging however since delamination is larger for E-Glass structures, they had higher ballistic performance than aramid and hybrid structures for the same thickness.

6.4.2. Ballistic Performance for the Same Thickness

According to the studies in the literature, there is a linear relationship between V_{50} performance of composites and thickness. In this regard, ballistic tests were applied to composite panels with two different thicknesses. Then a linear relationship was derived and V_{50} values for different thicknesses could be determined.

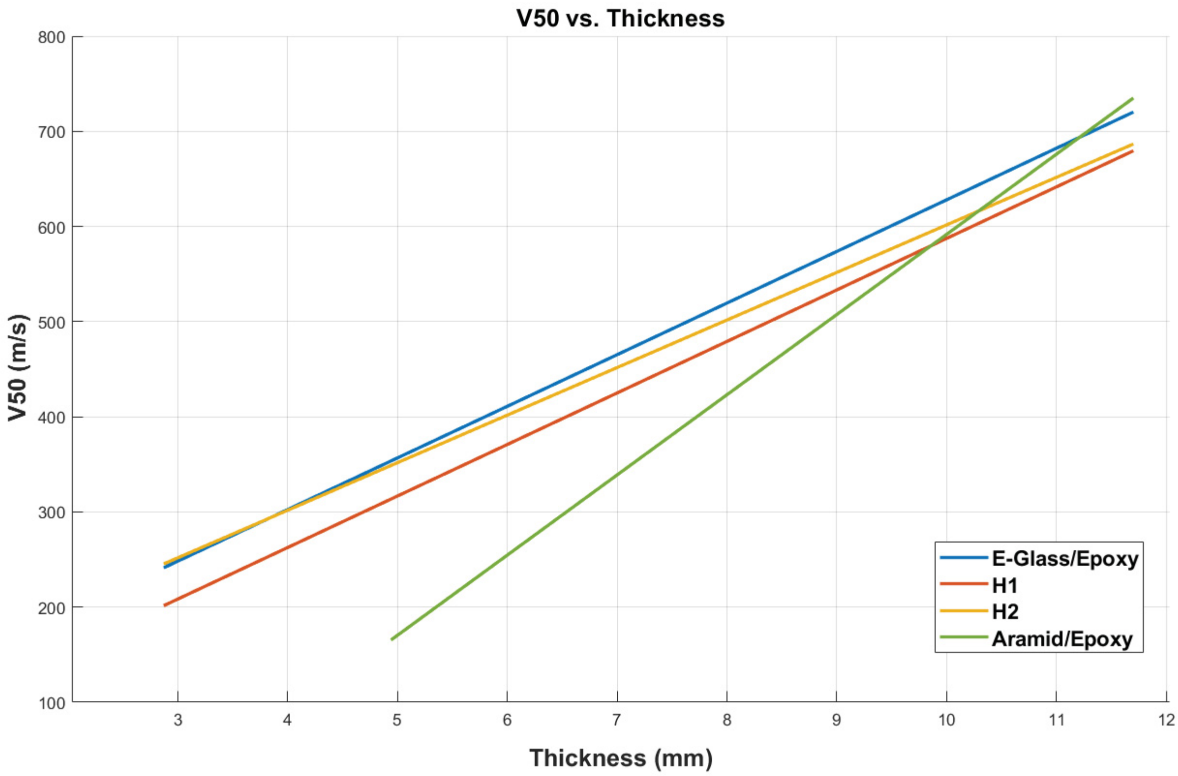


Figure 82. V50 vs Thickness of Composite Panels

As it is seen from the graph for thickness values lower 12 mm E-Glass composites have higher ballistic performance than aramid and hybrid structures. However, for the same thickness values E-Glass composites have higher areal density in other words it is heavier, and this is not a desired property for ballistic composites. As the thickness gets higher aramid structures become better than other composites due to the friction between fabrics and energy absorbing capability. For lower thickness values it is seen that hybridization method served the purpose and increased the ballistic properties while decreasing the weight.

6.4.3. Mass Efficiencies

Mass efficiency (E_m) is an important parameter to compare composite structures with each other. E-Glass composite was chosen as reference and mass efficiencies of aramid and hybrid structures was calculated. Formula below was used for E_m calculation.

$$E_m = {}^{\text{Areal Density}_{\text{REF}}}/_{\text{Areal Density}_{\text{COMP}}}$$

Having mass efficiency higher than 1 means for the same protection level, solution developed is lighter than reference which is desired. In the table below mass efficiencies of composite structures (aramid and hybrid) can be seen. Calculations are made for the same V_{50} value which is 700 m/s.

Table 7. Mass Efficiencies of Composite Panels

Sample	Mass Efficiency
A	1.23
E	1.00
H1	1.08
H2	1.15

It is clearly seen that aramid composites could provide lighter solution for the same level of protection. Among hybrid structures since there is more aramid layers in H2 it could provide lighter protection than H1. However, H1 also has E_m higher than 1.

6.4.4. Comparison with Ballistic Composites

In ballistic applications S2-Glass fiber and aramid fibers with high areal density are mostly preferred as it is stated above. S2-Glass fiber reinforced composites are used due to their high mechanical properties and ballistic aramid fibers are preferred due to their high energy absorbing capability. S2-Glass and ballistic aramid fiber reinforced composites are generally manufactured by using phenolic resin. Phenolic is more suitable for ballistic applications since it has tougher structure than epoxy resin system. Therefore, phenolic resin can absorb more kinetic energy than epoxy resin and any other thermoset resins. V_{50} comparison between hybrid structures manufactured and tested in this study and ballistic composites taken from the study of Merriman et. al. [38] are given in Figure 83.

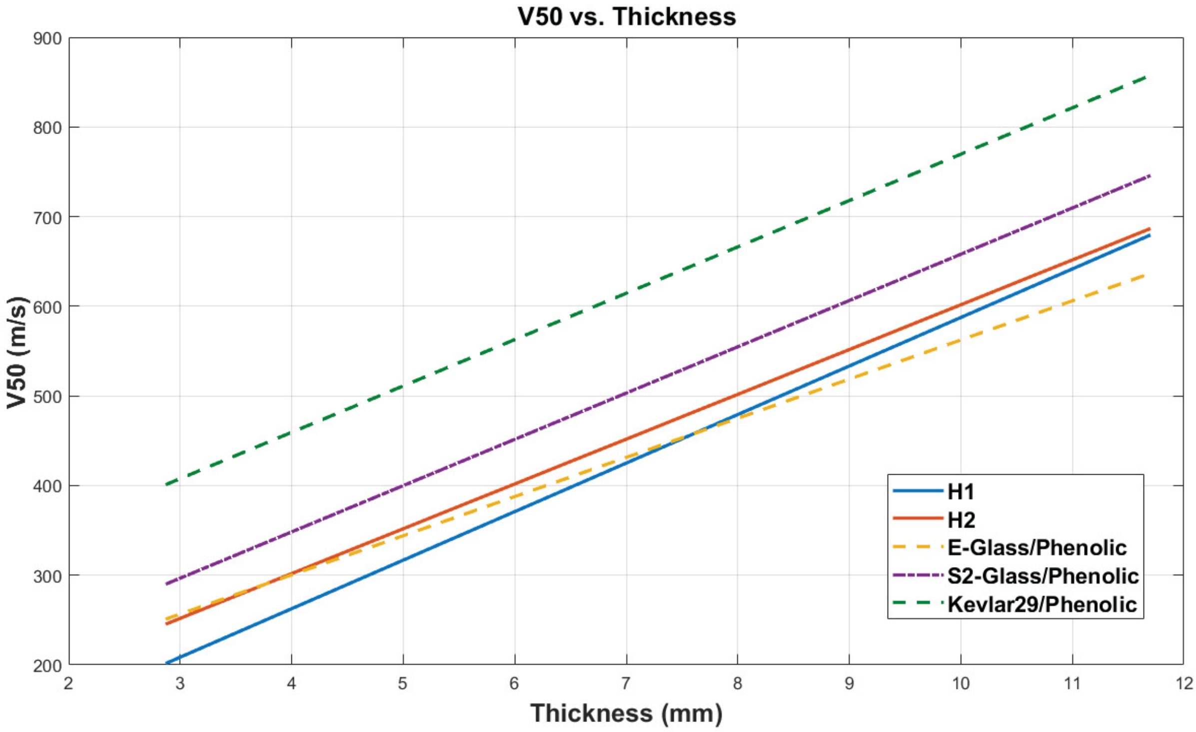


Figure 83. V50 Comparison of Ballistic Composites [38]

It can be seen that hybrid structures showed higher ballistic performance than 814 gr/m² E-Glass/Phenolic composite panels. There is a slight difference between H1 and H2 hybrid structures and S2-Glass/Phenolic composites which is approximately 50 m/s. Kevlar 29 reinforced phenolic composites have much higher ballistic limit performance than other ballistic fibers and hybrid composites due to their higher energy absorbing capability.

When the mass efficiencies were analyzed ("E" was taken as reference) it was found that H1 and H2 hybrid composites have higher mass efficiency than ballistic E-Glass and S2-Glass reinforced phenolic composite panels which refers to lighter solution against same level of threat (Table 7). However, Kevlar-29 composite panels have much higher mass efficiency among other composite panels due to their high energy absorbing capability and lower density.

Table 8. Mass Efficiency Comparison of Ballistic Composites

Sample	Mass Efficiency
E	1.00
H1	1.08
H2	1.15
E-Glass/Phenolic	0.83
S2-Glass/Phenolic	1.01
Kevlar29/Phenolic	1.65

CHAPTER 7

CONCLUSION

Fiber reinforced composites become more popular in each day for ballistic applications since they are lighter than traditional engineering materials as steel and aluminum. As the use of composites increases, more studies on ballistic performance of composite structures have been carried out. There are several methods for ballistic performance enhancement and one of them is hybridization method. In this regard ballistic improvement of composite structures by hybridization method was studied in this thesis.

The most used fiber types for ballistics which are aramid and E-Glass were used for homogeneous and hybrid composite manufacturing. Composite panels with two different thicknesses were manufactured and tested. Tensile, bending, and short beam strength tests were carried out as mechanical tests and V_{50} tests were applied to analyze ballistic performance of composite structures.

Tensile test results show that hybridization increased the tensile strength of E-Glass composites. During ballistic impact tension load is applied to the primary yarns and higher tensile strength is a desired property for impact. However, since elongation of E-Glass composite samples is higher than others, delamination and stretching are easier for E-Glass. Delamination can also be seen in bending and short beam strength test samples. Delamination is easily seen for E-Glass structures while for other composites it is not that clear. Bending and short beam strength of E-Glass composites are higher which means E-Glass layers could resist the impact longer while kinetic energy of the bullet is transferred from primary yarns to secondary yarns. All this characteristic provides E-Glass structures to experience delamination easier which is the most important deformation mechanism for impact events.

Delamination of composite structures are shown in Figure 80. As it is stated above E-Glass composite experienced more delamination while fiber breakage due to shear cutting and bulging are main deformation mechanisms for aramid and hybrid structures. In hybrid composites aramid layers had more delamination area than homogenous aramid composites. E-Glass layers in the front provide aramid layers more time for energy transfer to the secondary yarns and therefore, more delamination in aramid layers could be observed in hybrid structures for the same thickness.

E-Glass composites had higher ballistic performance than aramid and hybrid structures for the same thickness value. However, since E-Glass has higher density, for the same thickness it is heavier and as it is stated in the literature higher areal density provides higher ballistic performance to composite armor structures. For lower thicknesses than approximately 12 mm E-Glass showed better V_{50} performance but as the thickness increases, due to the friction between fibers aramid composites become better than E-Glass and hybrid composite structures. In the graph it can be seen that hybridization method can be used for ballistic improvement of fiber reinforced composites. When hybrid structures are compared with ballistic fiber reinforced composite panels which are 814 g/m² E-Glass and S2-Glass and Kevlar 29 fiber reinforced phenolic composites it is seen that H1 and H2 have higher ballistic performance than E-Glass phenolic composite panels while there is a slight difference between hybrid composites and S2-Glass Phenolic composite panels. Kevlar 29 phenolic composites have much higher V_{50} performance than H1 and H2 for all thickness values due to their high energy absorbing capability [38].

When the mass efficiencies of composites are analyzed, aramid and hybrid structures seem to have mass efficiency higher than 1. Having E_m higher than 1 means composite structure can provide same level of protection with lower areal density (lighter solution). Ballistic fiber reinforced composite panels also have mass efficiency more than 1 (Table 7). It is seen that H1 and H2 hybrid structures have higher mass efficiency than E-Glass and S2-Glass phenolic composites. Due to the low-density Kevlar 29 phenolic composites have much higher mass efficiency among all composites manufactured and tested in the study. This also proved that hybridization is an effective method and based on mechanical and ballistic test results it can be said that hybridization method can be used for ballistic performance enhancement of fiber reinforced composite structures.

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