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HYBRIDIZATION EFFECTS ON TENSILE AND FLEXURAL BEHAVIOR OF LAMINATED COMPOSITE PLATES

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SARKAUT AHMAD KCHANY
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Hybridization Effects on Tensile and Flexural behavior of Laminated Composite Plates

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Sarkaut Ahmad Ameen KCHANY

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Name of the student: Sarkaut Ahmad Ameen KCHANY

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Prof. Dr. Metin BEDİR
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. M. Sait SÖYLEMEZ
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Ahmet ERKLIG
Supervisor

Examining Committee Members:

Prof. Dr. I. Halil GUZELBEY ....

Assoc. Prof. Dr. Ahmet ERKLIG ....

Assist. Prof. Dr. Eyup YETER ....

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Sarkaut KCHANY

ABSTRACT

HYBRIDIZATION EFFECTS ON TENSILE AND FLEXURALE BEHAVIOR OF LAMINATED COMPOSITE PLATES

KCHANY, Sarkaut Ahmad Ameen

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In this study, the influence of hybridization with different stacking configurations on tensile and flexural behavior of hybrid epoxy composites with Carbon, Glass and Kevlar- 49 fibers were investigated. Tensile properties were obtained according to ASTM: D638–10 and flexural strength of the hybrid composites were obtained from the three point bending test according to ASTM: D790-10 at a span-to-depth ratio of 32. Hybrid composites were produced with different fiber weight fractions of Carbon/Glass, Carbon/Kevlar, Glass/Kevlar and Carbon/Glass/Kevlar. It is concluded that the hybridization phenomena is dependent on the strength ratios of Carbon/epoxy, Glass/epoxy and Kevlar/epoxy layers. The maximum change in tensile strength due to hybridization effect was achieved in Carbon/Glass epoxy laminate by replacing the two layers of a full Carbon/epoxy laminate with a Glass/epoxy, the strength decreased by 17.7%, and increased by 60% compared with those of the full Carbon and full Glass configurations, respectively. And also, the maximum change in flexural due to hybridization effect was achieved in Glass/Kevlar epoxy laminate by replacing the top two layers of a full Glass/epoxy laminate with a Kevlar/epoxy, the strength decreased by 26.5% and increased by 78% compared with those of the full Glass and full Kevlar configurations, respectively.

Keywords: Hybrid composites, flexural modulus, tensile strength

ÖZ

TABAKALI KOMPOZİT PLAKLARIN ÇEKME VE EĞİLME DAVRANIŞI ÜZERİNDEKİ HİBRİDİZASYON ETKİLERİ

KCHANY, Sarkaut Ahmad Ameen

Yüksek Lisans Tezi, Makine Müh. Bölümü

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63 sayfa

Bu çalışmada, karbon, cam ve Kevlar- 49 elyaflar ve epoksi reçine ile oluşturulan hibrid kompozitlerin çeki ve eğilme davranışları farklı istifleme konfigürasyonlarına göre hibridizasyon etkileri incelenmiştir. Çeki özellikleri ASTM:D638-10 standardına uygun olarak ve eğilme mukavemeti ASTM: D790-10 standına uygun olarak üç noktalı eğme testiyle elde edilmiştir. Üç noktalı eğme testinde mesnet arası mesafe/kiriş yüksekliği oranı 32 olarak alınmıştır. Karbon / Cam, Karbon / Kevlar, Cam / Kevlar ve Karbon / Cam / Kevlar'dan oluşan farklı konfigürasyonlarda farklı fiber ağırlığı fraksiyonları ile hibrid kompozit plakalar üretilmiştir. Bu melezleme olayları, Karbon / epoksi, cam / epoksi ve Kevlar / epoksi tabakalarının mukavemet oranlarına bağımlı olduğu sonucuna varılmıştır. Maksimum çekme dayanımı tam karbon / epoksi plakasında iki katmanın Cam/epoksi ile değiştirilmesi ile gerçekleşmiştir. Çekme mukavemeti tam Karbon/epoksi plakaya göre %17,7 azalmış ve tam Cam/epoksi plakaya göre %60 oranında artmıştır. Eğilmedeki maksimum değişiklik, tam Cam/epoksi plakasında iki katmanın Kevlar/epoksi plaka ile değiştirilmesiyle gerçekleşmiştir. Buna göre eğme mukavemeti tam Cam/epoksi plakaya göre %26,5 azaldığı, tam Kevlar/epoksi plakaya göre %78 oranında arttığı gözlenmiştir.

Anahtar Kelimeler: Hibrid kompozitler, eğilme modülü, çekme mukavemeti

*This thesis is dedicated to my beloved wife (**Aveen Kchany**), sons and daughters for their endless love, support and encouragement.*

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CHAPTER 1

INTRODUCTION

1.1 General introduction

A composite material is defined as a system made out of two or more phases, whose properties and performances are designed such as the result is greater than those of the constituent materials acting independently. Usually, one of the two phases is a discontinuous one, stiffer and stronger, and is known as the “strengthening”, whereas the other is weaker, less stiff, and continuous, and is called the “matrix”. In some cases, there can be an additional phase resulting from the chemical interactions or other effects, known as “interphase”, occurring between the strengthening and the matrix.

Composite materials mainly represent an evolution of the science and technology of materials, since they blend the best properties of several materials resulting from the most up-to-date technologies, which empower them with outstanding physical and mechanical properties. The study of composites is a kind of philosophy of materials design aiming at enhancing both the composition of materials themselves and their structure, thus leading to a converging and interactive process. It is both a science and a technology, demanding a strict interaction between different study subjects, such as design and structural analysis, study of materials, mechanics of materials, and process engineering.

The speed of technological developments results in an ongoing demand for new and developed materials, and has been a leading force for the progress of composite materials. Until the early twentieth century, no essential progress was noticed in composite materials. Because of the heavy cost of developed composites, cheaper and more resistant materials were utilized. Recently, fiber-reinforced polymer matrix composite materials, which can be rendered for a special area or use, began to be used increasingly.

During the last decades of the 1970s, applications with composites gained approval in the aeronautics, automotive, sports items, and biomedical sectors. Successively, the 1980s saw a meaningful development of the use of high-modulus fibers. Today, the focus is on the development of more modern composites with mixed matrix resins for high- temperature applications. There are several different applications of these composites: buried pipes, containers, boats, road vehicles, aeronautics and space devices, civil engineering applications, automotive components, sports equipment, biomedical products, and many other items designed to have high mechanical performance and/ or dimensional stability in different laminated and low-weight settings [1].

The properties of a composite result from the properties of its constituents, and from the geometry and distribution of the phases. One of the most relevant parameters is the volume (or weight) of the strengthening fraction or the volume ratio of the fibers. The distribution of the strengthening conveys the system its features. The less uniform the strengthening, the more heterogeneous the material and the higher the likeliness of failure in weaker portions, whereas the geometry and orientation of the strengthening impact on the anisotropy of the system. The composite phases play different roles and depend on the typology and application of the composite itself. In case of low- or medium-performance composites, the strengthening is usually made out of short fibers or particles, which allow for a certain stiffness and, at the same time, strengthen the material only locally.

On the other hand, the matrix is the main member responsible for load bearing and for defining the mechanical features of the material. In case of high structural performance composites, they are usually made out of continuous fibers building the frame of the material and conveying it stiffness and resistance toward the fiber direction. The matrix phase conveys protection, support for fibers, and transfer of local strains from one fiber to the other. The interphase, though small in dimension, can play a very important role in controlling the failure mechanisms, the tensile strength, and, above all, the strains/stresses behavior of the material [2].

At the present time, a rapid advancement in composite material technology can be observed, and this provides the market with new products. The expense of the materials decreased in reaction to the increasing demand. Composites are liable to be the material of the future because of their physical and chemical benefits when compared to old industrial materials [3].

Fiber-reinforced composites are rapidly gaining market share, but further growth is limited by their lack of toughness. Lightweight design is becoming increasingly important in various industries, particularly in aerospace, wind energy and automotive applications. Fiber-reinforced composites are attracting more interest for these weight-sensitive applications as their excellent stiffness and strength are combined with a low density. Unfortunately, the high stiffness and strength of these composites come at the expense of their limited toughness. Like most materials, fiber-reinforced composites also face the strength versus toughness dilemma.

Over the years, toughening of fiber-reinforced polymer composites has been a highly active research area. Many different strategies have been proposed to make these materials more damage resistant and less brittle. One of the most researched strategy is toughening of the polymer matrix by tuning the polymer chemistry or by rubbers, thermoplastics or nano-scale reinforcements. In this strategy, the increased matrix toughness has a beneficial effect on the matrix-dominated composite properties [4–6].

In search of new toughening mechanisms, there has been an increasing interest in structure–property relations of biological composites that are exceptionally resilient to failure [7–9].

1.2 Definition of hybrid composite

The failure strain and toughness can be significantly increased if brittle fibers are replaced by ductile fibers. In this respect, metal fibers have the potential of high stiffness and large failure strain, but they are hampered by their high densities. Polymer fibers, on the other hand, do have low densities and can be ductile, but are limited by their low stiffness and limited temperature resistance. Because of the drawbacks of these toughening strategies and the strong need for new lightweight materials with improved toughness, the research interest in ‘‘hybridization’’, is reviving. The term ‘hybrid composite’ is generally used to describe a matrix containing at least two types of reinforcements. Such composites are also called ‘fiber hybrids’ or ‘fiber hybrid composites. [9]

In other words, hybrid composites consist of two or more types of reinforcements or matrices or both. By mixing different fibers, it is possible to combine the advantages of different fibers while simultaneously mitigating their less desirable qualities. Normally, one of the fibers in a hybrid composite is a high strength, high cost and high modulus fiber such as carbon/graphite, and the other fiber usually is a low modulus, low cost fiber like Kevlar, S- glass or E-glass. Hybrid composites are attractive structural materials, because the composite properties can be tailored or designed to fit the requirements. [10]

Hybrid composites incorporate four major kinds:

- Interply hybrids, that are composed of plies from two or more different unidirectional composites stacked according to a specific sequence.
- Intraply hybrids, made of two or more different fibers jumbled in the same ply.
- Interply-intraply hybrids, in which interply and intraply hybrids are organized according to a given sequence.
- Super hybrids, which are resin-matrix composite plies arranged according to a certain order.

1.3 Definitions of tensile and flexural strength:

Tensile strength can be defined as the limit of a material to withstand tensile stress without causing failure to the material. Tensile stress occurs when an object is subjected to forces that make the object extends. Opposite of tensile stress is compressive stress. Common example of tensile stress is pulling a rubber band and if the stress is beyond its strength, then the rubber band will break.

Meanwhile, we can define the flexural strength as the limit of a material to resist flexural stress without failing. If an object is subjected to flexural stress, it will undergo both tension and compression behaviour because of bending moment.

Flexural strength of a material will depend on either its tensile strength or compressive strength, whichever is lesser. Most common example of a flexural stress is by bending a specimen into a U shape. The upper surface of the specimen will be subjected to compressive stress while bottom surface will undergo tensile stress. If you bend it further, you may see the bottom surface of the specimen will start to crack, which indicates that it the stress applied to it is beyond its flexural strength.

1.4 Significance of the study

The technological interest in producing lighter and higher quality materials is due to the possible reduction of the costs and this, consequently, attracts new customers. The composite quality is based on the phases involved and also on the process. Fiber construction in different weft and warp permits a variety of mechanical properties and can be generated for a given part design.

Carbon fibers are widely known reinforcement substance for their superior characteristics such as the ideal mechanical capacity and modulus of elasticity, low density, and good flame resistance. It makes carbon fiber irreplaceable in wide sectors of engineering technology such as for automobile, aircraft, ships, construction, and sport equipment. However, carbon fiber composites are rather susceptible to stress concentration due to the brittleness of carbon fiber. In addition, carbon fiber involves costly production. One way to improve the weakness of carbon fiber reinforced plastic (CFRP) composite is by replacing some layers of the carbon fiber by ductile fibers such as Kevlar fiber.

More durable and less flexural affected materials can be obtained with the use of hybrid composite material. Material distribution in layers, required number of layers to avoid flexural can be determined. In this way, the benefits of hybrid laminated composites can be determined specially for automotive and aircraft industry.

1.5 Methods and Outline of the Study

In this work, interply hybrid composites were prepared with carbon fiber, glass fiber and Kevlar fiber as reinforcements and epoxy resin as matrix. Then from these hybrid composite laminates, specimens for tensile and flexural tests should be prepared with dimensions as per ASTM standards.

The study has been divided into 5 chapters.

General introduction and definitions on composite materials and hybrid composites, tensile and flexural strengths are given in the first chapter. First chapter also includes importance of the study and outline of the study.

Literature review is given in chapter 2. Literature review has been grouped in five sections; Introduction, Composite laminates and some factors effect on their characteristics, studies about hybridization effect on general mechanical properties of fiber reinforced Composite plates, studies on hybridization effect on tensile and flexural strength of Carbon, Glass and Kevlar fibers reinforced composites plates and Conclusion on Literature Review.

In chapter 3, Information about producing composites and hybrid composites by hand lay-up process and production methods are given. Also mechanical properties, standards and test methods to determine these mechanical properties are given in this chapter.

Tensile and flexural experiments and the results which were conducted to see effects of different hybrid configurations on these properties are given in chapter 4 for different fiber stacking configurations.

General conclusions and future works are given in chapter 5.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

A brief literature related to composite, hybrid composite materials, tensile and flexural strength of composite materials is presented in this chapter. This literature review has been grouped in four sections: studies on Composite laminates and some factors effect on their characteristics are reviewed in section 2.2, studies on hybridization effect on General mechanical properties of fiber-reinforced Composite plates are reviewed in section 2.3, studies on Hybridization effect on Tensile and Flexural strengths of Carbon, Glass and Kevlar fibers reinforced composites plates are reviewed in section 2.4, Conclusion on Literature Review are reviewed in section 2.5

2.2 Composite laminates and some factors effect on their characteristics:

There are many factors that effect on the properties of laminate composites which cannot be confined to such research, but some of them can be mentioned:

Yousif et al. [11] studied the flexural properties of unidirectional long kenaf fiber reinforced epoxy (KFRE) composites. The kenaf fibers were prepared into two types as untreated and treated (with 6% NaOH). The results displayed that reinforcement of epoxy with treated kenaf fibers increased the flexural strength of the composite by about 36%, while, untreated fibers introduced 20% improvement.

Ahn et al. [12] are investigated the failure analysis of composite materials (unidirectional woven) which used in airplane control rod by experimentally and numerically. Specimens having many unlike geometries (formed changing the width to hole diameter and the edge distance to the hole diameter ratios, considering hole size constant) were used in the tests.

Failure modes and loads were determined by testing under pin loading and effects of different geometries were obtained. Also numerical analyses were done and results were compared. It was found that these different geometries have a huge effect on the composite properties.

Aktas and Karakuzu [13] investigated the effects of temperature on mechanical properties (tensile, compressive, shear) of glass/epoxy composite plates. The used temperatures of experiments were 20°C, 40°C, 60°C, 80°C, and 100°C. Laminated composite plates were cured at constant pressure of 250 KPa with a constant temperature of 120 °C and a curing time of 2h. After that, laminated composite plates were cooled to room temperature at constant pressure of 250 KPa. It was shown that reduction of mechanical properties caused by increasing of temperature.

Zou and Lam [14] investigated the effect of layer numbers, lamina thickness, ratio of Young's modulus in plane and lateral direction and fiber orientations (cross-ply and angle-ply) on buckling were researched using FEM (using high-order shear deformable finite strip). It was found that these factors have a huge effect on the composite properties.

Singh and Verma [15] analyzed the buckling characteristics of composite plate including temperature and moisture effects. In the study, FEM (using high-order shear deformation theory) were used to derive buckling equations. Influences of span to thickness ratio, stacking sequences, plate dimensions on the hydrothermal buckling were investigated. Also different boundary conditions were examined.

Sun et al. [16] studied numerically the delamination effects on compressive failure response of composites. Von Karman's equations to include nonlinearities was used to find buckling, post buckling, contact influences of delaminated region, progress of delaminated region, fiber and matrix cracking. Progress of delaminated region was considered by using a fracture theory which controls energy dissipated during fracture along delaminated region. It was concluded that delamination growth is influenced extremely from boundary types, and stiffness deterioration have considerable effects on buckling strength.

2.3 Hybridization effect on general mechanical properties of fiber reinforced composite plates:

Haq et al. [17] mentioned that hybridization enables to exploit the synergy between natural fibers and inorganic compounds, leading to properties improvement while maintaining environmental appeal. One advantage of hybridization is cost reduction; some reinforcements are very expensive and could be combined with less expensive materials maintaining good properties. For example, with the addition of natural fibers, good mechanical properties can be obtained at a lower cost.

Sarasini et al. [18] studied the effects of basalt fiber hybridization on low velocity impact behaviour of carbon/epoxy laminates. Interply hybrid specimens with two different stacking sequences (sandwich-like and intercalated) are tested. Results indicate that hybrid laminates with intercalated configuration (alternating sequence of basalt and carbon fabrics) have better impact energy absorption capability and enhanced damage tolerance with respect to the all-carbon laminates, while hybrid laminates with sandwich-like configuration (seven carbon fabric layers at the center of the laminate as core and three basalt fabric layers for each side of the composite as skins) present the most favourable flexural behaviour.

Peijs and De Kok. [19] Studied the tensile and fatigue behaviour of unidirectional carbon-high-performance polyethylene/epoxy hybrid composites, including the effect of hybrid design and surface treatment of the high-performance polyethylene (HP-PE) fibers. Results indicated that the tensile behaviour of carbon-HP-PE hybrids in both monotonic and fatigue testing can be interpreted, adopting the conventional ‘constant strain’ model for hybrid composites. Hybrid effects under tensile loading conditions were in reasonable agreement with calculations accounting for statistical effects and stress concentrations as determined by finite element analyses.

Shan et al. [20] studied environmental fatigue behavior and life prediction of unidirectional glass–carbon/epoxy hybrid composites. The results indicated that a much better performance in fatigue can be achieved for glass–carbon hybrid composite by incorporating appropriate amount of carbon fibers in glass fiber composite.

Gustin et al. [21] investigated Impact, compression after impact, and tensile stiffness properties of carbon fiber and Kevlar combination sandwich composites. The different samples consisted of impact-side face sheets having different combinations of carbon fiber/Kevlar and carbon fiber/hybrid. The bottom face sheets remained entirely carbon fiber to maintain the high overall flexural stiffness of the sandwich composite. It is shown that the addition of Kevlar to the face sheet improved the maximum absorbed energy, also the elastic moduli, E1 and E2, were reduced when Kevlar or hybrid were added to the face sheet. However, the reduction can be minimized to around 9% by replacing only one layer of carbon fiber with Kevlar or hybrid.

Yadav et al. [22] studied the Fracture toughness behaviour of carbon fiber epoxy composite with Kevlar reinforced interleave, this work was to evaluate as to how fracture toughness is affected by interleave having Kevlar fiber reinforcement in the fracture plane. Thermoset interleave and chopped Kevlar fibers were applied between the carbon/epoxy composite layers. Results obtained that fracture toughness enhanced up to about two times in all the laminates. However, enhancement in fracture toughness was more effective in interleaved laminate than Kevlar reinforced interleaved because of large energy absorbing capabilities of interleaf. Mechanism of fracture and toughening were examined by using scanning electron microscope.

Bazhenov [23] studied the flexural failure of a unidirectional aramid SVM/epoxy composite by using two-point loading of half-ring specimens. Similar to slip bands in metals, it was observed that failure originated near the compressive side of the specimen where several intersecting shear yield bands. The maximum failure stress of the composite in bending, 530 MPa, was approximately twice as high as the strength of the composite under pure axial compression (260-280 MPa). In bending the composite is elastic in the tensile part of the beam whilst the other, compressed, part is elastic-plastic.

Kitano et al. [24] investigated the influence of different types of fibers on the mechanical properties of hybrid composite materials. Long and short glass fibers (GF) and different types of organic fibers, Kevlar-49 (KF) and liquid crystalline polymer (LCP) in hybrid composites, were used to reinforce the high density polyethylene (HDPE) matrix. The influence of fiber content, length, and mixing ratio on mechanical properties, such as tensile, bending, was studied. Fracture surfaces of the materials were also examined using a scanning electron microscopy. It was observed that tensile strength of long fiber hybrid composites decreased with increasing Glass fibers content. For short fiber composites the change was small, and the Kevlar fiber hybrids showed better tensile strength than the other composites.

Fonseca et al. [25] studied the properties of high density polyethylene based hybrid composites made with two natural fibers: agave and pine. The results displayed that addition of agave fibers improves impact, tensile and flexural strength, while pine fibers decreases water uptake.

Ramesh et al. [26] prepared hybrid composites of sisal–jute–glass fibers and found that the incorporation of sisal–jute fibers can improve tensile, flexural and impact strength used as an alternate material for glass fiber reinforced polymer composites.

Arrakhiz et al. [27] elaborated PP/pine cone fiber/clay composites and found that the addition of clay to PP/pine composites improved the tensile properties.

Ashori [28] studied hybrid composites made from waste materials which are also a great option to develop new materials with specific properties and low costs. Hybrid composites made with newspaper fibers and poplar wood flour was prepared. It was observed that the addition of both fibers enhanced the tensile and flexural modulus compare with neat polypropylene, but increasing wood flour reduced flexural and tensile moduli.

Fernandes et al. [29] prepared composites from high density polyethylene (HDPE) filled with cork powder and coconut short fibers. The addition of coconut fiber to cork–HDPE composites increased the elastic modulus and tensile strength by 27% and 47% respectively, compared to cork–HDPE composites.

Boopalan et al. [30] observed the effect of adding banana fiber to jute–epoxy composites and obtained increased mechanical properties with lower moisture absorption.

Naik et al. [31] investigated impact behaviour and post impact compressive characteristics of carbon-glass/epoxy hybrid composites with alternate stacking sequences. In their study plain weave E-glass and twill weave T-300 carbon have been used as reinforcing materials. Also, laminates containing only-glass and only-carbon reinforcements have been studied for comparison. Experimental studies have been carried out on instrumented drop weight impact test apparatus. It is observed that hybrid composites are less notch sensitive compared to only-glass or only-carbon composites. Moreover, carbon-outside/glass-inside collected hybrid arrangement gives lower notch sensitivity compared to the other hybrid arrangements.

Pandya et al. [32] studied the mechanical properties of hybrid composites H1[G3C2]$_s$ and H2[C2G3]$_s$ which compared with those of 8H satin weave T300 carbon/epoxy and plain weave E-glass/epoxy. The specific observations are: For hybrid composites, placing glass layers in the exterior and carbon layers in the interior gives higher ultimate tensile strain and tensile strength than placing carbon layers in the exterior and glass layers in the interior. Also, a similar approach is used for the calculation of tensile strength of hybrid composites starting with properties of carbon fiber composite and glass fiber composite and composite volume fractions. It may be noted that the carbon fiber composite has higher elastic and strength properties than that for the glass fiber composite. At lower carbon composite volume fractions, the property of hybrid composites would be governed by glass fiber composites, whereas at higher carbon composite volume fractions, the property of hybrid composites would be governed by carbon fiber composites.

Hitchen and Kemp [33] studied the effect of stacking sequence on mechanical properties, including impact damage tolerance, has been studied in the study and the results compared with non-hybrid data. By optimizing the stacking sequence the hybrid material exhibited a mechanical performance similar to that of the ultra-high-performance material and a performance superior to the standard material.

Sevkat et al. [34] investigated the effect of repeated impacts on the response of plain-woven hybrid composites, the repeated low-velocity impact responses of hybrid plain-woven composite panels were studied by drop-weight experiments. Non-hybrid S2-glass-fiber/toughened epoxy and IM7 graphite fiber/toughened epoxy as well as hybrid S2-glass–IM7 graphite fiber/toughened epoxy composite panels were impacted repeatedly. The effects of hybridization and lay-up sequence on the repeated drop-weight impact responses of woven composites were investigated. It was observed that damage accumulations could be slowed down using hybridization. It was also witnessed that the lay-up configuration of a hybrid composite had a significant influence on damage accumulation rate. The hybrid specimens with glass–epoxy skins survived the double number of successive impacts compared to hybrid specimens with graphite–epoxy skins.

Hwang and Mao [35] investigated buckling characteristics of inter-ply hybrid composites (E-glass /Epoxy and Carbon/Epoxy) including delamination. It was found that nonlinear buckling analysis were given near results with experimental results.

Önal [36] studied the stability analysis of symmetrical and antisymmetric cross-ply layered hybrid composites (Boron/Epoxy and E-glass /Epoxy) plates having slope crack. The buckling characteristics were determined using FE and FSDT technics.

Kar et al. [37] searched Fatigue characteristics of hybrid composite rods containing unidirectional glass and carbon fibers. The rods were comprised of a carbon fiber core surrounded by a glass fiber shell. They determined Damage characteristics by considering stiffness reduction as a function of cycles, and fatigue failure was given with strength variation.

Hosur et al. [38] investigated Impact behaviors of hybrid composites with low velocity impact loads. Hybrid composites were produced with plain weave S2 glass and twill-weave carbon fibers. Square plates having dimensions 100x100 mm and thickness 3mm were exposed to low velocity impact loads at 4 energy levels of 10, 20, 30 and 40 J. An important increase on load carrying capability with small decrease in stiffness were found.

Sayer and Bektaş [39] studied impact characteristics of Carbon/Epoxy and Glass/Epoxy hybrid composites with increasing impact energies and different temperatures. The increasing impact energies were applied to the specimens until perforation took place at various temperatures as -20, 0, 20 and 40 ^{0} C of specimens. Those specimens were composed by two types of fiber orientation with eight laminates hybrid composites. In order to show relation between impact and absorbed energy, an energy profile diagram were used.

Also, Sayer et al. [40] investigated the impact characteristics of hybrid composites produced using (carbon-glass /epoxy). The increased impact energy was performed on two types of hybrid composite plates until complete perforation of specimens. The failure processes of damaged specimens for different impact energies were evaluated by comparing load–deflection curves and images of damaged samples taken from impacted sides and non-impacted sides. Cross-sections of damaged specimens were also checked visually and discussed to estimate the amount of damage, such as fiber fracture in layers, expansion of delamination between neighboring layers.

Ghasemnejad et al. [41] studied the influences of hybrid composite beams containing various delaminated region and locations. To see energy absorption ability of composite beams having delamination the Charpy impact tests were conducted. Hybrid composite beams were manufactured by combining Carbon/Epoxy and Glass/Epoxy. Results were shown that composite beams containing delaminated region near to impacted surface were absorbed higher energy than other locations.

Durao et al. [42] evaluated effect of drilling to delamination formations. Two types of laminates (Carbon/Epoxy and Glass/Epoxy) were drilled in this work using different machining parameters and comparing drill geometries. Results showed the importance of a careful selection of these variables when drilling of composites is involved.

Marom et al. [43] studied the effects of stacking sequence and degree of hybridization on the impact energy of carbon-Kevlar/epoxy hybrid composites. A positive hybrid effect was noticed for a segregated hybrid in which one layer of carbon fibers was sandwiched between two layers of Kevlar. Hybrids with a greater degree of hybridization showed a negative hybrid effect, irrespective of whether the outer layers were carbon or Kevlar.

2.4 Hybridization effect on tensile and flexural strengths of Carbon, Glass and Kevlar fibers reinforced composites plates:

2.4.1 Tensile and flexural strength of hybrid composite reinforced by carbon fibers:

Park and Jang [44] incorporated polyethylene (PE) fibers with carbon fibers in an epoxy matrix to form a hybrid composite laminate. They used PE fibers because of its high elongation at break, and high specific strength and stiffness. They concluded that the mechanical properties of hybrid composite strongly depended on the reinforcing fiber position, such that, when carbon fiber was positioned at the outermost layer, the hybrid composite showed the highest flexural strength.

GuruRaja and HariRao. [45] conducted experimentally on Glass fiber/Carbon fiber/Epoxy resin hybrid angle ply laminates with different fiber orientation to characterize the tensile properties. The following conclusions were drawn and recorded: (a) the glass fibers fail quickly than the carbon fibers. The five layers of glass plies at front opposed the applied load greater than the five layers of glass plies at back in woven glass/carbon hybrid composites. (b) Incorporation of woven glass/carbon in extreme plies of composites enhances the improved mechanical properties of hybrid composites. (c) Failures of composite materials include the fracture of fibers, fracture of matrix in tension normal to the fibers. And the nature of failure is also depends on the Angle ply between the fibers and specimen’s axis. (d) Scanning electron micrographs showed that the fiber pull out started from glass fibers and good interfacial bond was developed between woven glass and epoxy resin matrix. However, some micrographs are revealed the presence of voids, thus degrading the strength.

Subagia et al. [46] investigated the effect of different stacking sequences of carbon and basalt fabrics on the flexural properties of hybrid composite laminates. The hybrid composites were fabricated using a vacuum assisted resin transfer molding process. Their results showed that the flexural strength and modulus of hybrid composite laminates were strongly dependent on the sequence of fiber reinforcement. All the stacking sequences showed a positive hybridization effect. The interply hybrid composite with carbon fiber at the compressive side exhibited higher flexural strength and modulus than when basalt fabric was placed at the compressive side. Here, the proper stacking sequence of basalt and carbon fiber layers was found to improve the balance of the mechanical properties of the hybrid composite laminate.

Li et al. [47] investigated the compressive and flexural behavior of ultra-high-modulus polyethylene fiber and carbon fiber hybrid composites. Five types of unidirectional composites an ultra-high-modulus polyethylene fiber (UHMPE) reinforced composite, a carbon-fiber-reinforced composite and three UHMPE carbon hybrid composites with epoxy resin as the matrix, and different hybrid ratios were fabricated. The results show that the incorporation of a moderate amount of carbon fiber into a UHMPE-fiber-reinforced composite greatly improves the compressive strength, flexural modulus and flexural strength while the addition of a small amount of UHMPE fiber into a carbon-fib-reinforced composite significantly enhances the ductility with only a small decrease in the compressive strength.

Subagia et al. [48] are investigated the performances of the carbon-basalt/epoxy hybrid composites under flexural loading. In their work, the hybrid composites were manufactured by the vacuum assisted resin transfer molding (VARTM) process. The variations of flexural strength and modulus of the hybrid composite according to the number of basalt fabric were investigated, and they obtained the expression to calculate their mechanical properties. In the study of flexural properties for the hybrid composites with different stacking sequence of the reinforcements, they knew that their properties strongly depend on the reinforcing position of carbon and basalt fabric.

Dong et al. [49] are studied the flexural behaviour of hybrid composites reinforced by S-2 glass and T700S carbon fibers in an intra-ply configuration. For the purpose of confirmation, specimens of selected stacking configurations were manufactured following the hand lay-up process and tested in a three point bend configuration. It was shown that flexural modulus increases when the span-to-depth ratio increases from 16 to 32 but is approximately constant as the span-to-depth ratio further increases. Flexural strength increases with span-to-depth ratio. Utilization of hybridization can improve the flexural strength.

Furthermore, Dong et al. [50] investigated the flexural properties of hybrid glass and carbon fiber reinforced epoxy composites. Three combinations of the carbon and glass fibers, i.e. S-2&T700S, S-2&TR30S and E&TR30S, were chosen to make hybrid composite specimens.. It was found that the dominant failure mode was compressive failure. The experiments suggest flexural modulus decreases with increasing percentage of glass fibers. Positive hybrid effects exist by substituting carbon fibers with glass fibers on the compressive surface.

Sudarisman [51] are studied the hybridization effects on the flexural properties of unidirectional glass fiber-reinforced polymer composites. It was noted that the replacement 33% of E-glass fiber by S-2 glass fiber produced an increase in flexural strength of 23%, without any significant effects of the hybridization on the flexural modulus.

Diharjo et al. [52] studied the flexural properties of bisphenol-A reinforced woven roving carbon/glass fibers hybrid composites. The composites were manufactured using a hand lay-up process. The variables in this study were the replacement of glass fibers with carbon fibers on both upper and lower sides symmetrically. The result showed that the bending strength and modulus increased with the increasing of carbon fibers. The highest flexural strength is achieved when reinforcement fiber of the specimens consist 90% carbon fibers.

de Paiva et al. [53] investigated the mechanical and morphological characterizations of carbon fiber fabric reinforced epoxy composites used in aeronautical field, it was discovered that the side in which the crack propagation appears or the most susceptible to crack is the compressive side.

Also Dorigato, and Pegoretti [54] observed that in CFRP, the fatigue stress is effectively transferred along the carbon fibers, so that high flexural strength is achieved for CFRP but with more brittle property.

Davis et al. [55] studied the improvements in mechanical properties of a carbon fiber epoxy composite using nanotube science and technology, it was shown that one cause of the onset of buckling is due to the curvature or waviness of the component fabric.

Das S. [56], studied the cost of automotive polymer composites, it was investigated that the use of CFRP in cars could decrease the vehicle’s weight by 40–60%. However, the high cost of carbon fiber only limits its application to luxury cars and aerospace vehicles. Thus, there is a need to reduce the cost of CFRP without sacrificing a lot in its mechanical performance.

2.4.2 Tensile and flexural strength of hybrid composite reinforced by glass fibers:

Kalnin [57] studied the hybridization effect on flexural behavior of composite laminate consisting of glass and graphite reinforcement, it was found that the flexural strength decreases rapidly as an all-glass reinforcement is progressively replaced by graphite fiber.

Ho and Lau [58] introduced short silk fibers into the woven glass fiber reinforced polymer composites to form a new hybrid composite which possesses better Young’s modulus and impact resistance properties.

Rathnakar et al. [59] are studied experimentally the Strength and Stiffness of Fiber Reinforced Composites under Flexural loading. Their study aims at investigating the flexural parameters of epoxy glass & graphite fiber reinforced composites when subjected to static flexural loading using Flexural Test system. The main findings of this investigation are as follows:

- Effect of thickness on flexural strength and stiffness seems to play a critical role in assessing material behavior under flexural loading conditions.
- Three point bending method probably provides a better estimate of the actual material behavior under flexural loading.
- There is a significant improvement in strength and stiffness of graphite laminates as compared to glass for same thicknesses under test. This may be due to good adhesion between graphite fiber and matrix.

Babukiran and Harish [60] are investigated the influence of Resin & Thickness of laminates on carbon, glass and graphite fiber epoxy laminates with carbon, glass and graphite fiber polyester resin. Biwoven carbon fiber, glass fiber & graphite fiber are used as reinforcement materials in the form of bidirectional as shown in the Figure

2.1, the machine is designated as PNP-01 and is shown in the Figure 2.2 their research indicates that flexural strength is dependent mainly on the type of resin used and thickness of laminated polymer composites.

Figure 2.1 Bi woven carbon, glass and graphite fibers

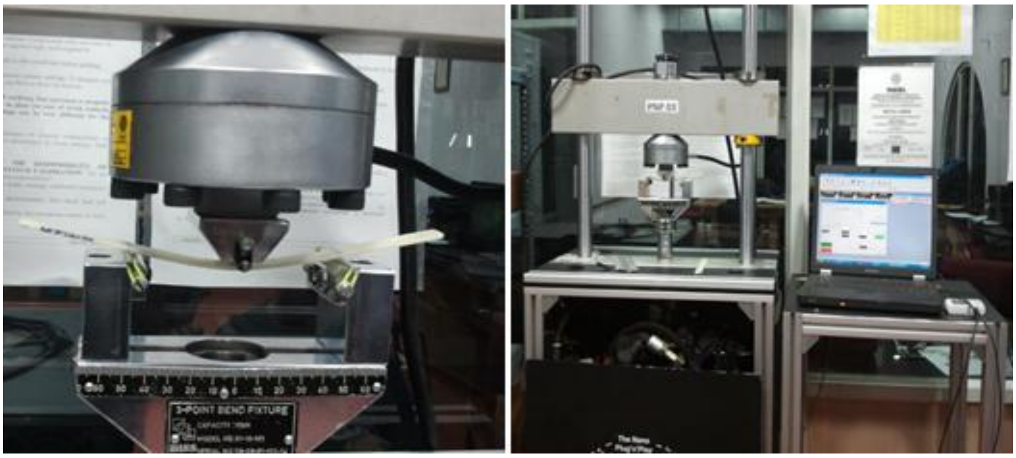


Figure 2.2 A versatile and comprehensive testing machine

Also Dong et al. [61] studied the flexural strength of hybrid epoxy composites reinforced by S-2 glass and T700S carbon fibers in an intra-ply configuration, different stacking configurations of carbon fiber (C) and glass fiber (G) laminas were studied as shown in the Fig. 2.3.The flexural strength was obtained from the three point bend test at various span-to-depth ratios as described in the Fig. 2.4. It is shown that the flexural strength increases with span to-depth ratio and converges when the span-to-depth ratio is greater than 32. Also, it was indicated that hybridization can be used to improve the flexural strength.

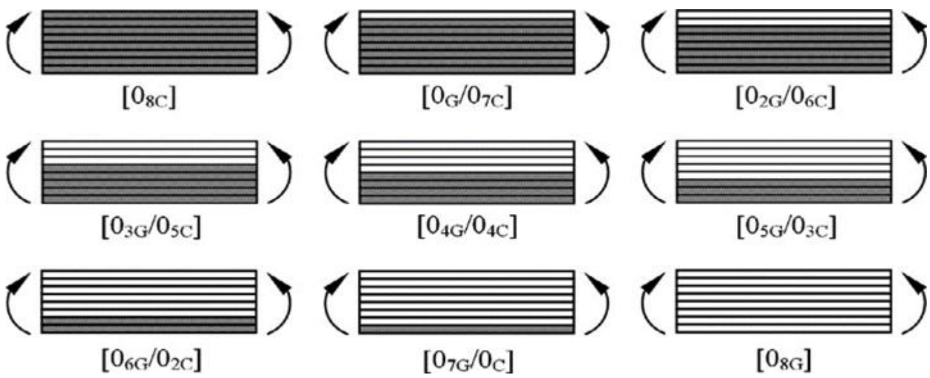


Figure 2.3 Stacking configurations of carbon fiber (C) and glass fiber (G) laminas.

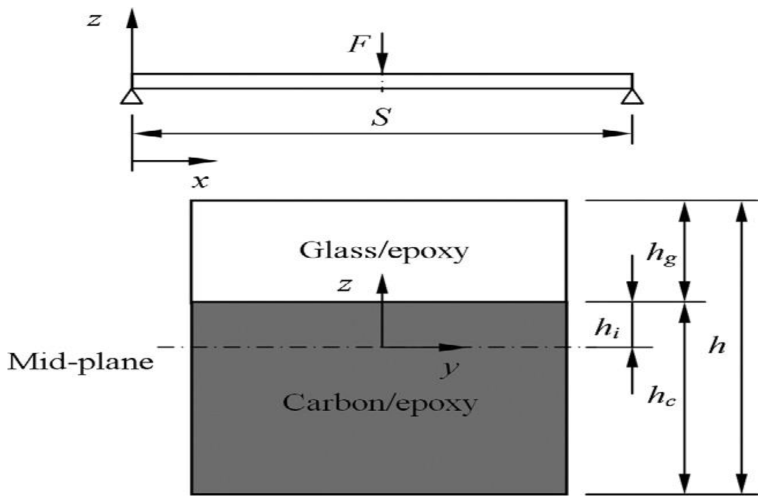


Figure 2.4 A hybrid composite specimen in the three point bending.

Valente et al. [62] studied hybrid thermoplastic composites from wood flour and recycled glass fibers. Also, hybrid composites containing virgin glass fibers were manufactured and tested in order to evaluate the effect of recycled glass fibers. Mechanical properties of the composites including flexural modulus and strength, hardness as a function of temperature were studied. The flexural modulus and hardness were found to increase as a function of increasing wood flour and glass fiber content, whilst the flexural strength decreased as a function of increasing wood flour content, even though a positive effect of the addition of glass fibers was found. The recycled glass fibers showed comparable behavior to that of the vestal ones.

Zhang et al. [63] studied the mechanical behaviors of unidirectional flax and glass fiber reinforced hybrid composites. The tensile properties of the hybrid composites were improved with the increasing of glass fiber. Based on the hybrid effect of tensile failure strain, a modified model for calculating the tensile strength was given. The stacking sequence was shown an influence on the tensile strength and tensile failure strain, but not the tensile modulus. The fracture toughness of the hybrid composites were even higher than those of glass fiber reinforced composites due to the excellent hybrid performance of the hybrid interface.

Thwe et al. [64] fabricated short bamboo fiber reinforced polypropylene composites (BFRP) and short bamboo-glass fiber reinforced polypropylene hybrid composites (BGRP) by using a compression molding method. By incorporating up to 20% (by mass) glass fiber, the tensile and flexural modulus of BGRP were increased by 12.5 and 10%, respectively; and the tensile and flexural strength were increased by 7 and 25%, respectively, compared to those of BFRP. Therefore, it is shown that the durability of bamboo fiber reinforced polypropylene can be enhanced by hybridization with small amount of glass fibers.

Petrucci et al. [65] studied the production by vacuum infusion and the comparison of the properties of different hybrid composite laminates, based on basalt fiber composites as the inner core, and using glass, flax and hemp fiber laminates to produce symmetrical configurations, with a 21–23% fiber volume for all of them, in an epoxy resin. The laminates have been subjected to tensile, three-point flexural strength tests. The mechanical performance of all the hybrid laminates appears superior to pure hemp and flax fiber reinforced laminates and lower to basalt fiber laminates. Among all of the hybrids, the best properties are offered by those obtained by adding glass and flax to basalt fiber reinforced laminates.

Almeida et al. [66] investigated the effect of hybridizing glass and curaua fibers on the mechanical properties of their composites. These composites were produced by hot compression molding, with distinct overall fiber volume fraction, existence each pure curaua fiber, pure glass fiber or hybrid. The mechanical characterization was performed by tensile, flexural, short beam. From the obtained results, it was observed that the tensile strength and modulus increased with glass fiber incorporation.

Brocks et al. [67] studied the flexural properties of hybrid composites reinforced by S-2 glass and T700S carbon fibers, a span to depth ratio of 32 is used. It is obvious that the dominant failure mode is compressive failure. Also it is seen that Flexural modulus decreases with increasing percentage of S-2 glass fibers. By substituting carbon fibers with glass fibers positive hybrid effects existed. The highest flexural strength is achieved when the specimens consist 24% S-glass fibers. The experiments show increases of 3.2% and 8.0% when compared with those of the full glass and carbon configurations respectively, and the FEA prediction shows increases of 31.1% and 27.5%.

Zhang et al. [68] investigated carbon/glass composite laminates under static loading under tension, compression and three-point-bending. To effectively improve the tensile, compressive and flexural strength of the plain glass fiber composite, glass/carbon (50:50) fiber reinforcement was used either by placing the carbon layers at the exterior or by placing different fiber types alternatively. With the same hybrid composition, the stacking sequence did not show noticeable influence on the tensile properties but affected the flexural and compressive properties significantly. The current composite system exhibited more matrix failure under flexural loading and more reinforcement failure under compressive loading.

2.4.3 Tensile and flexural strength of hybrid composite reinforced by Kevlar fibers:

Wan et al. [69] found that the hybrid composites showed significant improvements in flexural strength and interfacial adhesion strength after two-step surface treatment, suggesting this process was efficient. Furthermore, the two-step surface treated carbon/Kevlar hybrid fibers-reinforced composite showed a positive hybrid effect on flexural strength, indicating the existence of hybrid effect is related to the nature of fiber–matrix interface.

Rongxian and Hui [70] studied Kevlar fibers (KFs) which used as a reinforcement for wood-flour/high-density polyethylene composites (WF/HDPE) to improve the mechanical properties of the resulting composites. Addition of a small amount (2–3%) of KF caused an improvement in the tensile, flexural, and impact properties of WF/HDPE. It can accordingly be concluded that the grafted KF can be used as a reinforcement to improve the strength and toughness of WF/HDPE composites.

Valença et al. [71] used composite plates were manufactured by hand lay-up process with epoxy matrix (DGEBA) reinforced with Kevlar fiber plain fabric and Kevlar/glass hybrid fabric. By tensile, bending and impact tests the results of the mechanical properties of composites were obtained. Composites with Kevlar/glass hybrid structure in the reinforcing fabric showed the better results with respect to specific mechanical strength, as well as bending and impact energy.

Isa et al. [72] studied experimentally the effect of fiber types and their combinations on the properties of unsaturated polyester composite. The samples were produced using hand lay-up method followed by compression and tested according to ASTM standards. The results showed that the Kevlar reinforced composite (KFRP) had the highest tensile strength and hand woven nylon fiber reinforced composite (LNFRP) with the least value. Furthermore, the combination of fibers improved the thermal stability of the hybrid composites. Positive effects of hybridization were also observed for density and water absorptivity.

Wan et al. [73] investigated short, unidirectional and laminated hybrid composites extensively. 3-D braided carbon and Kevlar fibers were hybridized to reinforce a bismaleimide (BMI) resin. The effect of carbon to Kevlar ratio on such mechanical properties as load displacement behaviour, flexural strength and modulus, shear strength, and impact properties were investigated. The effect of surface treatment of hybrid fabrics on the flexural properties was also determined. Experimental results showed that the flexural strength and modulus of the 3-D braided carbon/Kevlar/BMI composites increased with relative carbon fiber loading up to a carbon to Kevlar ratio 3:2 and then dropped. Positive hybrid effects were observed for both flexural strength and modulus. The results proved that hybridization with certain amount of ductile Kevlar fiber significantly promoted the shear strength, impact energy absorption characteristics and damage tolerance of the all-carbon composite, which is of importance for the 3-D braided composites to be used in bone fixations.

2.5 Conclusion on literature review

The following conclusions can be derived from the literature review:

- Hybrid composites are attracting an ever growing attention from both academia and industry. More research is needed to fully exploit the potential of metallic and polymer fibers. Many processes have reached a certain maturity for non-hybrid composites, and open new opportunities for hybrid composites. It is expected that this will further widen the applicability of hybrid composites.

- In this literature, there are many investigations on polymer matrix composites, hybrid composites and some mechanical processing are conducted on them such as impact, buckling, fatigue and so on.
- Tensile and flexural strength of composites has been investigated by many researchers.
- More of the hybrid composites that are studied have two different types of fiber.
- Also, it is seen from the literature that the existence of hybrid effects is still a question because of the varied results. This study aims to elaborate on these results by utilizing different configurations of twill Kevlar-49 fiber, woven Glass fiber and woven Carbon fiber layers and investigates the effect of these hybrid composite laminates on the tensile and flexural behavior experimentally.
- In this study, Three types of fibers plain woven Carbon/epoxy (CFRP), plain woven Glass/epoxy (GFRP) and twill woven Kevlar- 49/epoxy (KFRP) are used. Interply hybrid composite plates having two different types of fiber (Carbon/Glass, Carbon/Kevlar and Glass/Kevlar) in 10 layers and hybrid composite plates having three different types of fiber (carbon/glass/Kevlar) in 12 layers as reinforcements and epoxy resin as the matrix have been produced.

CHAPTER 3

EXPERIMENTAL STUDIES

PRODUCTION OF COMPOSITE PLATES AND DETERMINATION OF MECHANICAL PROPERTIES

3.1 Introduction

This chapter demonstrates the production of composite plates and determination of mechanical properties of these laminates.

3.2 Materials:

In the production of composite plates, plain woven Carbon fibers (200 g/m^2), plain woven S-Glass fibers (200 g/m^2) and twill woven Kevlar- 49 fibers (170 g/m^2) have been used. MGS L285 epoxy resin and MGS H285 hardener are used at a ratio of (1/0.285) in the production of composite plates.

3.3 Production of hybrid composite laminates:

Fibers were cut to the required dimensions (for the present work 220mm x 250mm) by using EC fiber cutter as shown in Figure 3.1. The weight fraction of the fibers was about (45.76 - 69.58) wt. % in every panel of hybrid composite laminate. Composite laminates were fabricated by hand lay-up process at room temperature (25°C) in a clean environment, proper care was taken during the preparation of laminates to prevent the voids. The first layer of woven fiber cloth was laid and resin was spread uniformly over the cloth by means of brush, the same procedure was repeated for the second layer. After second layer, to enhance wetting and impregnation, a teethed steel roller is used to roll over the fabric before applying resin as shown in Figure 3.2. Also resin was tapped and dabbed with spatula before spreading it over fabric layer. This process is repeated till all the 10 layers were placed. After applying resin, the laminates have been placed in the production unit (Figure 3.3).

(a) (b) (c)

Figure 3.1 Cutting fibers by EC, a) S-glass, b) Carbon and c) Kevlar

(a) (b)

Figure 3.2 composite production a) resin application and rolling the laminate by teethed steel roller b) production unit

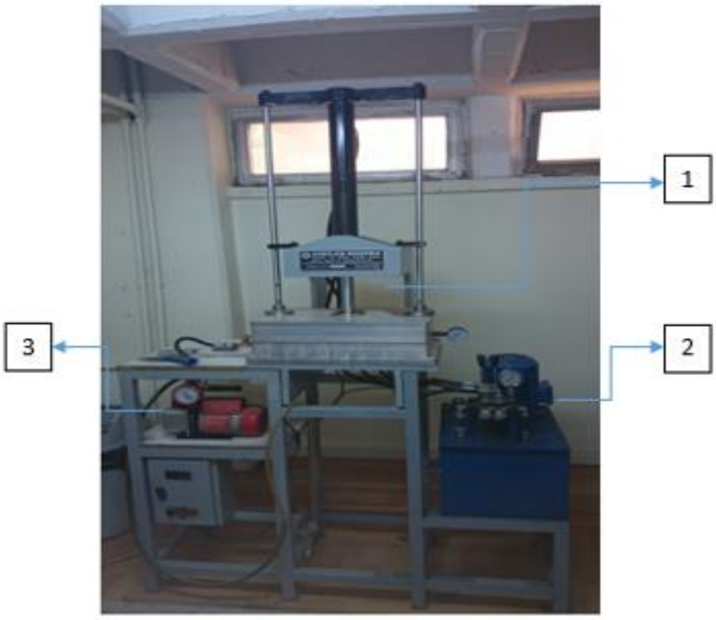
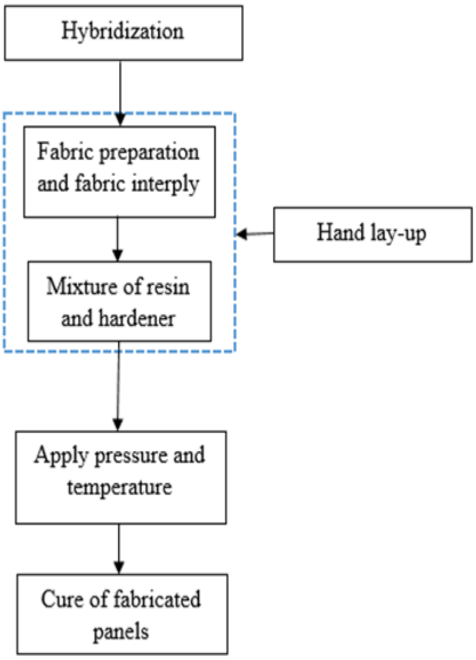
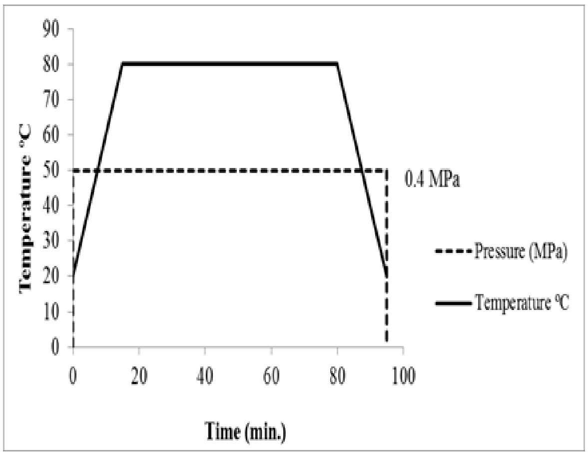


Figure 3.3 Production unit. (1) Combination of heat, pressure and vacuum, (2) Hydraulic unit, (3) Vacuum pump

The wetted fiber reinforcements were cured in the production unit for 1 hour at a temperature and pressure of 80 °C and 0.4 MPa respectively (curing time). Then, the composite laminates were cooled to room temperature under pressure for three hours at least. Finally the product laminate removed from the mold to get a fine finished composite plate. This process was repeated to prepare all of the hybrid laminates. A flow chart used in the fabrication of hybrid composites and curing process is given in Figure 3.4





(a) (b)

Figure 3.4 (a) Process flow chart used in the fabrication of hybrid composites, and (b) The curing process.

To check the effect of stacking configurations, different fabric layers of carbon, glass and Kevlar fibers were used for a total of 10 fabric layers incorporated in the composite laminate, and varied their stacking configurations according to the arrangements given in the Table 3-1 and also produced plates are shown in Figure 3.5. Six specimens (3 for tensile test and 3 for flexural) have been prepared from produced composite plates.

Table 3.1 Configurations of CFRP, GFRP, KFRP and hybrid composite laminates.

No	Naming	Laminate stacking configurations	Laminate Codes	Weight Fractions (%)		
				V_{fc}	V_{fk}	V_{fg}
1	C_{10}		CFRP	63.50	-	-
2	C_8K_2		$1H_2$	52.10	11.26	-
3	C_6K_4		$1H_4$	39.07	22.53	-
4	C_4K_6		$1H_6$	26.56	34.46	-
5	C_2K_8		$1H_8$	12.24	42.35	-
6	K_{10}		KFRP	-	55.62	-
7	G_{10}		GFRP	-	-	61.20
8	G_8K_2		$2H_2$	-	9.45	43.70
9	G_6K_4		$2H_4$	-	22.25	38.58
10	G_4K_6		$2H_6$	-	25.84	19.92
11	G_2K_8		$2H_8$	-	39.94	11.54
12	C_8G_2		$3H_2$	55.67	-	13.91
13	C_6G_4		$3H_4$	36.28	-	24.19
14	C_4G_6		$3H_6$	25.40	-	38.10
15	C_2G_8		$3H_8$	12.24	-	48.96
16	$K_4C_4G_4$		H_9	20.73	17.93	20.73
17	$C_4K_4G_4$		H_{10}	20.09	17.39	20.09
18	$K_4G_4C_4$		H_{11}	20.92	19.63	20.92

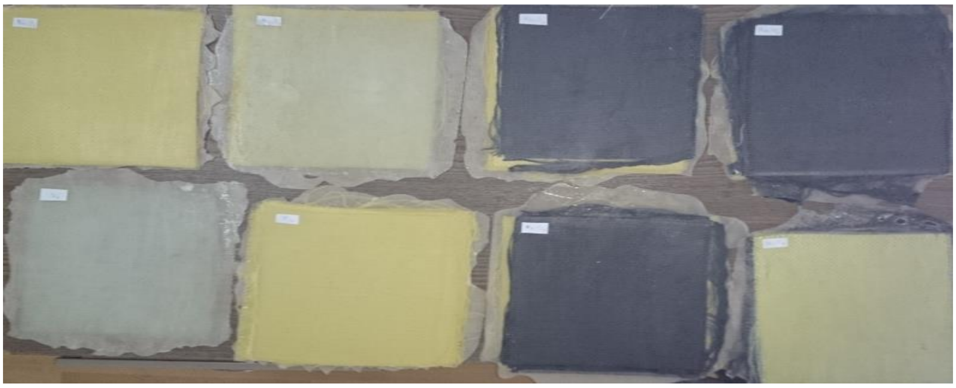


Figure 3.5 Examples of produced composite and hybrid composite plates.

3.4 Preparation of test specimens:

After the cure process, the test specimens were cut from the sheet to the required size as per ASTM standards (D638–10) [74] for tensile test and (D-790) [75] for flexural test, by using CNC machine. All the specimens were finished by abrading the edges on a fine emery cloth paper. Example of produced tensile test specimens was given in Figure 3.6.

Figure 3.6 Examples of tensile test specimens

3.5 Determination of the mechanical properties

S-Glass/Epoxy, Carbon/Epoxy and Kevlar/Epoxy composite materials having different stacking configurations have been produced to determine mechanical properties. Then, specimens have been prepared from produced composites plates. The main mechanical properties of laminated composite plates are tensile strength (σ_t), flexural strength (σ_f) and flexural modulus (E_f). These mechanical properties were determined according to the American Society for Testing and Materials (ASTM) standards.

3.5.1 Determination of tensile properties

Tensile properties of specimens of plates were determined according to the ASTM D638–10 standard test method. Suitable dimensions for this standard are given in the Figure 3.7. Type 1 configuration of ASTM 638-10 standard have been used considering specimen dimensions as width of narrow section (W) 13 mm, length of narrow section (L) 57 mm, overall width (WO) 19 mm, overall length (LO) 165 mm, gage length (G) 50 mm, distance between grips (L) 115 mm and radius of fillet (R) 76 mm.

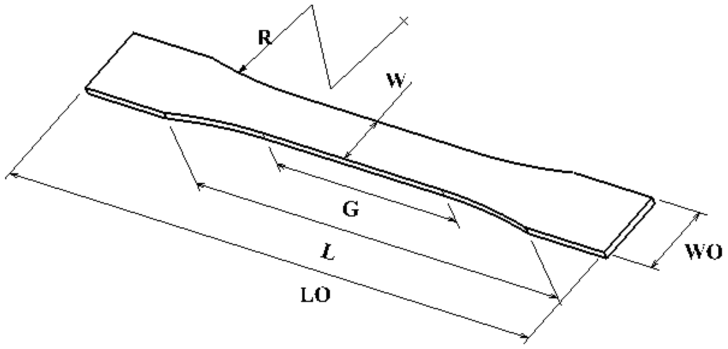


Figure 3.7 The dimensions of the tensile specimens according to ASTM 638-10

Mechanical properties of samples were obtained using Shimadzu AG-X series testing machine (Figures 3.8 and 3.9). To determine tension properties, specimens were loaded in tension direction with the 2 mm/min speed up to failure. Then tensile strength (σ_t), were determined using the stress and strain data's obtained from the testing machine. Example of produced flexural test specimens was given in Figure 3.10.

Figure 3.8 Test set-up Shimadzu AG-X series testing machine (tensile test)

Figure 3.9 Test set-up Shimadzu AG-X series testing machine (flexural test)

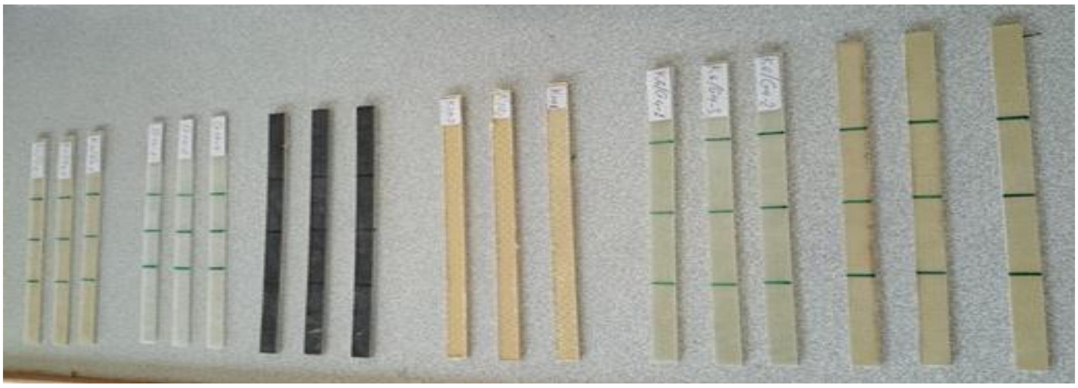


Figure 3.10 Examples of flexural test specimens

3.5.2 Determination of flexural properties

Flexural properties of specimens were determined according to the ASTM D790- 00 standard test method, a suitable specimens of rectangular cross section (L= 200mm, w =12.7mm and t = thickness of the laminate) rests on two supports and was loaded by means of a loading nose midway between the supports (Figure 3.11). A support span-to-depth ratio of 32:1 was used (These test methods utilize a three-point loading system applied to a simply supported beam). To determine flexural properties, specimens were loaded in perpendicular direction with the 3 mm/min speed up to failure.

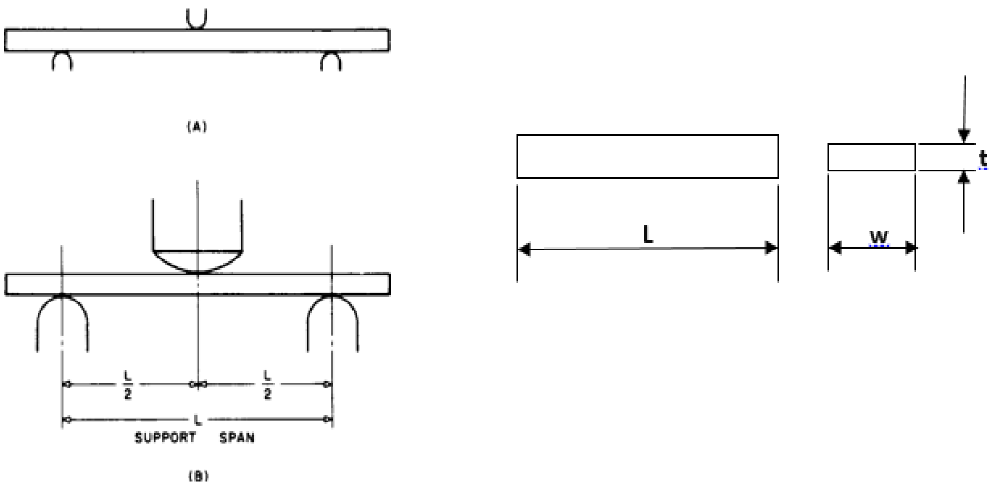


Figure 3.11 the dimensions of the flexural specimens according to ASTM D 790 - 00

The mechanical properties of the samples (Tensile strength and strain, Flexural strength, flexural modulus & strain) were determined from the test machine data's by using the following equations. [75]

$$\sigma_F = \frac{3P_{max}\,L}{2bh^2}\left[1 + 6\left(\frac{D}{L}\right)^2 - 4\,\left(\frac{h}{L}\right)\,\left(\frac{D}{L}\right)\right] \qquad (1)$$

$$E_F = \frac{m\,L^3}{4bh^3} \qquad (2)$$

$$\varepsilon_F = \frac{6Dh}{L^2} \qquad .(3)$$

Where L, b and h are the span, width and depth of the specimen, m is the slope of the tangent to the initial straight-line portion of the load–deflection curve, D is the maximum deflection before failure and P is the load at a given point on the load-deflection curve.

Because the loading nose is wider than the test specimen's width, the center load is uniformly distributed along the width of the specimens, and the load is unidirectional.

CHAPTER 4

EXPERIMENT RESULTS AND DISCUSSION

4.1 Tensile properties

The results obtained from the experimental work on the tensile testing of different fibers of laminated composites were illustrated in the Tables 4.1-4.4, which represent averages of maximum tensile strain and maximum tensile stress of the different stacking configuration of the laminates.

Table 4.1 Tensile Properties for CFRP, GFRP and KFRP interply hybrid composites.

Laminate	Max. strain	Max. Stress (MPa)	Average Stress (MPa)
CFRP- 1	0.0465	773.82	
CFRP- 2	0.0413	727.47	750.64
CFRP- 3	0.0445	750.64	
$1H_2$- 1	0.0416	704.69	
$1H_2$- 2	0.0413	612.79	681.67
$1H_2$- 3	0.0407	727.54	
$1H_4$- 1	0.0403	632.03	
$1H_4$- 2	0.0382	620.50	625.83
$1H_4$- 3	0.0438	624.97	
$1H_6$- 1	0.0393	551.31	
$1H_6$- 2	0.0376	534.03	543.12
$1H_6$- 3	0.0440	544.03	
$1H_8$- 1	0.0445	465.65	
$1H_8$- 2	0.0408	443.21	453.43
$1H_8$- 3	0.0397	451.44	

KFRP- 1	0.0430	415.72	
KFRP- 2	0.0478	455.35	447.46
KFRP- 3	0.0476	471.28	

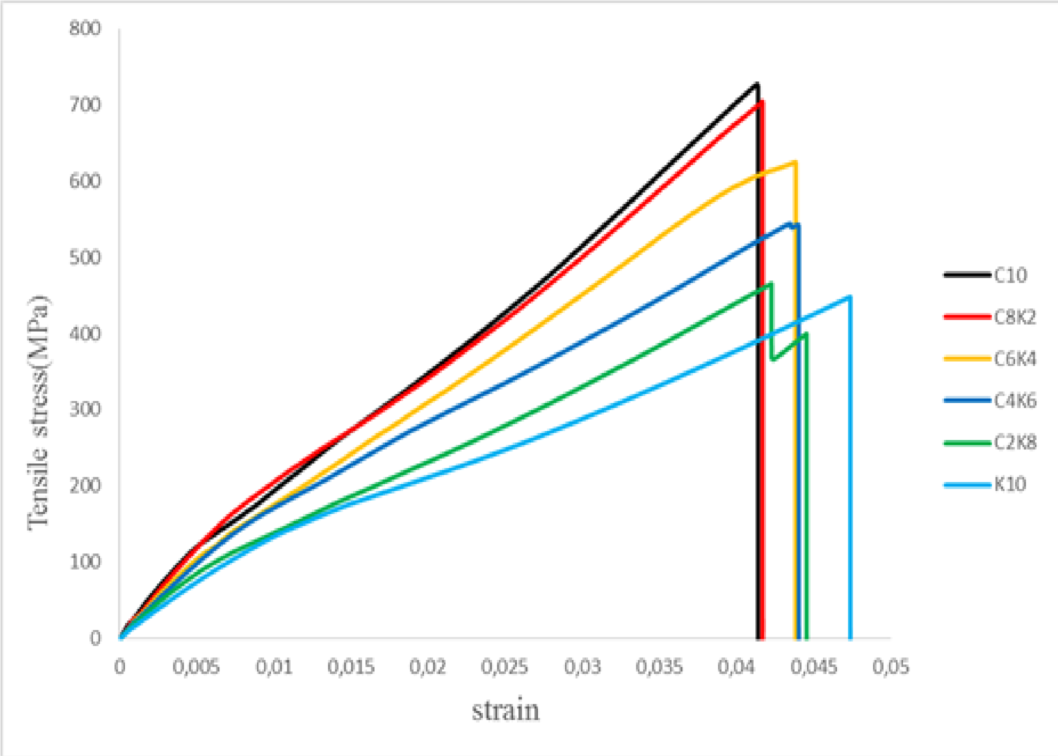


Figure 4.1 Tensile stress–strain curves for CFRP. KFRP and interply hybrid composites.

Table 4.2 shows tensile strength values of hybridization of Glass fibers with Kevlar fibers and also tensile stress to strain curves were given in Figure 4.2.

Table4.2: Tensile Properties for GFRP. KFRP and interply hybrid composites.

Laminate	**Max. strain**	**Max. Stress (MPa)**	**Average Stress (MPa)**
GFRP-1	0.0374	385.80	
GFRP-2	0.0360	378.58	384.73
GFRP-3	0.0370	389.80	
$2H_2$ -1	0.0373	407.35	
$2H_2$ -2	0.0384	409.18	407.30
$2H_2$ -3	0.0362	405.36	
$2H_4$ -1	0.0364	412.26	
$2H_4$ -2	0.0369	417.25	419.35
$2H_4$ -3	0.0419	428.54	
$2H_6$ -1	0.0483	453.06	
$2H_6$ -2	0.0430	433.50	443.58
$2H_6$ -3	0.0435	444.17	
$2H_8$ -1	0.0392	396.01	
$2H_8$ -2	0.0444	469.45	444.83
$2H_8$ -3	0.0443	469.03	
KFRP -1	0.0430	415.72	
KFRP -2	0.0478	455.35	447.46
KFRP -3	0.0476	471.28	

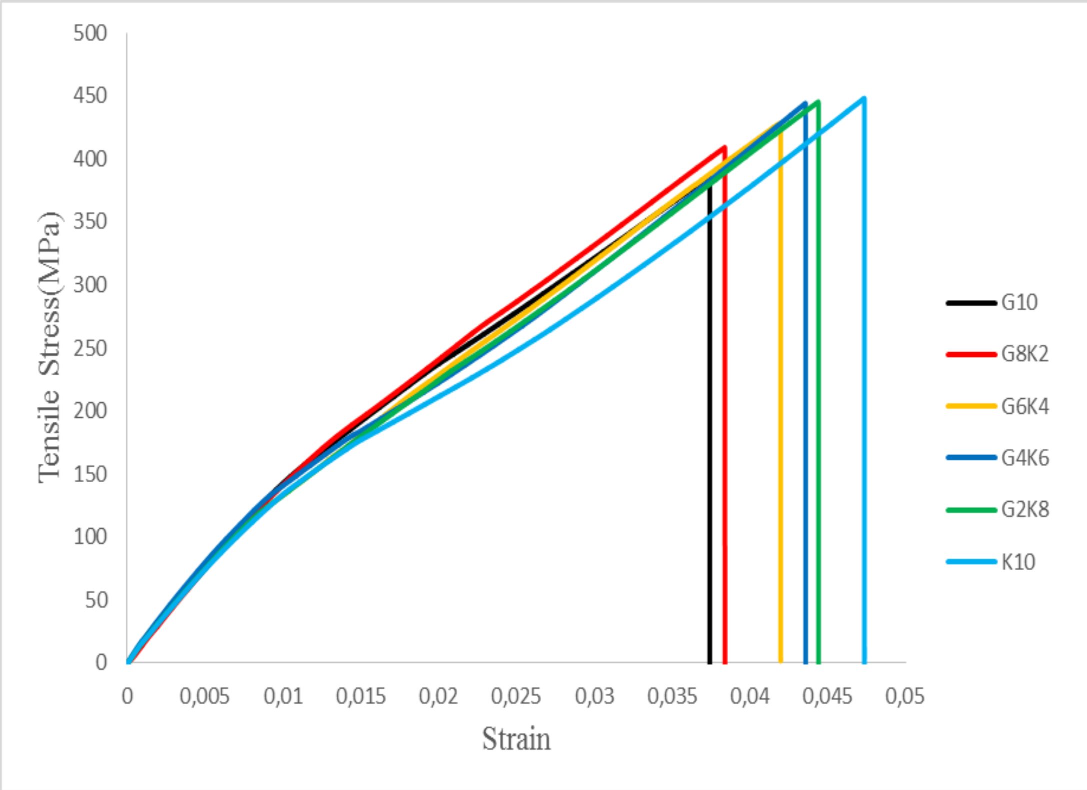


Figure 4.2 Tensile stress–strain curves for GFRP. KFRP and interply hybrid composites.

Table 4.3 shows tensile strength values of hybridization of Glass fibers with Carbon fibers and also tensile stress to strain curves are given in Figure 4.3.

Table 4.3: Tensile Properties for CFRP. GFRP and interply hybrid composites with different stacking configurations.

Laminate	Max. strain	Max. Stress (MPa)	Average Stress (MPa)
CFRP- 1	0.0465	773.82	
CFRP- 2	0.0413	727.47	750.64
CFRP- 3	0.0445	750.64	
$3H_2$ - 1	0.0403	608.66	
$3H_2$ - 2	0.0415	617.59	611.64
$3H_2$ - 3	0.0403	608.66	
$3H_4$ - 1	0.0388	548.78	
$3H_4$ - 2	0.0354	519.22	534.00
$3H_4$ - 3	0.0262	360.27	
$3H_6$ - 1	0.0396	466.61	
$3H_6$ - 2	0.0436	530.18	488.03
$3H_6$ - 3	0.0384	467.30	
$3H_8$ - 1	0.0383	423.77	
$3H_8$ - 2	0.0409	400.52	418.70
$3H_8$ - 3	0.0405	431.81	
GFRP-1	0.0374	385.80	
GFRP-2	0.0360	378.58	384.73
GFRP-3	0.0370	389.80	

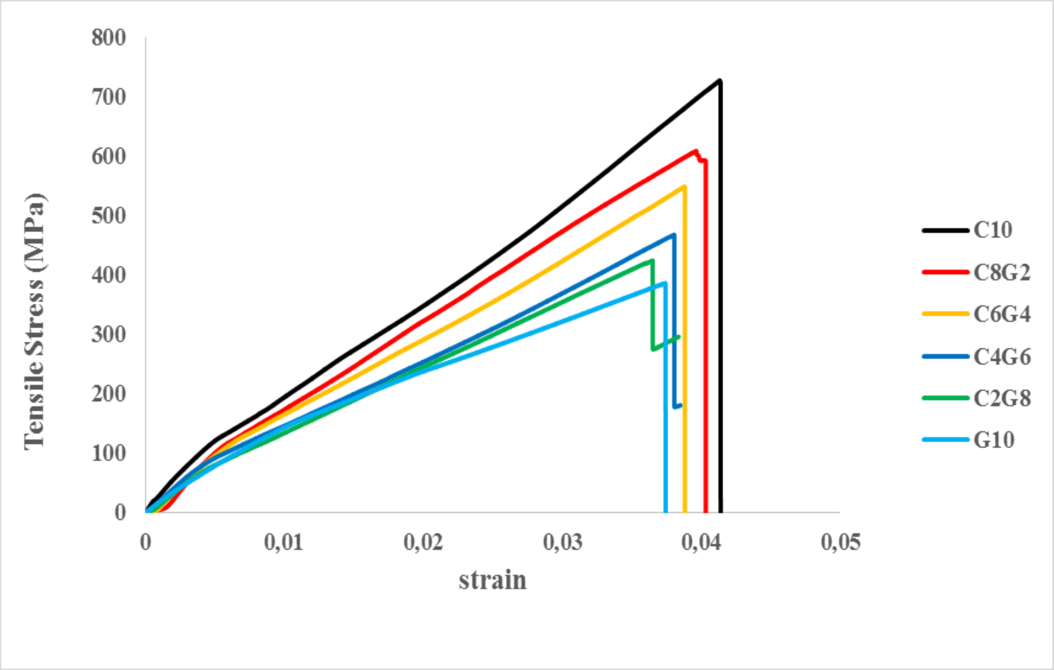


Figure 4.3 Tensile stress–strain curves for CFRP, GFRP and interply hybrid composites.

Table 4.4 shows tensile strength values of hybridization of Carbon, Glass and Kevlar fibers and also tensile stress to strain curves are given in Figure 4.4.

Table 4.4: Tensile Properties for CFRP. GFRP and KFRP interply hybrid composites with different stacking configurations.

Laminate	**Max. strain**	**Max. Stress (MPa)**	**Average Stress (MPa)**
H_9 -1	0.0370	439.47	
H_9 -2	0.0479	432.21	439.61
H_9 -3	0.0464	447.16	
H_{10} -1	0.0458	456.89	
H_{10} -2	0.0455	476.98	467.33
H_{10} -3	0.0406	468.14	
H_{10} -1	0.0460	501.88	
H_{10} -2	0.0480	506.31	488.53
H_{10} -3	0.0522	457.44	

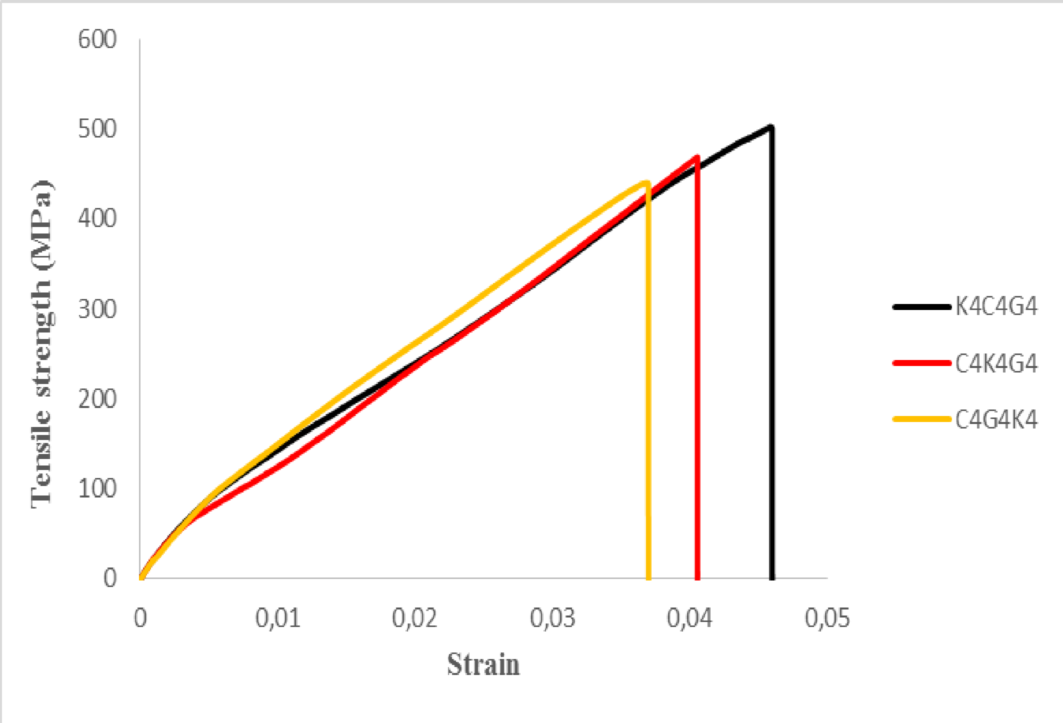


Figure 4.4 Tensile stress–strain curves for CFRP, GFRP and KFRP interply hybrid composites.

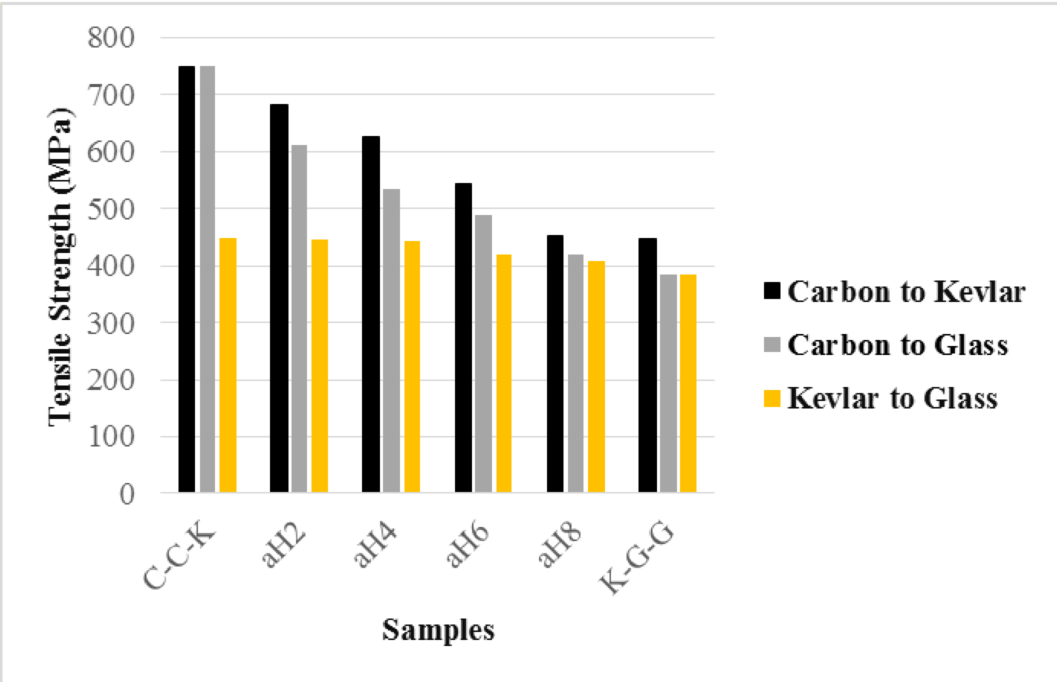


Figure 4.5 Comparison of average tensile strength of CFRP, GFRP and KFRP of interply hybrid composites.

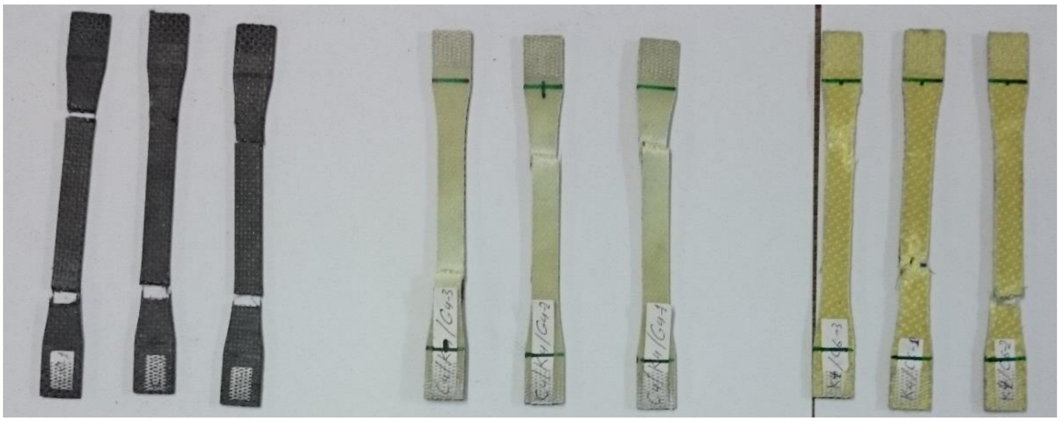


Figure 4.6 Failure specimens of different composite laminates after tensile test.

From the experimental study, it was observed that Carbon/epoxy composite has the maximum tensile strength of 750 MPa, where Kevlar/epoxy composite has (447 MPa) and Glass/epoxy composite has minimum tensile strength about (385 MPa). Also, it is shown from the results above that the hybridization strongly effects on the tensile strengths of composites. This is in agreement with previous studies [57, 60 and 76].

For Carbon/ Kevlar epoxy interply hybrid composites, as expected, the CFRP showed a rapid and steep load rise, showing the highest stress (i.e. tensile strength) among the tested samples, but it also showed a low strain, indicating a brittle property. In contrary, the KFRP showed a slow load rise, obtaining the largest strain and the lowest stress among all tested samples, suggesting that KFRP has good ductility primarily due to the high elongation property of Kevlar fiber. Thus, the presence of Kevlar fabric in carbon fiber-reinforced plastic is expected to add ductile properties to the hybrid composite material, but at the same time decrease the tensile strength. The hybrid composites with different stacking configurations of carbon and Kevlar fabrics showed average values between those of CFRP and KFRP (see Fig. 4.1 and Table 4.1). Here, changing the stacking configurations clearly showed differences in the resulting properties of the composite laminates. Addition of two layers of Kevlar to the Carbon/epoxy layers (i.e. $1H_2$ laminate), nearly a % 10 reduction in tensile strength was seen and strength of Kevlar/epoxy increased by 52%.

For the hybrid Kevlar/Glass epoxy laminate configurations, a positive hybrid effect exists when the two topmost lamina of a full glass/epoxy laminate is replaced by a Kevlar/epoxy lamina, as more glass/epoxy laminas are replaced by Kevlar/epoxy laminas the tensile strength increases gradually up to $2H_6$ (two layers glass with 8 layers Kevlar), after that a slight increase in the hybrid effect occurred till the full Kevlar/epoxy laminate. The maximum hybrid effect occurs at ($2H_2$) laminate, where the tensile strength increased by a ratio of 5.7% from full Glass and decreased by a ratio of 9% from full Kevlar.

As well as the same outcome for the hybrid laminate configurations of Carbon/Glass epoxy composite was obtained, i.e. a negative hybrid effect exists when the two topmost lamina of a full Carbon/epoxy laminate is replaced by a glass/epoxy lamina, as more carbon/epoxy laminas are replaced by Glass/epoxy laminas, the hybrid effect decreases till the full Glass/epoxy laminates. Also the maximum hybrid effect occurred at ($3H_2$) laminate, where the tensile strength of the Carbon/epoxy composite decreased by 17.7% while for Glass/epoxy increased nearly 60%.

When the tensile strength results of the hybrid Kevlar/Carbon epoxy and Glass/Carbon epoxy configurations were compared with the results of the hybrid Kevlar/Glass epoxy, we found that there is a marked difference between them, as the influence of the hybridization in the first two groups is more than the second one, as a result of the great difference between the tensile strength of Kevlar and Glass fibers to Carbon fibers as compared with the tensile strength of Glass to Kevlar fibers, this comparison was clearly illustrated in Table 4.1 and Figure 4.5 (where a=1,2 or 3).

As for the hybrid Kevlar, Glass and Carbon/epoxy composite configurations of 12 layers laminates, the results are different between the three different stacking sequences depending on the type of fiber putted in the middle of the laminate which is carried most of the tension load supplied, according to this analysis the maximum hybrid effect occurs at (H_9) followed by (H_{10}) and (H_{11}) respectively, because, as it is known that carbon fibers are stronger than Kevlar and Glass fibers in tension. Because of affecting the position of the fiber on the tensile strength of hybrid composites, it’s required to put the stronger fiber in the middle of the laminates to get the better mechanical properties.

4.2 Flexural results:

The average results that obtained from the experimental work on the flexural testing of different fibers of laminated composites were illustrated in the Tables 4.5 - 4.8, which represent maximum flexural strain, maximum flexural stress and modulus of the different stacking configurations.

Table 4.5 shows flexural strength values of hybridization of carbon fibers with Kevlar fibers and also flexural stress to strain curves were given in Figure 4.7.

Table 4.5: Average flexural Properties for CFRP, KFRP and interply hybrid composites with different stacking configurations.

Laminate	Depth(mm)	Max. strain	Max. stress (MPa)	Average Stress (MPa)	E_f modulus (GPa)
CFRP- 1	2.2	0.0162	787		50.16
CFRP- 2	2.2	0.0152	944	827	58.05
CFRP- 3	2.2	0.0137	750		59.34
$1H_2$- 1	2.3	0.0194	515		32.80
$1H_2$- 2	2.3	0.0196	561	555	30.84
$1H_2$- 3	2.3	0.0197	588		31.33
$1H_4$- 1	2.3	0.0277	518		32.25
$1H_4$- 2	2.3	0.0308	625	532	35.83
$1H_4$- 3	2.3	0.0310	453		32.25
$1H_6$- 1	2.3	0.0431	364		33.94
$1H_6$- 2	2.3	0.0411	359	349	32.25
$1H_6$- 3	2.3	0,0352	325		32.25
$1H_8$- 1	2.5	0.0382	308		29.31
$1H_8$- 2	2.5	0.0358	324	296	29.31
$1H_8$- 3	2.6	0.0284	257		28.04
KFRP- 1	2.6	0.0344	333		21.50
KFRP- 2	2.6	0.0368	341	313	21.50
KFRP- 3	2.9	0.0292	266		21.50

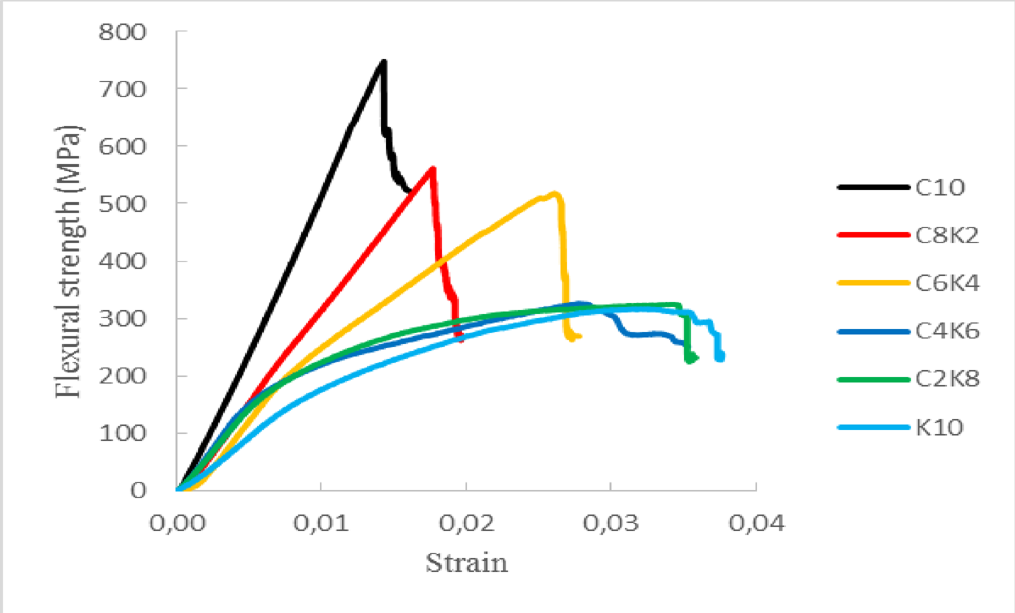


Figure 4.7 Flexural stress–strain curves for CFRP. KFRP and interply hybrid composites

Table 4.6 shows flexural strength values of hybridization of Glass fibers with Kevlar fibers and also flexural stress to strain curves were given in Figure 4.8.

Table 4.6: Average flexural Properties for GFRP, KFRP and interply hybrid composites.

Laminate	Depth (mm)	Max. strain	Max. stress (MPa)	Average Stress (MPa)	E_f modulus (GPa)
GFRP-1	1.9	0.0251	772		28.60
GFRP-2	1.9	0.0264	787	772	27.31
GFRP-3	1.9	0.0255	720		26.60
$2H_2$ -1	2.0	0.0365	554		21.50
$2H_2$ -2	2.0	0.0354	531	558	20.15
$2H_2$ -3	2.0	0.0345	589		23.00
$2H_4$ -1	2.2	0.0317	358		20.15
$2H_4$ -2	2.2	0.0336	364	358	21.50
$2H_4$ -3	2.2	0.0340	352		20.15
$2H_6$ -1	2.7	0.0367	356		17.90
$2H_6$ -2	2.6	0,0344	303	331	17.40
$2H_6$ -3	2.8	0.0377	334		16.97
$2H_8$ -1	2.8	0.0308	301		20.15

$2H_8$ -2	2.7	0.0322	338	321	21.50
$2H_8$ -3	2.7	0.0336	323		20.15
KFRP -1	2,6	0.0344	333		21.50
KFRP -2	2,6	0.0368	341	313	21.50
KFRP -3	2.9	0.0292	266		21.50

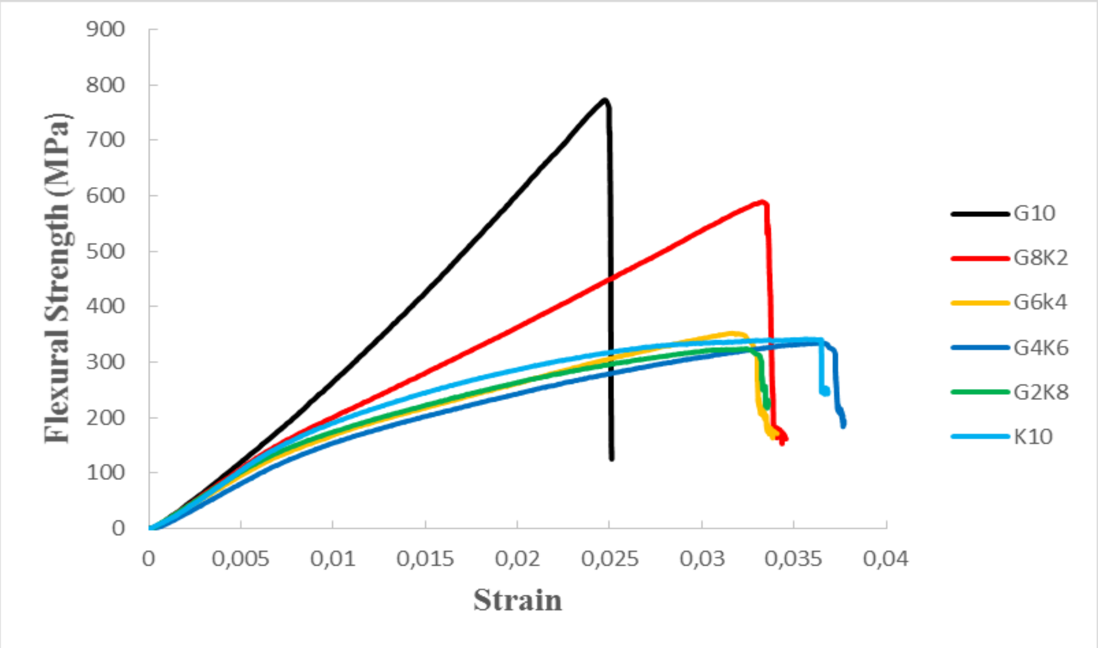


Figure 4.8 Flexural stress–strain curves for GFRP. KFRP and interply hybrid composites.

Table 4.7 shows flexural strength values of hybridization of Carbon fibers with Glass fibers and also flexural stress to strain curves were given in Figure 4.9.

Table 4.7: Average flexural Properties for CFRP, GFRP and interply hybrid composites

Laminate	Depth (mm)	Max. strain	Max. stress (MPa)	Average Stress (MPa)	E_f modulus (GPa)
CFRP- 1	2.2	0.0162	787		50.16
CFRP- 2	2.2	0.0152	944	827	58.05
CFRP- 3	2.2	0.0137	750		59.34

$3H_2$ - 1	2.0	0.0251	960		44.65
$3H_2$ - 2	1.9	0.0188	910	910	39.60
$3H_2$ - 3	1.9	0.0171	736		42.60
$3H_4$ - 1	1.9	0.0287	831		24.00
$3H_4$ - 2	2.2	0.0214	647	831	18.50
$3H_4$ - 3	2.2	0.0314	669		25.80
$3H_6$ - 1	2.2	0.0206	902		32.25
$3H_6$ - 2	1.9	0.0216	1093	941	34.80
$3H_6$ - 3	1.9	0.0205	941		35.80
$3H_8$ - 1	1.9	0.0248	1116		30.55
$3H_8$ - 2	1.9	0.0220	1049	1049	37.00
$3H_8$ - 3	1.9	0.0219	895		33.00
GFRP-1	1,9	0,0251	772		28.60
GFRP-2	1,9	0,0264	787	772	27.31
GFRP-3	1,9	0,0255	720		26.60

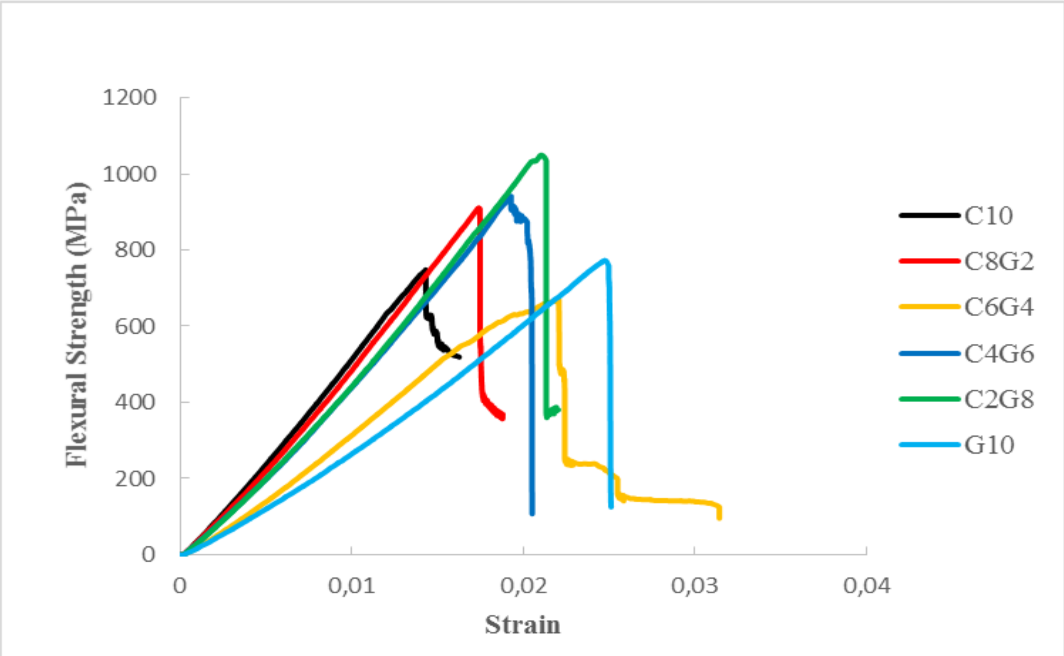


Figure 4.9 Flexural stress–strain curves for CFRP. GFRP and interply hybrid composites.

Table 4.8 shows flexural strength values of hybridization of Carbon, Glass and Kevlar fibers and also flexural stress to strain curves are given in Figure 4.10.

Table 4.8: Flexural Properties for CFRP. GFRP and KFRP interply hybrid composites.

Laminate	Depth (mm)	Max. strain	Max. stress (MPa)	Average Stress (MPa)	E_f modulus (GPa)
H_9 -1	2.5	0.0328	548		32.25
H_9 -2	2.5	0.0339	505	526	24.18
H_9 -3	2.5	0.0318	524		27.45
H_{10} -1	2.5	0.0181	736		42.37
H_{10} -2	2.5	0.0195	772	715	40.10
H_{10} -3	2.6	0.0178	638		37.00
H_{11} -1	2.6	0.0296	465		23.00
H_{11} -2	2.5	0.0290	482	471	24.18
H_{11} -3	2.5	0.0302	467		22.50

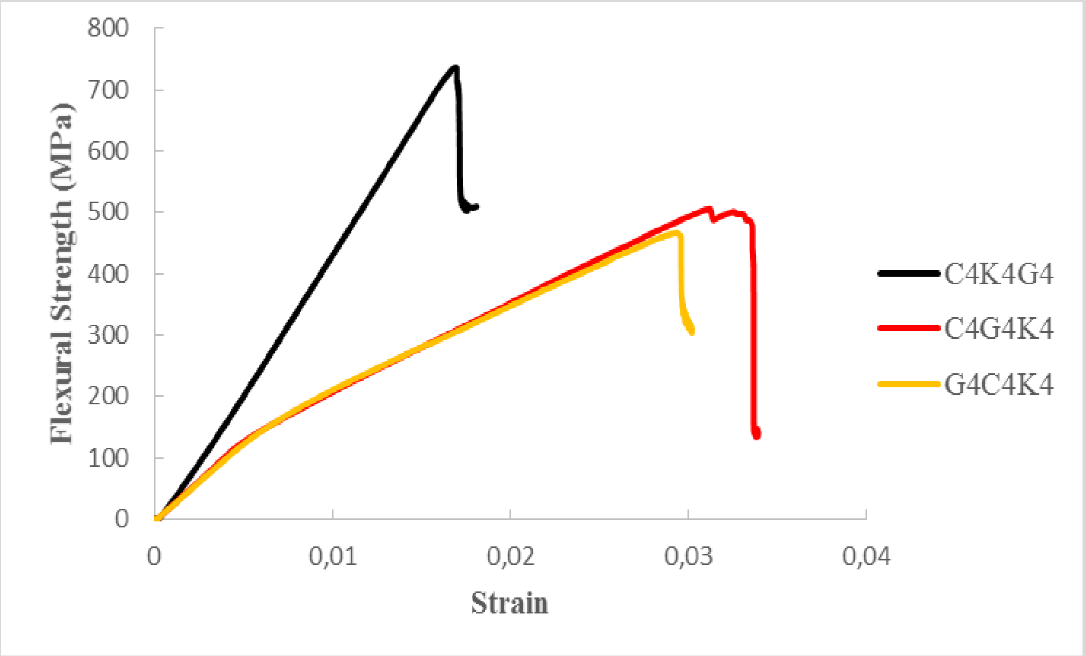


Figure 4.10 Flexural stress–strain curves for CFRP. GFRP and KFRP interply hybrid composites

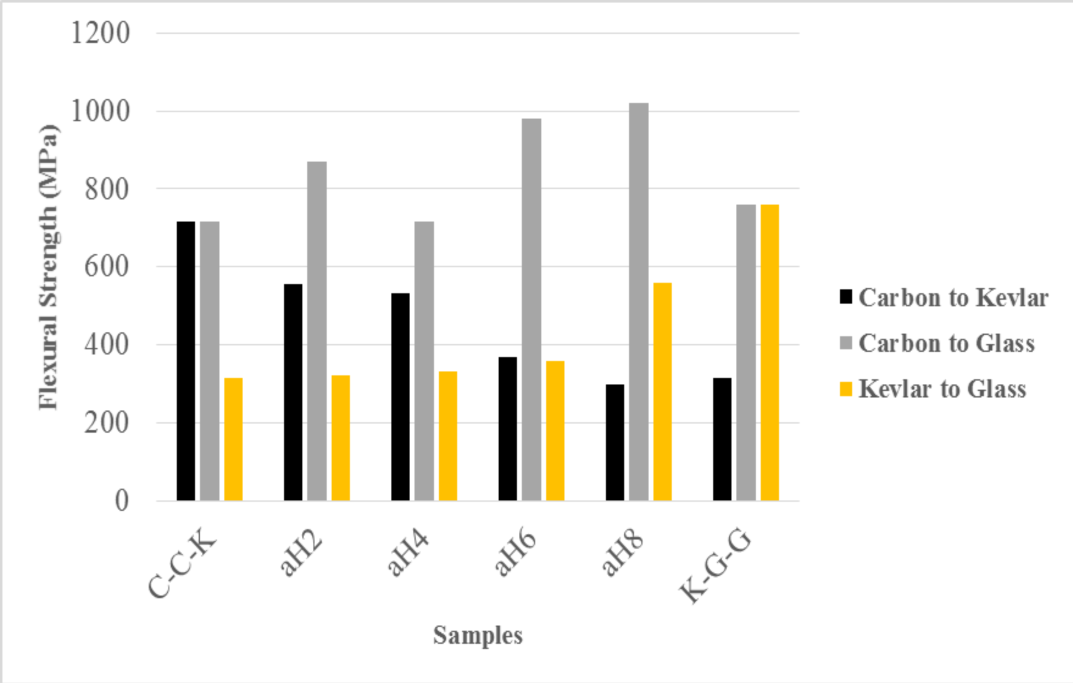


Figure 4.11 Comparison of flexural strength curves of CFRP, GFRP, KFRP and interply hybrid composites.

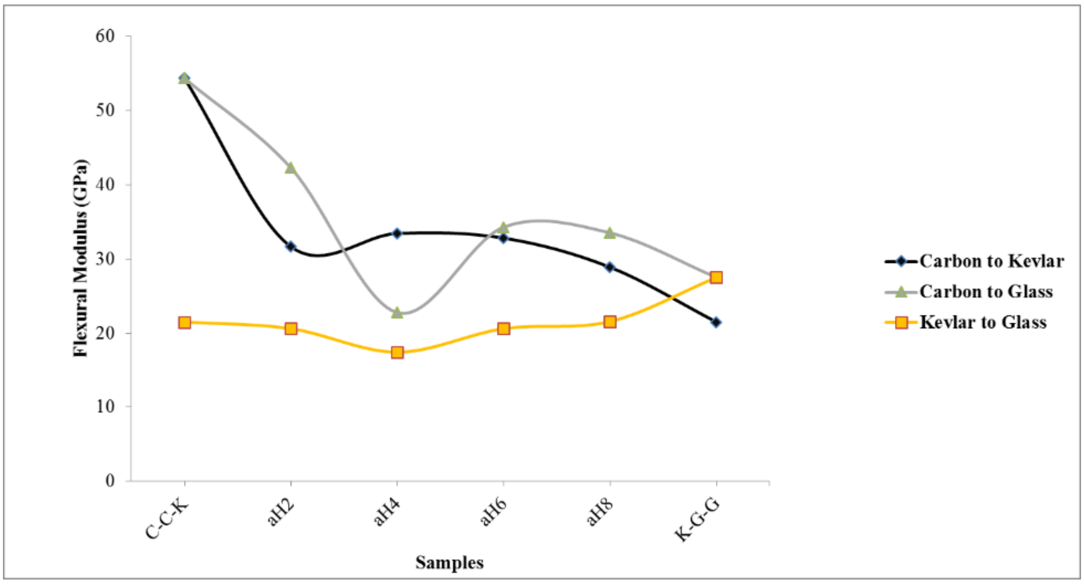


Figure 4.12 Comparison of flexural modulus curves of CFRP, GFRP, KFRP and interply hybrid composites.

The table 4.8 shows that the glass / epoxy composite has a flexural strength of 827 MPa, while Carbon/epoxy composite has 772 MPa and Kevlar/epoxy composite has about 447 MPa.

In Figure 7, the CFRP shows a high flexural strength among the tested samples, but it also showed a low strain, while the KFRP shows a low strength with a high strain among all tested samples, signifying that KFRP has good ductility mainly due to the high elongation property of Kevlar fiber. Also, the different stacking configurations of Carbon and Kevlar hybrid fabrics showed average values between those of CFRP and KFRP (see Table 3.8 and Figure 7).

Similarly, the same behavior obvious of the hybrid composites with different stacking configurations of Glass and Kevlar fabrics. Also, from the results it was found that placing Glass fiber layers at the compressive side increased the flexural strength and modulus of the hybrid composites when compared to placing Kevlar fiber layer on the compressive side.

The comparison of flexural strength and flexural modulus curves of CFRP, GFRP, KFRP and their interply hybrid composites are shown in the Figures. (11 and 12), (where a=1, 2 or 3).

The interpretation of these results is that, when the load was applied, the outermost layer bears most of the applied load, so that a high flexural strength was achieved when Glass fibers were located in the skin region at the compressive side and Carbon fibers located at the tensile side.

Zhang et al. [68] also reported increasing flexural strength when they placed two Carbon fiber layers on the compressive side of their Glass/Carbon hybrid composite laminates. Furthermore, Park and Jang [44] observed similar results when they combined Carbon fiber and PE fiber in different sequences.

The present results suggest that the incorporation of Kevlar fiber layer in CFRP or GFRP could improve the balance of the mechanical properties depending on the stacking configurations.

4.3 Fracture characteristics of the hybrid laminates:

The common failures under flexural loading include compressive failure, tensile failure, shear and/or delamination, wherein failure by compression is the most common [19]. The failure of a hybrid composite is dependent on the maximum bending moment that the individual constituent material could carry. To provide the damage mechanism of the present samples after flexural test, some images were taken on the fractured surfaces of the hybrid composites.

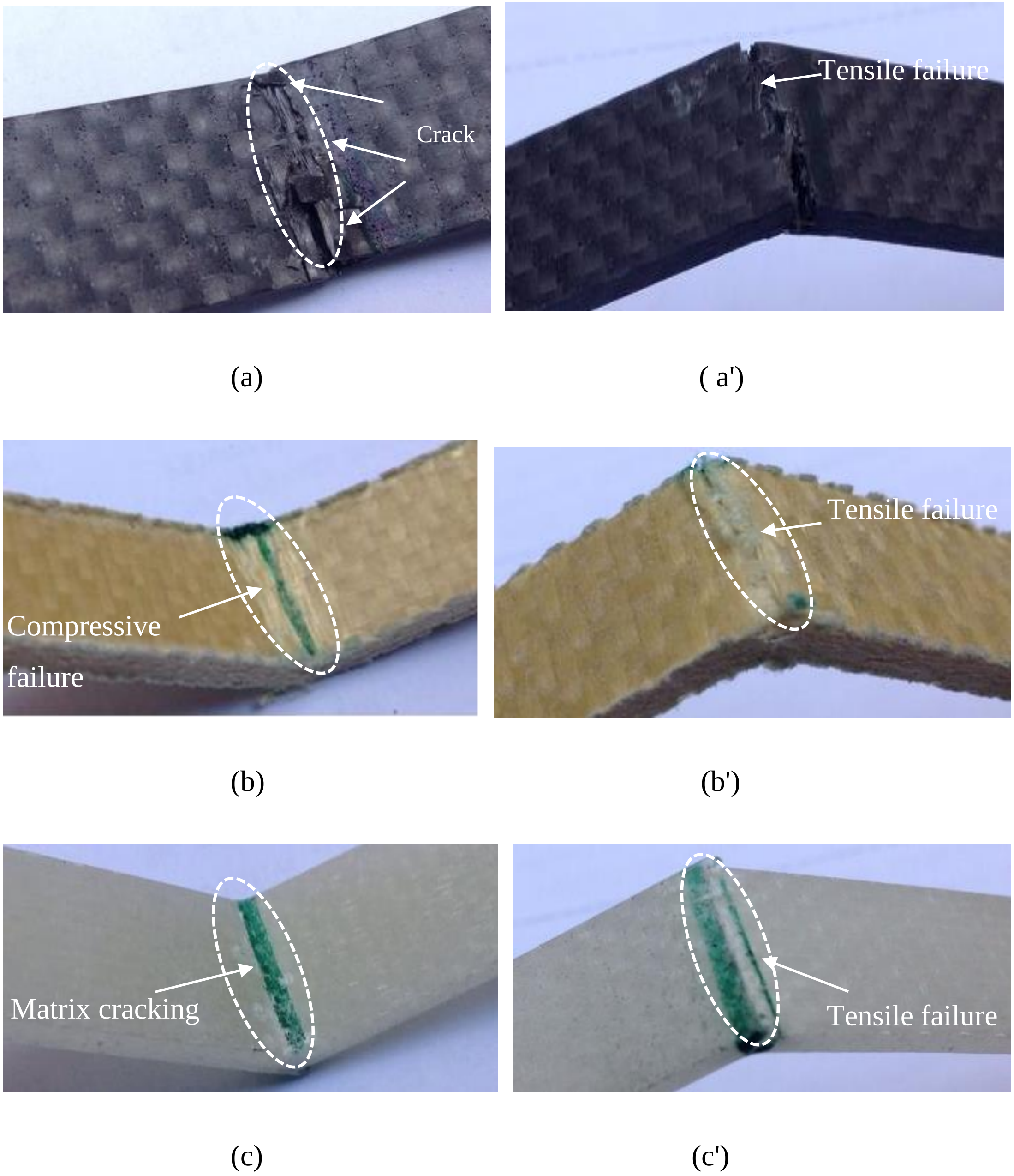
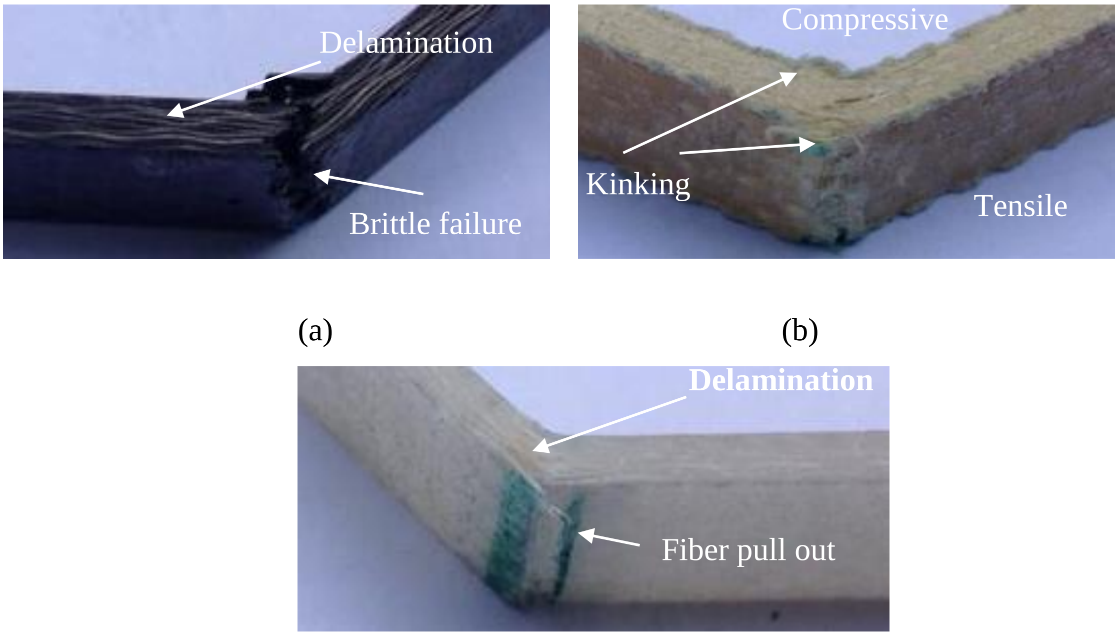


Figure 4.13 Failure surfaces of hybrid laminates after flexural test: Carbon fabric (a and a'), Kevlar fabric (b and b') and Glass fabric (c and c'), at the compressive side (a, b and c), and at the tension side (a', b' and c'), respectively.



(c)

Figure 4.14 Typical failure modes on (a) Carbon/epoxy, (b) Kevlar/epoxy, (c) Glass/epoxy laminates

Representative photographic images are shown in Fig. 4.13 for the top and bottom sides of the tested specimens. From Fig. 4.13 (a), it can be seen that the typical failure of carbon fiber stacked at the compressive side is the crack propagation, whereas, no obvious cracks were seen when Kevlar fibers were placed at the compressive side after the flexural load (Fig. 4.13b). When carbon fiber layer was placed on the tension side (Fig. 4.13a'), few straight cracks were observed after the flexural load. This phenomenon is attributed to the brittle failure of carbon fibers, where the specimen broke through all layers with abundant carbon fiber rupture [18]. Crack propagation at the compressive side was also observed by Paiva et al. [53] using CFRP for aerospace field. Usually, in CFRP, the fatigue stress is effectively transferred along the carbon fibers [21], so that high flexural strength is achieved for CFRP but with more brittle property. On the other hand, the tested specimen with Kevlar fibers placed on the tension side showed tensile failure mode (Fig. 4.13b'), which is consistent with the observation of other studies. As for the glass fibers, the results are roughly located between the two (carbon and Kevlar) fibers, but approximately closer to the carbon fibers (Fig. 4.13c and c'). Figure 4.14 shows typical failure modes for laminated full composite plates after three point bending test. Brittle fracture and delimitations between lamina occur in Carbon/epoxy laminate (Figure 4.14 a). Due to toughness of the Kevlar fiber, kinking and delamination are occurred on cracked surface (Figure 4.14 b). In a Glass/epoxy laminate fiber pullout and delamination are occurred (Figure 4.14 c).

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

This study explored the possibility of incorporating Kevlar & Glass fibers with Carbon fiber reinforced composite and also, Kevlar fibers with Glass fiber reinforced composite and investigated the effect of stacking configurations on the tensile and flexural properties of the hybrid composite. Hand lay-up resin transfer molding process was used to fabricate the interply hybrid composites. Interply hybrid composites containing 10 layers of Kevlar/Carbon, Kevlar/Glass and Glass/Carbon fabrics with different stacking configurations were tested for their tensile and flexural properties. The results showed that the dominant failure mode was compressive failure.

Main results can be summarized as:

- The tensile and flexural properties of the hybrid composites were significantly affected by the stacking configurations.
- Higher tensile, flexural strengths and modulus were obtained with ($1H_2$), ($2H_2$) (i.e., stacking two Kevlar fiber layers at the compressive side), and ($3H_2$) (i.e., stacking two Glass fiber layers at the compressive side) showing the best tensile, flexural strength and modulus from among the stacking configuration arrangements.
- For Kevlar- Carbon/epoxy the flexural strength follows the trend: CFRP > $1H_2$ > $1H_4$ > $1H_6$ > $1H_8$ > KFRP

- Also for Kevlar - Glass/ epoxy follows the trend: GFRP > $2H_2$ > $2H_4$ > $2H_6$ > $2H_8$ > KFRP.
- However, a more ductile material could be obtained when several Kevlar fibers are incorporated with Carbon or Glass fibers. All the stacking configurations showed a positive hybridization effect. The highest hybrid flexural strength was achieved with ($1H_2$) arrangement, showing an increase of 77% from KFRP and about 22% lesser strength than CFRP and also with ($2H_2$) arrangement, showing an increase of 78% from KFRP and about 26% lesser strength than GFRP. The advantage of hybridization in the present study is lesser cost compared to plain CFRP with comparable flexural strength and improved ductility.

5.2 Future Works

- Although carbon, glass and Kevlar fibers are used in this study, the methodology is suitable for other fiber types provided that they have different strains-to-failure. Future work includes multi-objective optimization study is needed to achieve the best design depending on the requirement of optimum and durability.
- In future the study can be extended to new polymer composites having different fabric/matrix combinations and the resulting experimental findings can be further analyzed.

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