CUKUROVA UNIVERSITY

INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

The Effect of Additives on Flexural and Flame Retardant Properties of Carbon Fiber/Epoxy Sandwich Structures

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ABSTRACT

Sandwich structures, consisting of a carbon fiber-epoxy surface layer and a PVC foam core structure, are known for their high flexural strength. In this study, it was aimed to increase the flexural strength and flame retardant properties of the sandwich structures by adding additives in powder form to the epoxy resin without increasing the weight too much. Matrix toughening method was applied by adding Graphene, Boron Carbide and Kaolin in powder form at the rates of 2%, 5% and 10% into the epoxy resin. A homogeneous matrix material was obtained by mixing the epoxy with additives with an ultrasonic mixer. Sandwich panels are produced by hand laying and vacuum bagging method. The produced sandwich plates were subjected to the Three Point Bending Test and the Vertical Flammability Test. According to the Three Point Bending Test results, the sandwich structure that exhibited the highest bending strength was 10% added Boron Carbide. When the Vertical Flammability Test results were evaluated, no effect of the additives on the laminated structure was observed.

Keywords: Carbon Fiber, Sandwich Structures, Graphene, Boron Carbide, Kaolin.

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YÜKSEK LİSANS TEZİ

Katkı Maddelerinin Karbon Elyaf/Epoksi Sandviç Yapıların Eğilme ve Alev Geciktirici Özelliklerine Etkisi

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ÖZ

Karbon fiber-epoksi yüzey tabakadan ve PVC köpük çekirdek yapıdan oluşan sandviç yapıların yüksek eğilme direncine sahip olmalarıyla bilinirler. Bu çalışmada sandviç yapıların ağırlığını arttırmadan epoksi reçine içerisine toz formda eklenen katkı maddeleri ile eğilme dirençlerinin ve alev geciktirici özelliklerinin arttırılması amaçlanmıştır. Epoksi reçine içerisine %2, %5 ve %10 oranlarında toz formda Grafen, Bor Karbür ve Kaolin eklenerek matris toklaştırma methodu uygulanmıştır. Katkı maddeleri eklenen epoksi ultrasonik karıştırıcı ile karıştırılarak homojen bir matris malzeme elde edilmiştir. Sandviç plakalar el yatırması ve vakum torbalama methodu ile üretilmiştir. Üretilen sandviç plakalar ve lamine yapılar Üç Nokta Eğilme Testi' ne ve Dikey Yanmazlık Testi' ne tabi tutulmuştur. Üç Nokta Eğilme Testi sonuçlarına göre en yükske eğilme dayanımını sergilen sandviç yapı %10 katkılı Bor Karbür olmuştur. Dikey Yanmazlık Testi sonuçları değerlendirildiğinde ise katkı maddelerinin lamine yapı üzerinde etkisi görülmemiştir.

Anahtar Kelimeler: Karbon Fiber, Sandviç Yapılar, Grafen, Bor Karbür, Kaolin.

EXTENDED ABSTRACT

Hybrid materials are combinations of two or more chemically different materials in a given configuration and scale. Although these basic materials have different properties, in essence, a structure with new properties can be obtained as a result of the combination. Composite materials are hybrid materials that are widely preferred today. In addition, polymeric composite materials have become increasingly used in aerospace, automotive, marine and military fields, as they are low density and high strength by combining two or more materials. Sandwich structures are obtained by using fiber-reinforced polymeric composites as a surface layer and using low-density intermediate materials. These structures provide higher bending resistance per unit weight. In some cases where traditional materials are insufficient in the industry, hybrid, i.e. composite materials are preferred. Traditional materials cannot always provide different properties at the same time in line with the design conditions. When a material with high mechanical properties cannot have low density, it is not preferred in areas such as aviation and the automotive industry. Instead, carbon fiber-epoxy composites that exhibit high mechanical properties at low density provide great advantages. Carbon fiber sandwich structures are known to have high bending resistance.

Polymeric composites, which provide high performance in terms of strength, are also expected to be resistant to flame retardant in some applications. Fiber reinforced polymeric composite materials can be exposed to fire in line with their usage areas and in the face of this situation, the matrix, which is responsible for holding the load-bearing fibers together, exhibits flammable properties due to the hydrogen and carbon atoms it contains and does not show the desired performance.

In this study, the bending properties and flame retardant properties of sandwich structures consisting of carbon fiber/epoxy surface layer and polyvinyl chloride (PVC) foam core material are discussed and the matrix toughening method is used to improve these properties of the structure. Although there are other methods in the literature, the matrix toughening method was the most effective method in terms of both strength and flame retardancy. In previous studies; in order to improve the flexural strength, the increase in flexural strength can be achieved by changing the reinforcement material or weave form of the polymeric composite or by changing the matrix material. On the other hand, the structures obtained by changing the material, form or dimensions of the core structure, which is indispensable for sandwich structures, give very good results. However, the disadvantage observed in this study is the increase in the weight of the sandwich structure, and this is not suitable for applications where weight is at the forefront. In addition, such applications do not provide flame-retardant properties to the structure.

Studies carried out to improve the flammability properties generally do not increase the strength of the structure. Therefore, these methods are insufficient when flexural strength and flame

retardant properties are required together. The matrix toughening method using additives that have proven themselves in terms of both strength and flammability can meet these desired properties.

In this study, the reinforcing material used in the surface plates of the sandwich structures produced is carbon fibre with a plain weave type and a fibre density of 200 g/m^2. Hexion MGS H160 hardener and MGS L160 epoxy resin were used as the matrix material. The core material of the sandwich structure has a density of 48 kg/m^3 PVC foam, and its closed-cell form. Micro-sized powders are used for the matrix toughening process. These additives are Graphene, Boron Carbide and Kaolin. The additives were added to the epoxy resin at 2%, 5% and 10% by weight and samples were produced. In total, 10 specimens were produced together with the control specimen (plain-epoxy).

ASTM C393 and ASTM D3801/UL94 tests were carried out to determine the flexural strength and flame retardant properties of the produced samples. According to ASTM C393 standard, a three-point bending test was performed to calculate the flexural strength of sandwich panels, i.e. surface layer stress and core shear stress. According to ASTM D3801 standard, a vertical flammability test was performed to determine the flame-retardant properties of plastics. For the three-point bending test, a total of 50 specimens were produced, 5 of each combination. Likewise, a total of 50 specimens, 5 from each combination, were produced for the vertical flammability test.

Sandwich plates with additives were produced by hand lay-up and then vacuum bagging method. Although this method requires high labour, it is a low-cost method preferred for low numbers of productions. The surface layers of the sandwich panels consist of four carbon fibers and 10 mm thick PVC foam between them. In accordance with the relevant standards, the dimensions of the test specimens were determined and the sandwich panel size was calculated and the carbon fibers and PVC foam were cut. The weight of the total structure was measured and matrix materials were prepared. This means matrix material and reinforced material in a 1:1 ratio for hand layup followed by vacuum bagging. Vacuum consumables which are vacuum bagging, vacuum materials, vacuum nylon, vacuum blankets, vacuum hoses and sealing tape were also cut into appropriate sizes. The matrix toughening process was carried out after all materials were prepared. For each plate, 250 g matrix material was prepared. The matrix material consists of epoxy resin and hardener in a ratio of 100:25. Additives at the rates of 2%, 5% and 10% by weight of the matrix material are prepared and added into the epoxy resin. The epoxy resin is reduced as much as the added additive material, that is, the weight of the epoxy resin does not change in total. Afterwards, it was mixed with an ultrasonic mixer to realise a homogenous mixing process.

In order to test the flexural strength of the sandwich structure, sandwich panels were cut in appropriate dimensions according to the ASTM C393 test. The parameters of the machine for the three-point bending test were adjusted and the specimens were placed respectively. In the same way,

the specimens cut in the dimensions specified in the standard for the vertical flammability test were attached to the test apparatus and experiments were carried out.

As a result of the three-point bending test, sandwich panels with additives were indicated in the load-deformation graph. The standard deviation values of the specimens were calculated and shown in the table and graph in order to compare all materials. In line with the results, the surface stress and core shear stress values of the sandwich structures were calculated and indicated in the table.

The results of the vertical flammability test are shown in the table after the measurements are made and the self-extinguishing status of the structure and whether dripping occurs when exposed to flame are indicated in the table.

When all materials were compared and the results were evaluated, Boron Carbide was determined as the additive material that showed the best performance when the structure was exposed to bending resistance. On the other hand, Graphene significantly increased the bending strength even when added in low amounts. The addition of 2%, 5% and 10% Boron Carbide to the sandwich structure increased the maximum load carried by the structure by 7%, 14.4% and 19.4%, respectively. On the other hand, Graphene is another additive that provides good bending strength, although its cost is higher. As a result of the three-point bending test, the addition of 10% Graphene increased the maximum load by 19.1% compared to the control sample. With kaolin, the results are not as impressive as with graphene and boron carbide.

When the flammability properties of laminates with additives added were examined, no effect of the additives added into the matrix material was observed. No change in the flame retardant properties of carbon fiber/epoxy structures in this combination was observed.

As a final evaluation, it would be the best choice to choose Boron Carbide added sandwich panels in applications where the effects of strength and weight increase are important. On the other hand, the use of Graphene can be preferred in applications where the increase in the cost of the structure is considered as a secondary parameter.

GENİŞLETİLMİŞ ÖZET

Hibrit malzemeler belirli bir konfigürasyonda ve ölçekte kimyasal olarak farklı iki ya da daha fazla malzemenin kombinasyonlarıdır. Özünde bu temel malzemeler farklı özelliklere sahip olsa da, kombinasyon sonucunda yeni özelliklere sahip bir yapı elde edilebilir. Kompozit malzemeler ise günümüzde yoğunlukla tercih edilen hibrit malzemelerdir. Buna ek olarak polimerik kompozit malzemeler iki ya da daha fazla malzemenin birleştirilip, düşük yoğunluk ve yüksek mukavemet gerektiren bilhassa havacılık, otomotiv, denizcilik ve askeri alanlarda kullanımı gittikçe yaygınlaşmıştır. Elyaf takviyeli polimerik kompozitleri yüzey tabaka olarak kullanıp, düşük yoğunluklu ara malzemeler kullanılarak sandviç yapılar elde edilmektedir. Bu yapılar birim ağırlık başına daha yüksek eğilme direnci sağlamaktadır. Endüstride geleneksel malzemelerin yetersiz kaldığı bazı durumlarda hibrit yani kompozit malzemeler tercih edilmektedir. Geleneksel malzemeler her zaman tasarım koşulları doğrultusunda farklı özellikleri aynı anda sağlayamamaktadır. Yüksek mekanik özelliklere sahip malzeme düşük yoğunluğa sahip olamadığında havacılık ve otomotiv endüstrisi gibi alanlarda tercih edilmemektedir. Bunun yerine düşük yoğunluktaki yüksek mekanik özellikler sergileyen karbon fiber-epoksi kompozit yapıları büyük avantaj sağlamaktadır. Karbon elyaflı sandviç yapıların yüksek eğilme direncine sahip olduğu bilinmektedir.

Dayanım açısından yüksek performans sağlayan polimerik kompozitlerin aleve maruz kalma durumuna karşı dayanıklı olması da bazı uygulamalarda beklemen özelliklerdendir. Elyaf takviyeli polimerik kompozit malzemeler kullanım alanları doğrultusunda ateşe maruz kalabilmektedirler ve bu durum karşısında yük taşıyıcı elyafları bir arada tutmakla görevli matris içinde bulundurduğu hidrojen ve karbon atomlarından dolayı yanıcı özellik sergileyip istenen performansı göstermemektedir.

Bu çalışmada karbon elyaf/epoksi yüzey tabakalı ve Polyvinyl chloride (PVC) köpük çekirdek malzemeden oluşan sandviç yapıların eğilme dirençleri ve karbon elyaf/epoksi laminelerin alev geciktirici özellikleri ele alınmıştır ve yapının bu özelliklerinin iyileştirilmesi için matris toklaştırma metodu kullanılmıştır. Literatürde başka yöntemler bulunmakla birlikte matris toklaştırma yöntemi hem dayanım hem de yanmazlık açışından en etkileyici yöntem olmuştur. Önceki çalışmalarda; eğilme dayanımını iyileştirmek için polimerik kompozitin takviye malzemesini veya örgü biçimini değiştirerek ya da matris malzemede değişiklik yapılarak eğilme dayanımında artışlar sağlanabilmektedir. Öte yandan sandviç yapıların olmazsa olmazı çekirdek yapının malzemesini, formunu veya boyutlarını değiştirerek elde edilen yapılar gayet iyi sonuçlar vermektedir. Ancak bu çalışmada gözlemlenen dezavantaj ise sandviç yapının ağırlığında artıştır ve bu özellikle ağırlığın ön planda olduğu uygulamalar açısından uygun bulunmamaktadır. Ayrıca, bu tip uygulamalar yapıya alev geciktirici özellik kazandırmamaktadır.

Yanıcılık özelliklerini iyileştirmek için yapılan çalışmalar ise genellikle yapının dayanımını arttırmamaktadır. Bu nedenle eğilme dayanımı ve alev geciktirici özellikler bir arada istendiğinde bu yöntemler yetersiz kalmaktadır. Hem dayanım hem de yanıcılık açısından kendisini kanıtlamış katkı maddeleri kullanarak matris toklaştırma metodu bu istenen özellikleri karşılayabilmektedir.

Bu çalışmada, üretilen sandviç yapıların yüzey plakalarında kullanılan takviye malzeme karbon elyaf olup düz örgü tipine sahiptir ve elyafın yoğunluğu 200 gr/m^2. Matris malzeme olarak ise Hexion MGS L160 epoksi reçine ile MGS H160 sertleştirici kullanılmıştır. Sandviç yapının çekirdek malzemesi ise kapalı hücreli PVC köpük olup 48 kg/m^3 yoğunluğa sahiptir. Matris toklaştırma işlemi için ise mikro boyutta tozlar kullanılmaktadır. Bu katkı maddeleri Grafen, Bor Karbür ve Kaolin' dir. Katkı maddeleri epoksi reçine içerisine ağırlıkça %2, %5 ve %10 oranlarında eklenerek numuneler üretilmiştir. Toplamda kontrol numunesi (sade-epoksi) ile birlikte 10 adet sandviç panel üretilmiştir.

Üretilen numunelerin eğilme dayanımlarını ve alev geciktirici özelliklerini tespit etmek için ASTM C393 ve ASTM D3801/UL94 testleri gerçekleştirilmiştir. ASTM C393 standardına göre sandviç panellerin eğilme dayanımlarının yani yüzey gerilmesini ve çekirdek kayma gerilmesini hesaplanabilmesi için üç nokta eğilme testi yapılmıştır. ASTM D3801 standardına göre ise plastiklerin alev geciktirici özelliklerinin tespit edilmesi için dikey yanmazlık testi yapılmıştır. Üç nokta eğilme testi için her bir kombinasyondan 5 adet olmak üzere toplamda 50 adet sandviç panel üretilmiştir. Aynı şekilde dikey yanmazlık testi için her bir kombinasyondan 5 adet olmak üzere toplamda 50 adet numune üretilmiştir.

Katkı malzemeli sandviç plakalar el yatırması ve sonrasında vakum torbalama metodu ile üretilmiştir. Bu metot yüksek işçilik gerektirmekle birlikte düşük sayılardaki üretimler için tercih edilen düşük maliyetli bir yöntemdir. Sandviç panellerin yüzey tabakaları dörder adet karbon elyaftan oluşmaktadır ve arasında 10 mm kalınlığı olan PVC köpükten oluşmaktadır. İlgili standartlar doğrultusunda, deney numunelerinin boyutları belirlenip sandviç panel boyutu hesaplanarak, karbon elyaflar ve PVC köpük kesilmiştir. Toplam yapının ağırlığı ölçülüp 1:1 oranında matris malzemenin hazırlanabilmesi için epoksi reçine ve sertleştiricisi hazırlanmıştır. Vakum torbalama için ise vakum malzemeleri, vakum naylonu, vakum battaniyesi, vakum hortumları ve sızdırmazlık bandı de uygun ölçülerde kesilmiştir. Matris toklaştırma işlemi ise bütün malzemeler hazırlandıktan sonra yapılmıştır. Her bir plaka için 250 gr matris malzeme hazırlanmıştır. Matris malzeme ise 100:25 oranında epoksi reçine ve sertleştiricisinden oluşmaktadır. Matris malzemenin ağırlığınca %2, %5 ve %10 oranlarında katkı malzemeleri hazırlanıp epoksi reçine içerisine eklenmektedir. Eklenen katkı malzemesi kadar epoksi reçine azaltılmaktadır yani toplamda epoksi reçinen ağırlığı değişmemektedir. Sonrasında homojen bir karışım işlemi gerçekleştirmek için ultrasonik karıştırıcı ile karıştırılmıştır.

Sandviç yapının eğilme dayanımının test edilmesi için ASTM C393, testine göre sandviç paneller uygun ölçülerde kesildi. Sonrasında üç nokta eğilme testi için makinenin parametreleri ayarlandı ve numuneler sırasıyla yerleştirildi. Aynı şekilde dikey yanmazlık testi için standartta belirtilen ölçülerde kesilen numuneler test düzeneğine takılıp deneyler yapıldı.

Üç nokta eğilme testi sonucunda katkı maddeli sandviç paneller yük-deformasyon grafiğinde belirtildi. Bütün malzemelerin karşılaştırılmasının yapılabilmesi için numunelerin standart sapma değerleri hesaplanarak tabloda ve grafikle gösterildi. Çıkan sonuçlar doğrultusunda sandviç yapıların yüzey gerilme ve çekirdek kayma gerilme değerleri hesaplanıp tabloda belirtildi.

Dikey yanmazlık testi sonuçları ise ölçümler yapıldıktan sonra tabloda yapının kendi kendine sönme durumu ve aleve maruz kaldığında damlama gerçekleşip gerçekleşmediği tabloda belirtildi.

Tüm malzemeler karşılaştırıldığında ve sonuçlar değerlendirildiğinde Bor Karbür, yapının eğilme direncine maruz kalması durumunda en iyi performansı sergileyen katkı malzemesi olarak belirlenmiştir. Öte yandan Grafen ise düşük oranda eklendiğinde bile eğilme direncini önemli ölçüde arttırmıştır. Sandviç yapıya %2, %5 ve %10 oranında Bor Karbür ilavesi, yapının taşıdığı maksimum yükü sırasıyla %7, %14,4, ve %19,4 artırmıştır. Öte yandan maliyeti daha yüksek olmakla birlikte iyi seviyede eğilme mukavemetini sağlayan diğer katkı maddesi Grafen' dir. Üç nokta eğme testi sonucunda %10'luk Grafen ilavesi, kontrol numunesine göre maksimum yükü %19,1 arttırmıştır. Kaolinde sonuçlar grafen ve bor karbür kadar etkileyici değildir.

Katkı maddesi eklenmiş laminelerin yanmazlık özellikleri incelendiğinde matris malzeme içerisine eklenen katkı maddelerinin etkisi gözlemlenmemiştir. Bu kombinasyondaki karbon elyaf/epoksi yapıların alev geciktirici özelliklerinde herhangi bir değişim gözlemlenmemiştir.

Nihai değerlendirme olarak, mukavemet ve ağırlık artışı etkilerinin önemli olduğu uygulamalarda Bor Karbür katkılı sandviç panellerin tercih edilmesi en iyi seçim olacaktır, Öte yandan yapının maliyet artışındaki artışın ikincil parametre olarak değerlendirildiği uygulamalarda ise Grafen kullanımı tercih edilebilmektedir.

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SYMBOLS AND ABBREVIATIONS

ASTM	:	American society for testing and materials	
b	:	Sandwich width	mm
BFRP	:	basalt fiber-reinforced polymer	
c	:	Core thickness	mm
CF	:	Carbon fiber	
CNT	:	Carbon nanotube	
d	:	Sandwich thickness	mm
DOCF	:	Desized oxidized carbon fiber	
EDS	:	Energy dispersive spectrometry	
FRP	:	Fiber reinforced polymer	
F_s^{ul}	:	Core shear ultimate stress	MPa
GnP/GNP	:	Graphene nanoplate	
HS	:	Harness Satin	-
ILSS	:	Interlaminar shear stress	
MWCNT	:	Multiwall carbon nanotube	
NC	:	Nano clay	
PMDI	:	polymeric diphenylmethadi isocyanate	
PU	:	Polyurethane	-
PVC	:	Polyvinyl chloride	-
RSM	:	Response surface methodology	
S	:	span length	mm
SBS	:	short beam strength	
SEM	:	Scanning electron microscope	
t	:	Facing thickness	mm
VARTM	:	Vacuum assisted resin transfer molding	-
σ	:	Facing stress	MPa

1. INTRODUCTION

Traditional materials cannot always provide different properties simultaneously in line with design conditions or aviation, automotive and marine industry or military applications. In some cases, hybrid materials are preferred since the traditional materials are insufficient in the industry. Thanks to hybrid materials, materials with different properties desired in the industry can be obtained. Hybrids materials are combinations of two or more chemically different materials in a particular configuration and scale. Although the basic materials in the combination have specifically different structures, after the combination they represent a special properties. Therefore, those properties make them unique.

Composites are classified as a hybrid material since they are combination of two or more material without any chemical reaction between them. Composites consist of reinforcement and matrix materials. The simplest example for composite materials is concrete, cement and sand supported by steel rods. Composite materials have many superiority over conventional materials, such as their comparatively high strength and light weight, outstanding corrosion resistance and thermal properties, and better resistance to impact forces, fatigue and other dynamic and static loads. At the present time, modern composites which are polymer matrix composites widely used in industry. Since they have low weight and high strength, they are mostly preferred in the aviation and automotive industries. While polymer matrix composites are of different types and classified as thermoplastic and thermoset, they are used together with different types of reinforcing fibers depending on the application field (Elmarakbi, 2015). Fiber reinforced polymer matrix composites are made up of high strength fibres bound to a matrix with different boundaries between them. Typically, fibers serve as the primary bearers of the load, with the encompassing polymer matrix ensuring their intended positioning and alignment. In Figure 1.1 formation of polymer composites is shown.

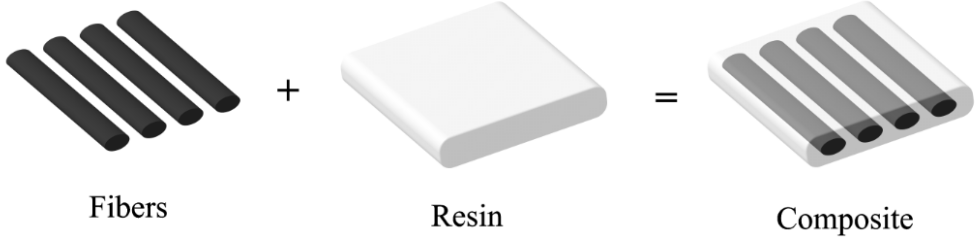


Figure 1.1. Formation of Polymer Composites

1.1. Development of Composites

The lineage of composite materials stretches over numerous decades, yet it was in the 1960s, with the evolution of polymeric composites, that their industrial application proliferated. Since then, composite materials have taken their place among the traditional materials as a common engineering material (Mazumdar, 2002). In Figure 1.2 relative importance of the materials is shown. The evaluation of composite materials until today, even the first emergence, was to meet the needs of the industry. The fact that efficiency is a very important factor in the mechanized world after the industrial revolution has created the need for materials with high performance in the industry. It was not easy to obtain an efficient product that would meet the design requirements with traditional materials. Therefore, composite materials that can carry different properties together have been developed.

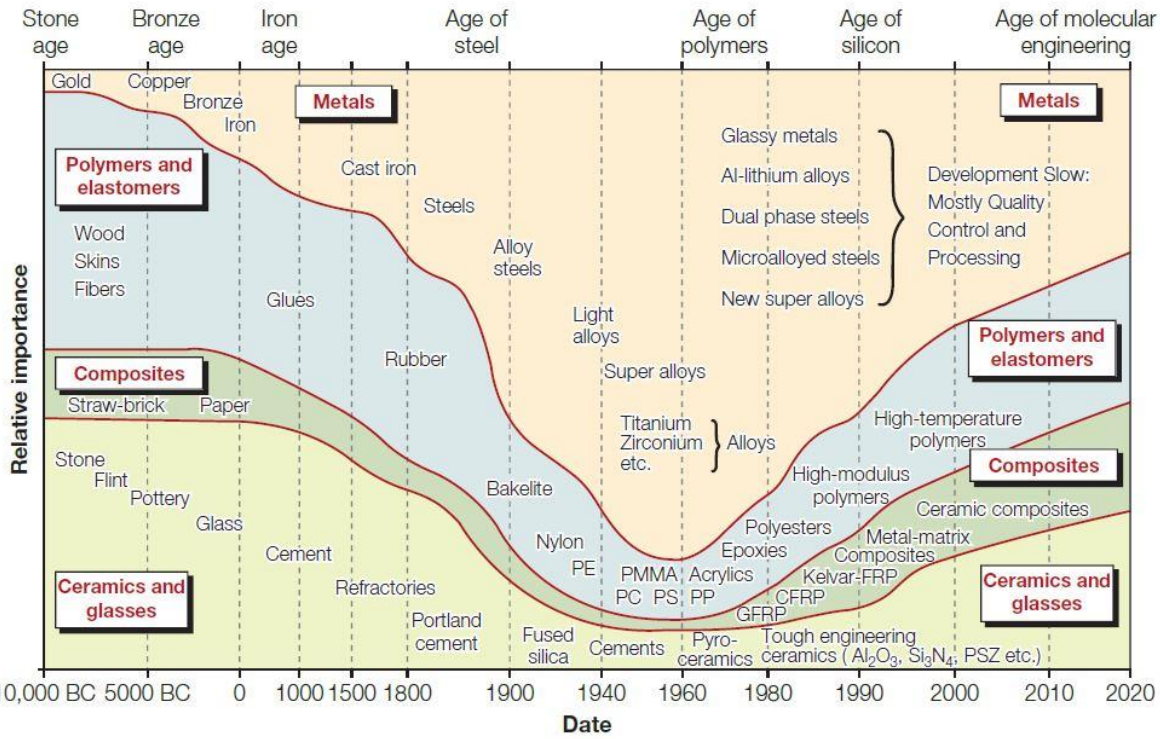


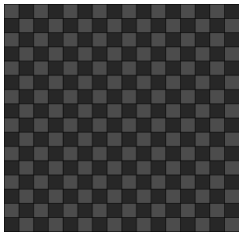
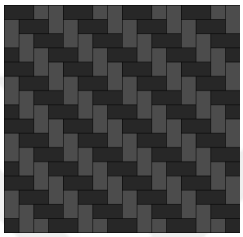
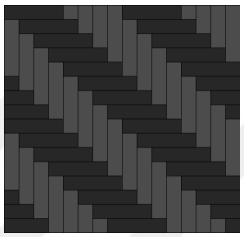
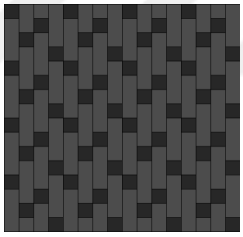
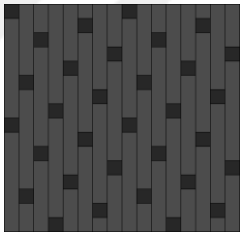
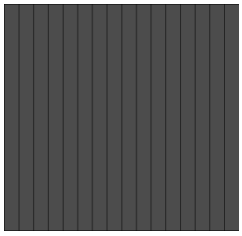
Figure 1.2. Relative Importance of Materials (Ashby, 2011)

1.2. Fiber Reinforced Composites

Composite is basically formed by reinforcing plastics with fibers. Fiber reinforced composites consist of reinforcement and matrix materials. While the duty of the reinforcement material is to carry the load, the matrix material is responsible for keeping the structure together. At this point, the reinforcement material is fibers which are load carrying member.

While fiber types are preferred depending on the application area and production method, they are also preferred according to the loads to be affected. Fiber types and their most important properties are defined in Table 1.1.

Table 1.1. Types of Fibers

Type	Illustration		Property
Plain (Woven Fabric)			• Stability level high because of short space between interlaces. • The plain isn't compatible for layups with advanced contours. • Not very flexible compare to other weaves. • Suitable for flat sheets and tubes.
Twill (Woven Fabric)			• It has good flexibility. • It can form advanced contours. • Fabric stability is better than harness satin. • 2x2 Twill has higher stability. • 4x4 Twill is more formability because the weave is not tight as much as 2x2 Twill.
	2x2 Twill	4x4 Twill	
Harness Satin (Woven Fabric)			• Easily wrap and form around advanced contours. • High formable. • Low stabile. • Increasing satin weave number (4HS, 8HS) formability increase, fabric stability decrease.
	4HS	8HS	
Unidirectional			• Provide high strength and stiffness due to continuous fibers. • Low workability.

1.2.1. Carbon

The superiority of carbon fibers include extraordinary high tensile strength-to-weight ratios, besides tensile modulus-to-weight ratios, very low linear coefficient of thermal expansion, high thermal conductivity and high fatigue strengths (Zhou et al., 2008). Carbon fibers have superior properties from a point of strength than glass and aramid fibers.

1.2.2. Glass

Glass fiber exhibits impressive strength, low weight, and exceptional durability. Its weight-to-strength ratio proves highly advantageous when contrasted with metals, and it readily lends itself to fabrication via molding techniques. However, glass fibers major drawback lies in its vulnerability to elevated temperatures. (Singh et al., 2013).

1.2.3. Aramid

Aramid fiber is an artificial organic polymer created by spinning a solid fiber from a liquid chemical mixture. Among its benefits are its notable specific tensile strength, resistance to impacts and wear, and resistance against fatigue. (Uzay et al., 2018). The weakness are low compression, attack by UV and acids, and low temperature resistance (Zhou, 2015).

1.3. Sandwich Structures

Sandwich structures, as a type of composite structures, are a special laminate by bonding materials in different forms to each other to obtain the desired properties. Traditionally, a composite sandwich structure consists of two main parts: the core structure, which is preferred more thicker between thin surface layers. The surface materials are a laminated and consist of a composites matrix and reinforcement material. In addition to that, the core material is preferred in a thick structure from low density materials. The reason of that, while the weight of the sandwich structure is increasing to a small extent, the moment of inertia of the structure increased in order providing a better bending resistance. For this reason, the flexural strength-density ratios of sandwich structures are quite high.

Sandwiches are functionally similar to I-beams, which are heavily preferred in the metal industry, as seen in Figure 1.3. The flanges of I-beams bear compression and tensile loads, just as the surface layer of sandwich structures performs this function in a similar way. Likewise, the interconnecting section between the flanges in an I-beam provides resistance against shear forces, in sandwich structures, the core substance counters the shear force experienced by the combined top and bottom surface layers. (DIAB Group, 2012).

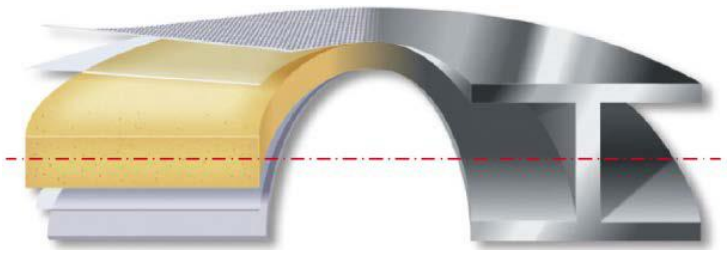


Figure 1.3. Comparison between sandwich composite and I-beam (DIAB Group, 2012)

1.3.1. Skin Materials

The materials used for the skin materials are generally in the form of thin sheets. Generally, both metals and non-metallic materials used as surface layers, but non-metallic skin material are widely preferred by reason of their excellent weight reduction and stiffness improvement (Joseph et al., 2022). As seen in Figure 1.4, in a load acting on the surfaces of sandwich structures, the surface layers are subjected to compressive and tensile loads.

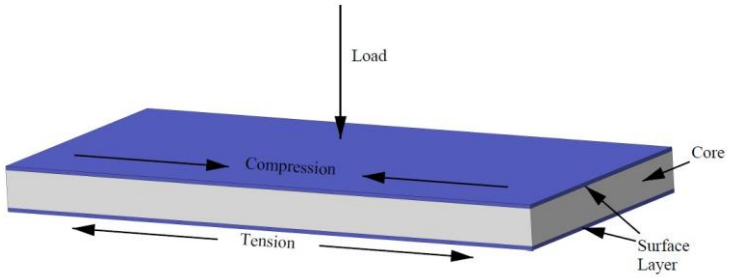


Figure 1.4. Schematic of sandwich structures

1.3.2. Core Material

The main purpose of using core material is to reduce the overall weight of the sandwich structure and increase the bending strength, so low density materials are generally preferred. Core materials are mainly subjected to shear loads caused by loads acting on the sandwich structure. Core materials also subjected to the compressive loads, and they should be stable under compressive without buckling. There are various core material structures, such as; honeycomb, foam, prismatic, truss and textile. These structures are designed and used in different sizes and types or as closed and open cells. In addition to that core materials can be metal, Polyurethane (PU), Polyvinyl chloride (PVC), biomaterial foams (such as balsa wood) (Ma et al., 2021).

1.4. Manufacturing Methods of Sandwich Structures

Due to the attractive properties of fiber-reinforced polymer composites, the demand for their use in many engineering fields is increasing day by day. Additionally, the development of new types of polymers and reinforcement has made it possible to achieve improved physical and mechanical properties. The manufacturing process used to achieve these properties plays an important role in the design and construction of composite materials (Uzay, 2020).

There are several polymer composite manufacturing techniques, such as resin transfer molding, hand lay-up, automated lay-up, resin infusion, vacuum bag, autoclave and hot press molding pultrusion process. Some of these methods are traditional and some them advanced technique. Since there are a lot of manufacturing method, considering of design conditions will be ensure to select the most appropriate method. Besides the most used methods are, resin transfer molding, vacuum bagging, hand lay-up and autoclave methods.

Although the hand lay-up method is the simplest and cheapest, products with high labour skill low production volume, low mechanical properties and poor surface are obtained. On the other with hand vacuum bagging method better mechanical properties can be obtained however, production volume is low and high labour skill is needed. With the resin transfer molding method production volume is increased, but the dimensional accuracy is poor and cost of the tools are high, and also there is an insufficient resin impregnation risk. In autoclave method, the mechanical properties are high however, the operation is costly, complex, relatively simple shaped product is obtained and a secondary finishing process is needed (Uzay and Geren, 2020).

1.5. Flexural and Flame Retardant Properties of Carbon Fiber Structures

Sandwich composites will obviously play a significant place in the near future because of their enhanced features. They provide thermal and sound insulation, impact load resisting, improved fatigue life, corrosion resistant and humidity, invisible to radar waves, durable at extremely high speeds, and aerodynamic surfaces, in addition to lightweight and bending stiffness. Because of these advantageous features, the majority of conventional metallic materials used in industry, that are all of importance to new technology, will be changed or reinforced with sandwich structures (Uzay et al., 2019).

One of the most significant property of sandwich structures, especially using as a load-carrying structure with the effect of the bending stresses is flexural stiffness. Because a sandwich structure can be made from a wide range of materials, flexural stiffness is becoming an important criterion for comparing the efficiency of sandwich structure (Uzay et al., 2018).

Among polymer composites, carbon-based fillers attract considerable attention due to their ability to beneficially change their properties at low filler concentration, to establish strong interfacial bonds with polymers, and to exist in different forms. The versatility of polymeric composites in applications in many fields is due to the alternation of properties. Building fires highlight the necessity of flame-retardant polymer composites, which are directly connected to human life protection and safety. (Babu et al., 2020).

Today, the need to examine the flammability properties of fiber reinforced composites; this is because they have started to be used as publications in the automotive, construction or aerospace industries. Since some polymers and plant-based natural fibers are flammable, their use in such applications may pose a threat (Kamaraj et al., 2019). At the same time, it is observed that there are losses in the mechanical properties of fiber-reinforced composites exposed to fire for a while. In industrial applications, structural stability plays a limiting role (Timme et al., 2017).

The examination encompasses aspects such as combustion speed, flame spread, and the ability to self-extinguish following the removal of the ignition source. The vertical flammability test assigns a classification to materials, encompassing the highly flame-resistant V-0, V-1, and V-2 ratings.

Where;

V-0: Materials that achieve self-extinguishment within a span of 10 seconds subsequent to each flame application without any occurrence of flaming drips.

V-1: Materials that achieve self-extinguishment within a span of 30 seconds subsequent to each flame application without any occurrence of flaming drips.

V-2: Materials that achieve self-extinguishment within a span of 30 seconds subsequent to each flame application, albeit with the possibility of limited flaming drips.

1.6. Industrial Applications of Sandwich Composites

Sandwich structures, which are widely used in the industry, provide low weight and high bending resistance, and the structures can be classified according to the design conditions according to their usage areas. Although sandwich structures vary according to the application area, different combinations of surface materials, core materials and matrix materials are preferred. The designers obtain the final product by creating the most suitable combination to meet the requirements.

Today, when we look at the automotive industry, these sandwich structures are mostly used in motor sports and some super sports cars. The fact that sandwich structures are not used in passenger cars, which are currently in large numbers, is due to the high production cost. Similarly, sandwich structures appear in applications where more specific performance-based products are used instead of mass-produced products such as aviation and the military industry. As its shown in the Figure 1.5, the majority of today's aircraft are composed of composite structures, and sandwich structures have an important place among them.

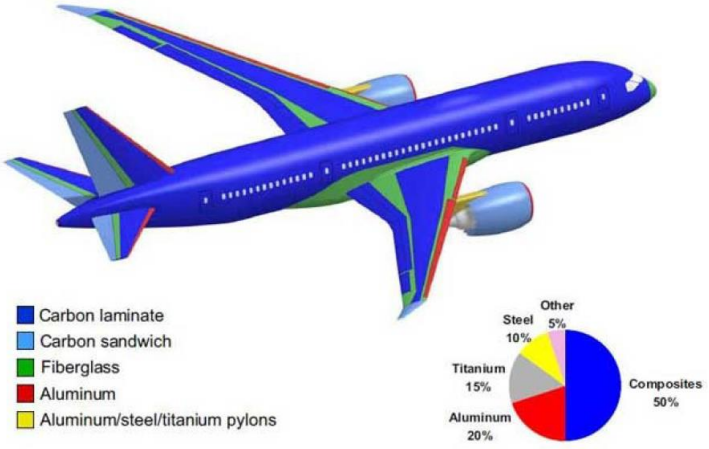


Figure 1.5. Distribution of the Materials on Boing 787 (Boeing Company, 2017)

Another benefit of using sandwich panels in industrial applications is to eliminate the corrosion problem caused by steel or aluminium alloys, especially in marine applications, or to overcome the environmental degradation to which wood is exposed (Selvaraju et al., 2011)

Payload fairings are another increasing application for composites in space launch vehicles. With the carbon-epoxy skin materials and aluminium honeycomb core materials are becoming the preferred designs due to their lightweight and high stiffness (Vicario et al., 2018)

Also, the manufacturing methods of the sandwich composites are playing a important role for industrial applications. In other words, for the shape structure or the material cost is an important factor in whether the application will be used or not. For example, it will be very difficult to use a sandwich structure in high curvatures. Because, while the fiber can be shaped as desired, the same cannot be said for the core material.

1.7. Aim of the Study

The increasingly widespread use of carbon fiber/epoxy sandwich structures in the industry is due to the low density and high flexural strength they provide. In particular, increasing the strength of sandwich structures by maintaining low weight is mostly required application. At the same time, flame resistance is expected from these materials in some applications in the industry. Although their enormous mechanical characteristics and also its low weight, they have very low fire resistance. Structures with both high strength and non-flammability will increase the preference of these structures. In cases where these two features are required together in areas such as transportation and military, the presence of a structure with high mechanical properties and flame retardant properties will inevitably lead to the choice of the material. In this study, it is aimed to improve the bending resistance and flame retardant properties of carbon fiber/epoxy sandwich plates by matrix toughening method. Many studies in the literature have increased the flexural strength of sandwich structures. However, it is extremely important to keep the weight of the structure low while achieving this increase. The matrix toughening method will be the best option to improve the mechanical properties and at the same time to provide flame retardant properties to the structure. The fact that this method has not been widely used in sandwich composites shows a gap in the literature. Also with this study aimed to fill this gap in the literature and obtain carbon fiber/epoxy sandwich structures that have high bending strength and flame retardant properties at the same time. In addition to the excellent mechanical properties of graphene, its superior thermal characteristics make it inevitable for it to be preferred as an additive (Babu et al., 2020). On the other hand, boron carbide is known for its ballistic performance due to its high hardness value (Tan, 2014), and kaolin is known to improve the mechanical properties and thermal properties of polymeric composites as a natural filler. (Selvan et al., 2023). For this reason, flexural strength and flame retardant properties of sandwich plates were investigated by adding Boron Carbide, Graphene and Kaolin in powder form at 2%, 5% and 10% to epoxy resin. In this method, it is expected to increase the flexural strength and flame retardant properties without high rate increasing of the structure weights.

2. PRELIMINARY WORK

Although carbon fiber sandwich structures have high bending strength, this property varies depending on the type, size and density of the core material of the sandwich structure. Likewise, the number of layers of the fiber, which is the surface material, also affects this. In the literature, it has been tried to increase the bending strength by adding some additives into the matrix material without increasing the unit weight of the sandwich structure by using low- density core material. The additives used are generally preferred from materials with low density and high strength.

2.1. Overview of Composite Structures

Composite materials are macroscopic mixtures of two or more different materials separated by a clear and identifiable interface. Outcomes of the increasing of fiber volume fraction help increase the mechanical properties of the composite structure, especially where the matrix material is insufficient to transfer the load. The engineering attributes can be influenced by factors such as length of fiber, orientation of fiber, and volume fraction of fiber. Continuous fiber-reinforced composites offer the most effective translation of fiber properties into pertinent engineering features. As fiber length diminishes, there is a corresponding decline in the composites mechanical properties. Ultimately, as fiber length decreases further, the composite characteristics start to resemble those of a system filled with particles (Reinhart, 1998)

2.1.1. Sandwich structures

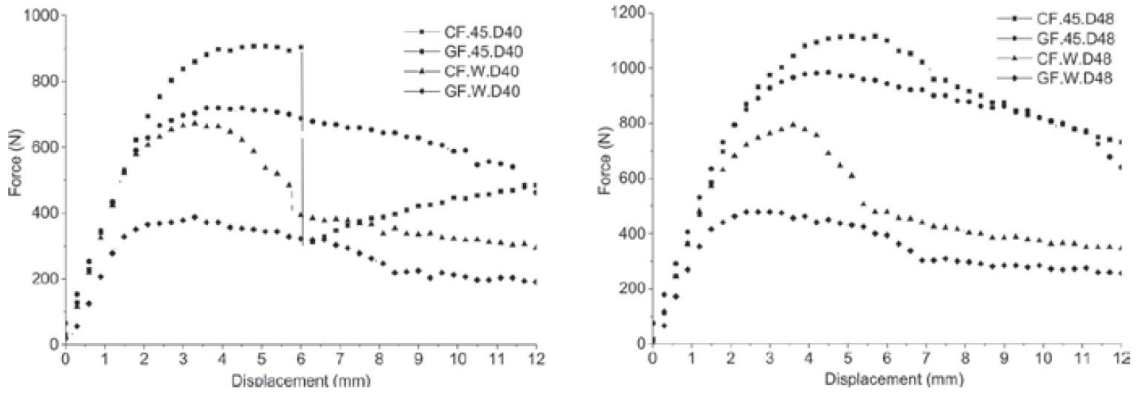
Sandwich structures are lightweight and stiff structures obtained by combining low-density core structures between stiff surfaces. In the literature, desired strength values have been provided with core materials of different types, densities and dimensions. The skin materials of sandwich structures carry practically all of the in-plane loads, while the core material supports the skins and defines flexural stiffness and compressive behaviour. Since the surface layers are subject to bending, they should be stiff in tension and compression, whereas the core needs to be stiff because it will be exposed to shear loads and local failure may occur (Uzay et al., 2018).

Ma et al. (2021), generally focus on the recent developments of core structures of sandwich structures. Cellular foam, periodical two and three dimensional cores have been properly characterized and summarized in terms of core structural trends. Cellular foam can be divided into metallic, polymeric and bio metals, and these can also be classified as open-celled and closed-celled in themselves. The densities of closed-cell structures are higher than that of open cells. Sandwich structures with different cores were investigated by three common impact load types, compression, velocity impact and three-point bending tests. It was specified that the impact resistance performance of sandwich panels is influenced by the following factors: loading type, surface layer, core structure, and impact speed.

Furthermore, while sandwich structures exhibit better impact performance and can absorb more energy their use is increasing in a number of lightweight structural applications.

Uzay and Geren (2020), investigated the bending characteristics of sandwich structures with carbon fiber/epoxy surface layer hybridised with stainless-steel wire mesh and PVC core material. It has been stated that the use of wire mesh sheets together with carbon fiber/epoxy coatings leads to significant increases in the bending properties of sandwich structures. Moreover, the wire mesh sandwich reinforced layers effectively prevented the occurrence of sudden catastrophic failures, which is a common problem observed in carbon/epoxy polymer foam core sandwiches. It has been found that following failure, when sandwiches without wire mesh lose their ability to carry bending loads, sandwiches containing wire mesh sheets show continued ability to carry significantly higher bending loads at equivalent deflection values. In particular, the bending load capacity of wire mesh reinforced sandwiches during failure decreased by 25.37%, 30.91%, and 44.67% for 30 mm, 20 mm, and 10 mm, respectively. However, for the 100M1 configuration, the reductions were observed to be relatively lower, with 11.27%, 4.94% and 4.28%, respectively.

Uzay et al. (2019), the focus was on investigating the influence of exceptionally PVC foam core materials which are low-density (40 kg/m^3 and 48 kg/m^3) on the bending behaviour of sandwich structures, incorporating surface layers of 200 g/m^2 glass and carbon fiber fabrics with various fiber orientations. Sandwich structures were fabricated using the hand lay-up and after vacuum bagging method. The researchers remained the thickness of the foam core constant at 16 mm in all specimens. Figure 2.1 illustrates the comparative presentation of force-displacement curves acquired from three-point bending tests. All sandwich panels exhibit analogous behaviour, with specimens containing higher density foam core showcasing superior bending load capacities. Across different carbon fiber facings, while the increment in bending load varies, there is a 21.44% increase in force for woven plain fabric and a 26.49% increase for ±45° fabrics, respectively. Conversely, glass fiber facings' in the case, there is a 31.15% increase for woven plain fabric and a 33.66% increase for ±45° fabrics.



(a) (b)

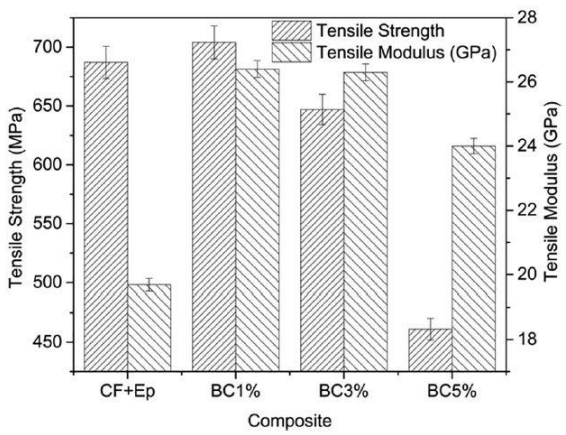
Figure 2.1. Force and displacement graph due to the bending test of sandwich structures (a) 40 kg/m^3 core density (b) 48 kg/m^3 core density (Uzay et al., 2019)

2.2. Effect of Additives

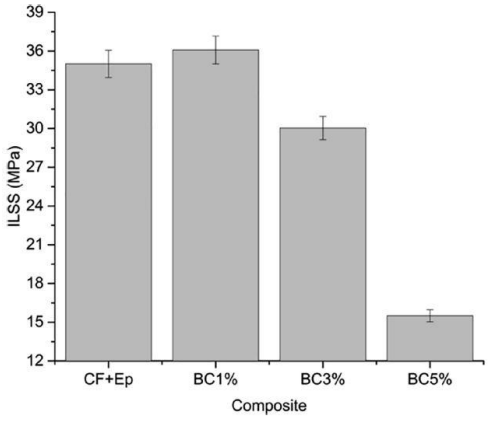
Since the matrix materials of composite structures, which are generally exposed to impact loads, exhibit brittle behaviour, its causes the composite structure with a low toughness. In order to overcome this deficiency, scientists have been adding nano and micron-size particles into the matrix material over the past decades. The method of adding particles, or in other words, adding additives to the matrix material, has been applied to both laminated composites and sandwich structures.

Geren et al. (2021), have done studies to increase the toughness of the sandwich structure, and in line with their findings, the toughness can be increased by choosing the core materials of the sandwich structures from high-density materials, but this will cause an increase in the residual of the structure. In this case, adding Boron Carbide in micro sizes to the matrix material minimized the increase in the weight of the structure and increased its toughness. In the study, Boron Carbide was added to the matrix material at the rate of 2%, 5% and 10% by weight, and comparisons were made 25 J, 17.5 J and 10 J energy levels by low-velocity weight drop test. Researchers stated that the results a sandwich structure containing 10% Boron Carbide can withstand a high impact load while providing low energy absorption.

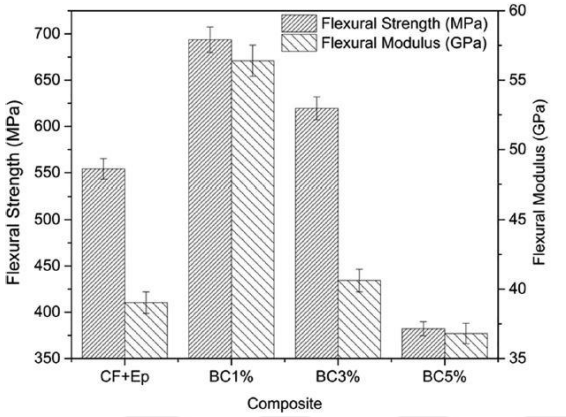
Muralidhara et al. (2019) worked on the effect of the Boron Carbides added carbon fiber/epoxy composites mechanical properties. The specimens consist of T800 twill carbon fiber as reinforced material, and a homogeneous matrix material with 1%wt, 3%wt and 5%wt boron carbide added, and the laminate specimens are produced by hand layup-vacuum bagging method. The tensile strength, bending strength, interlaminar sheer stress (ILSS), impact strength and hardness values of the structure were examined to learn how the mechanical properties of the Boron Carbide filler material in the carbon fiber/epoxy composite material are affected. Test results are shown in Figure 2.2.



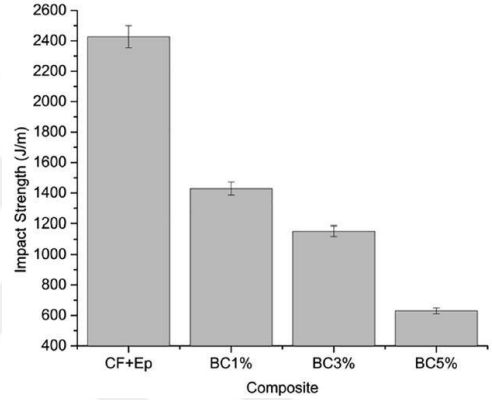
(a)



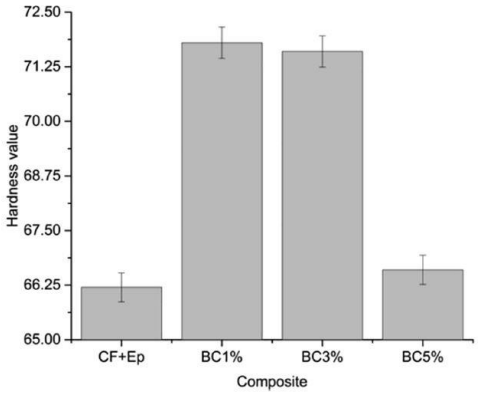
(c)



(b)



(d)



(e)

Figure 2.2. Mechanical properties of Boron Carbide filler bidirectional carbon fiber/epoxy composites; (a) tensile strength, (b) flexural strength, (c) ILSS, (d) impact strength, (e) hardness (Muralidhara et al., 2019)

When the test results were examined, it was observed that there was a significant improvement in all mechanical properties of Boron Carbide-filled CF/Epoxy laminates. Boron Carbide additive added by weight showed an effective scale of 1%>3%>5%. In addition, when the failure mechanism of the

structure was examined by SEM, all the fibers were covered with epoxy and no matrix cracking, delamination and interfacial debonding was observed at the interface.,

Poomarimuthukumar and Siva (2021) examined the mechanical properties and flammability properties of Boron Carbide added basalt/epoxy composite structures. They added Boron Carbide filler at the rates of 5%, 10% and 15% to the samples they produced with the compressed manufacturing technique. Flexural strength, tensile strength, hardness, impact strength and flammability properties of the samples examined after production. According to the test results, when the mechanical properties were examined, an increase in tensile strength and hardness values was observed with the increase in the filling material in the structure, but the highest result for impact strength and flexural strength was seen in the 5% filled sample. Researchers state that the reason for this is due to insufficient bonding of fiber and resin due to the increase in the filling material ratio. Figure 2.3 shows the bending test results of the structure. When they examine the flammability test results, they see that flame retardancy increases with the increase of boron carbide filling material. They revealed that 15% filled samples produced the best results and fire resistance increased with the use of more boron carbide. UL 94 horizontal flammability test results are given in Table 2.1.

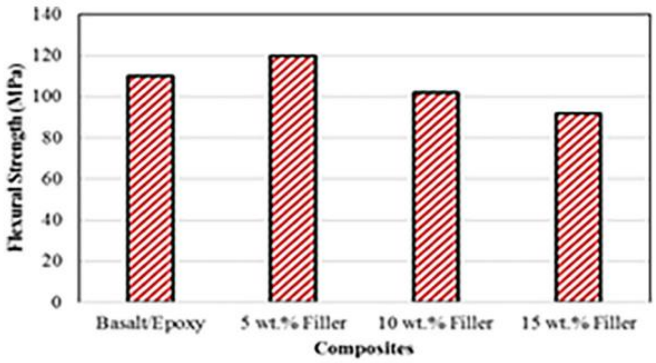


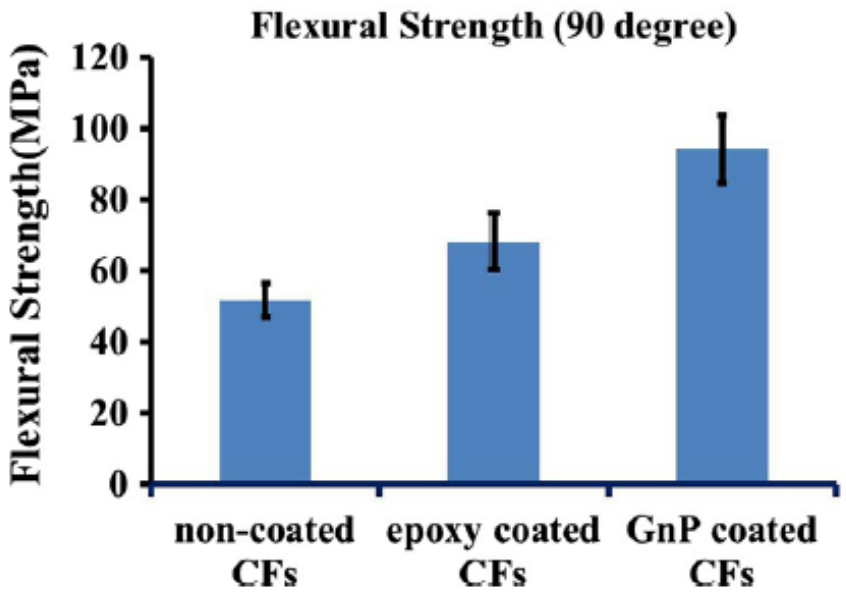
Figure 2.3. Effect of filler on flexural strength (Poomarimuthukumar and Siva, 2021)

Table 2.1. Horizontal flammability test results (Poomarimuthukumar and Siva, 2021)

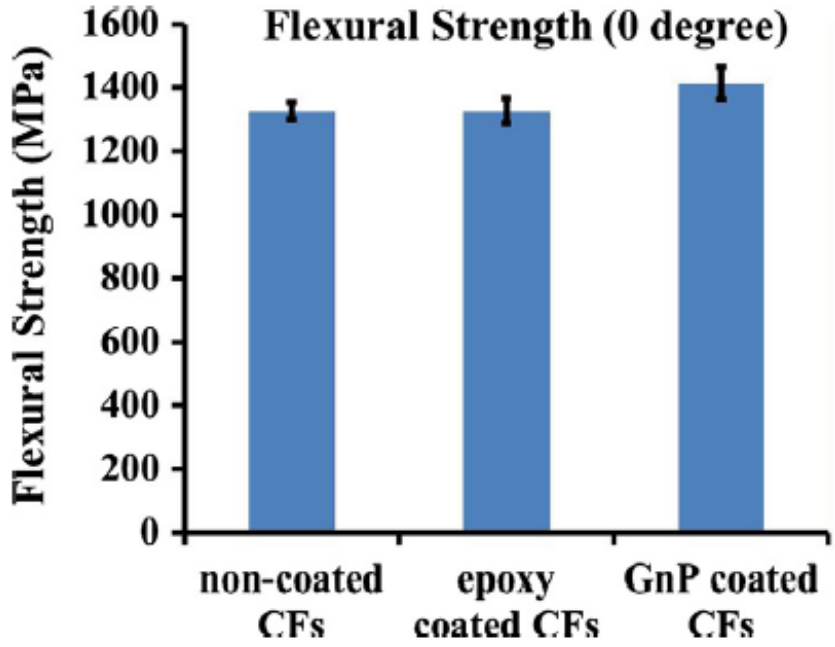
Ratio	Forced burning		Natural burning		Weight Loss %	Particle drip
	Time to 20 mm reach (sec)	Burn for 30 sec (mm)	Time to 20 mm reach (sec)	Burn for 30 sec (mm)		
0%	–	19	–	1.3	14	No
5%	–	18	–	1.2	11	No
10%	–	15	–	1.1	10	No
15%	–	11	–	1	8	No

Qin et al (2015), were investigated the 90° and 0° flexural strength, inter-laminar shear strength and electrical conductivity of Graphene Nanoplate (GnP) coated CF-epoxy composite structures which were obtained by manufacturing prepregs produced with the drum-winder technique after hand lay-up and followed autoclave composite processing. In line with their findings, the 90° flexural test compared to non-coated fibers, only epoxy coated fibers, and GnP-coated fibers, with GnP-coated CFs exhibiting

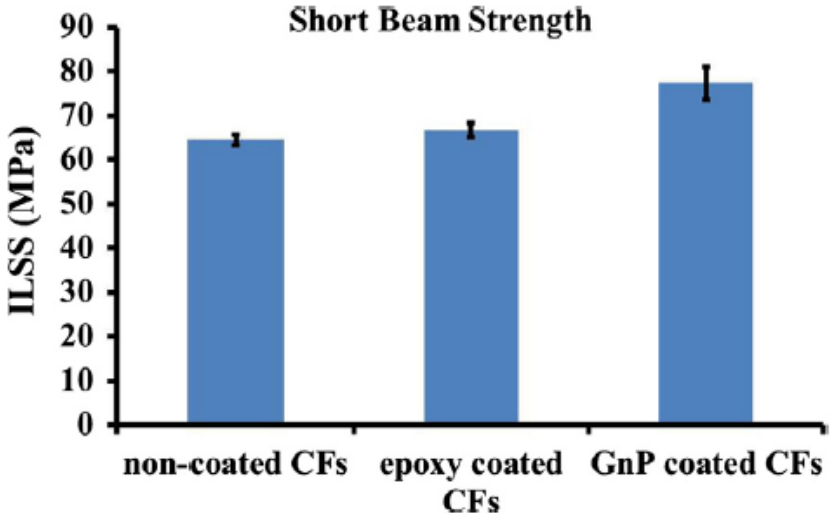
the highest strength. As its shown in the Figure 2.4a GnP-coated CFs showed an increase of 51% compared to only epoxy coated, and an 82% increase against non-coated fibers. GnP-coated CFs according to 0° flexural test; for non-coated and only epoxy coated CFs, it showed a slight increase of 7% for both situations as seen in Figure 2.4b. According to the results of the interlayer shear strength (ILSS) test performed to show the adhesion strength of the composite between the fiber and the matrix, the fracture resistance of the matrix and the level of porosity, an increase of 19% was observed in GnP-coated CFs compared to only epoxy coated and non-coated fibers as shown Figure 2.4c. They stated that the addition of GnP to the structure increases the shear modulus by increasing the bonding between the matrix and the fiber. When they compared the electrical conductivity of the structures, GnP-coated CFs showed a high increase of 165% compared to only epoxy coated fibers and non-coated fibers.



(a)



(b)



(c)

Figure 2.4. (a) Evaluation of 90° flexural properties, (b) Evaluation of 0° flexural properties, (c) Evaluation of the ILSS (Qin et al., 2015)

Srivastava et al. (2019), were investigated the Graphene Nanoplates (GNPs) coating fibers as well as fiber oxidative treated carbon fiber composites on the bending features. The specimens were produced the vacuum assisted resin transfer molding (VARTM) method. Carbon fiber fabrics were made ready for production by going through a series of surface treatment processes. The GNP-acetone suspension was coated on oxidized carbon fabric with the help of an airbrush. As seen in Table 2.2, five

different types of samples were produced and their bending strengths were observed. Figure 2.5 shows a schematic comparison of composite interphases.

Table 2.2. Specimens (Srivastava et al, 2019)

Name	Desized	Oxidized	GNP Spray coating
Pristine (Control Sampling)	-	-	-
0.4 GNP	-	-	0.4 wt%
DOCF15 / 0GNP	72 h	15 min	-
DOCF15 / 0.2GNP	72 h	15 min	0.2 wt%
DOCF45 / 0.2GNP	72h	45 min	0.2 wt%

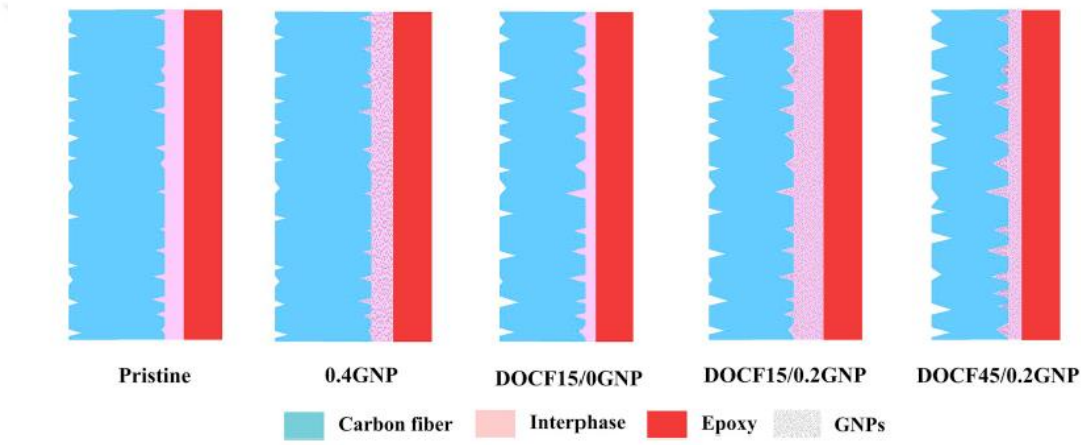
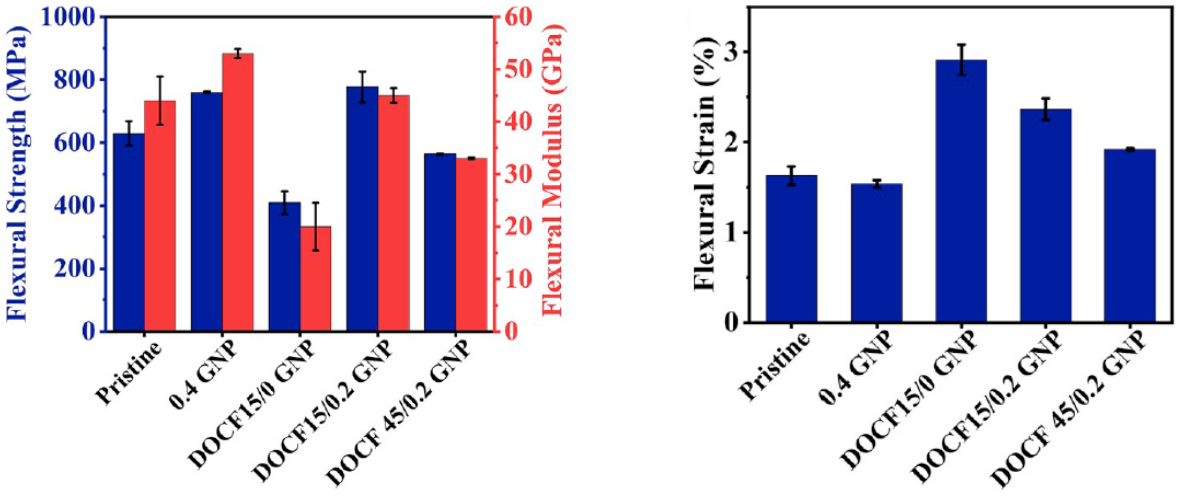


Figure 2.5. Different conditions of GNP/CF/Epoxy composite interphases (Srivastava et al, 2019)

When the researchers examined the test results, they found that the flexural strength of the 0.4 GNP laminate structure increased by 20% equivalent to the intact laminate structure, as shown in Figure 2.6. The thicker interface between fiber and matrix enabled effective load transfer while exhibiting high flexural strength. They concluded that the DOCF15/0.2GNP laminate structure exhibited the highest bending strength. They said that this was successful because sufficient time was allowed for desizing without fiber damage. When the widest interfaces of the structures were examined by SEM-EDS mapping, the widest interface was observed in the DOCF15/0.2GNP laminate structure.



(a) (b)

Figure 2.6. Flexural test outcomes for epoxy composites containing GNP/CF under various circumstances. (a) Flexural modulus and stress (b) Flexural strain (Srivastava et al, 2019)

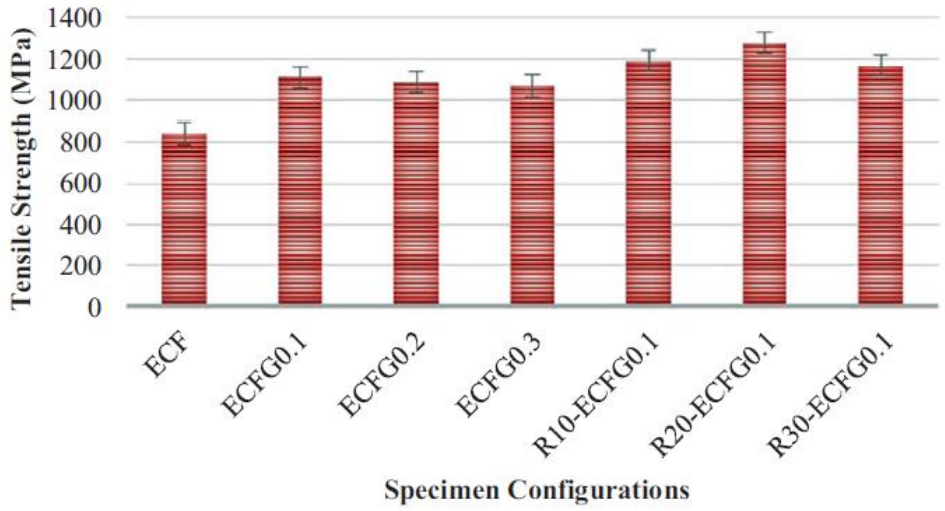
Hawal et al. (2020) investigated the effect of hybridization and multiple reinforcement on the mechanical properties of composites produced by vacuum bagging method. They examined the tensile and bending properties by adding rubber to carbon fiber epoxy composites containing graphene as a nanofilling material. They added graphene as a nanofiller to carbon fiber-epoxy composites at 0.1% by weight, 0.2% by weight, and 0.3% by weight. 10%, 20% and 30% liquid rubber was added to modify the matrix of carbon fiber epoxy graphene composites. The nomenclature of the samples is shown in Table 2.3.

Table 2.3. Nomenclature used for different samples (Hawal et al, 2020)

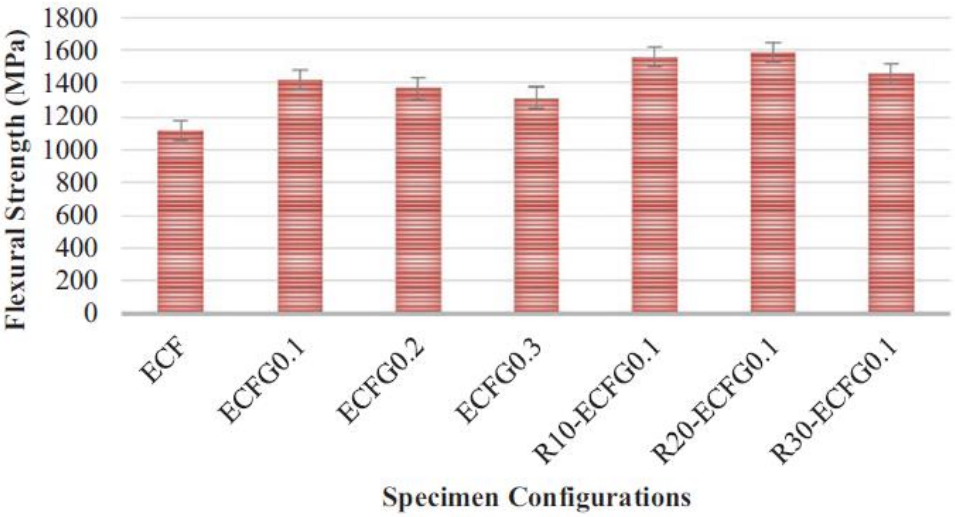
Sl. No.	Terminology	Carbon fiber mat in number of layer	Graphene in weight percentage	Liquid Silicone rubber in weight percentage
1	ECF	4	Nil	Nil
2	ECFG0.1	4	0.1	Nil
3	ECFG0.2	4	0.2	Nil
4	ECFG0.3	4	0.3	Nil
5	R10-ECFG0.1	4	0.1	10
6	R20-ECFG0.1	4	0.1	20
7	R30-ECFG0.1	4	0.1	30

When the test results were examined, they were stated that while an increase was observed in the bending and tensile properties of carbon fiber-epoxy composites with 0.1% graphene added, the

expected increase was not observed in the samples with 0.3% and 0.2% graphene added due to the agglomeration of graphene. % in the matrix. As seen in Figure 2.7, the addition of 0.1% graphene increased the tensile and bending strengths of the composite structure by 32% and 27%, respectively. Adding a certain level of liquid rubber to the sample containing 0.1% graphene improved the bending and tensile properties, but adding too much caused a sharp decline. They also say that the addition of liquid rubber ensures that the graphene is distributed evenly within the matrix.



(a)



(b)

Figure 2.7. Different specimen configurations (a) Tensile Strength, (b) Flexural Strength (Hawal et al, 2020

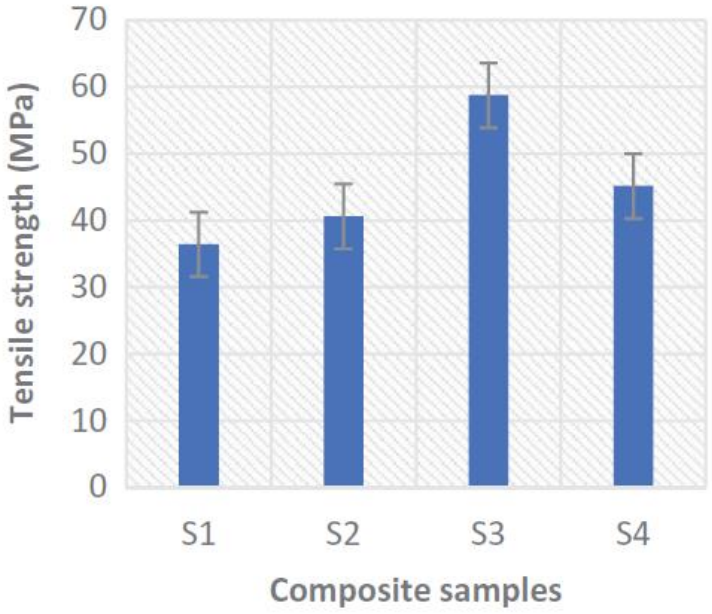
Kamaraj et al. (2019), researched the flammability, water absorption and mechanical properties of flax-epoxy composites by using graphene as matrix reinforcement. They were added the Graphene at 0.025%, 0.1% and 0.2% by weight in epoxy, and samples were named S2, S3, and S4,

respectively. The neat epoxy which is used as the control/reference sample was named S1. They were used manufactured technique which is vacuum resin infusion modified matrix and flax fabric. They stated that Graphene creates a thick and permanent layer that reduces heat transfer, giving the structure a flame-retardant property. Flax-epoxy samples filled with 0.2% by weight graphene were graded as V-0 as its represented in Table 2.4, and they commented that flame resistance will increase with increasing graphene filling in flax-epoxy composites.

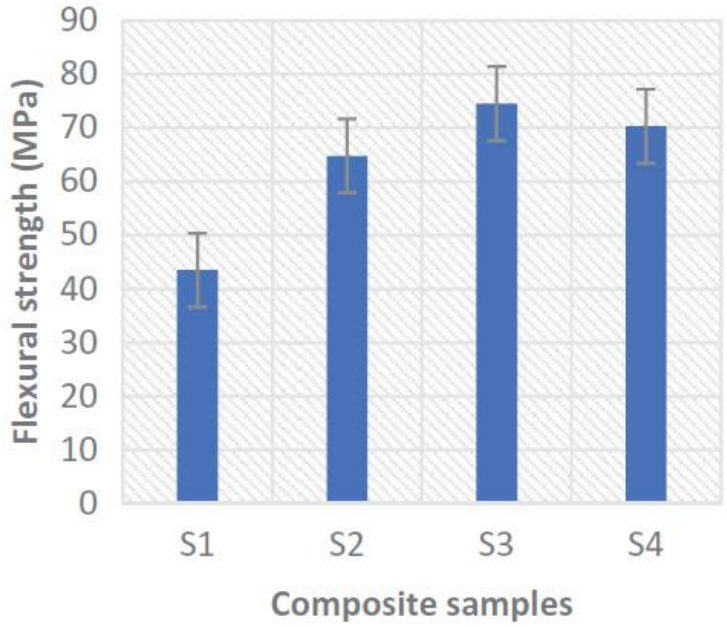
Table 2.4. Results of vertical flame test (Kamaraj et al, 2019)

Sl. No.	Samples	Self-extinguishing time (s)	Cotton ignited by flaming drips	Rating
1	S1	33	No	V-1
2	S2	21	No	V-1
3	S3	13	No	V-1
4	S4	9	No	V-0

Flax-epoxy composites filled with 0.1% graphene by weight demonstrated better performance than the pure epoxy sample determined in Figure 2.8, with tensile and flexural strengths of 61% and 71%, respectively. They say that the increase in load carrying capacity is due to the Graphene's homogeneous distribution in the epoxy. They observed a decrease in tensile and bending strength when the graphene content was increased to 0.2%. They revealed that the reason for this is that when the graphene ratio increases or graphene agglomeration occurs, they speculate that this is because the structure begins to exhibit brittle behaviour.



(a)

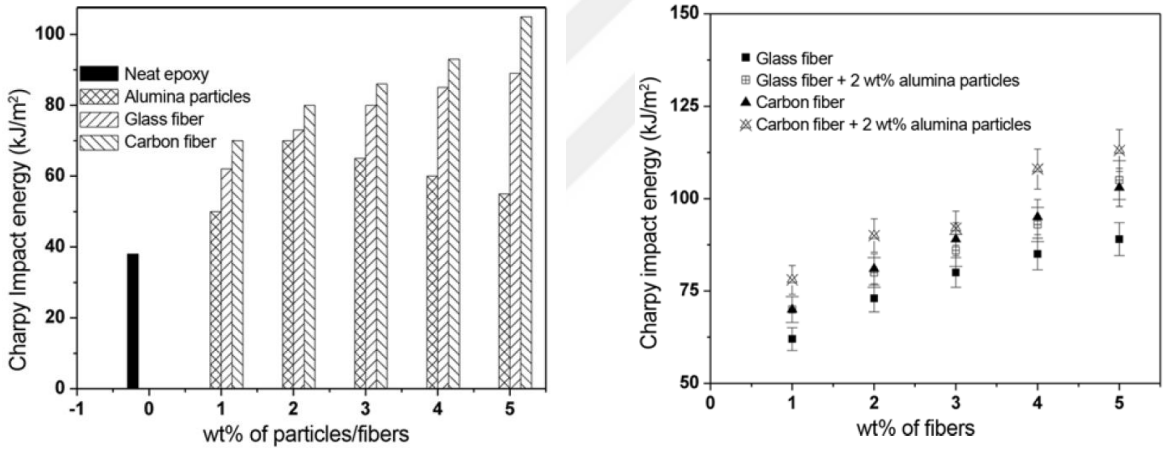


(b)

Figure 2.8. (a) Tensile strength (b) Flexural strength of samples (Kamaraj et al, 2019)

The primary objective of Mohanty and Srivastava (2015) in this study was to examine the effect of the flexural and impact properties by adding Alumina Nanoparticles into the epoxy matrix as well as glass and carbon fibres. They employed two strategies to achieve superior properties for flexural and impact: identifying the optimal alumina fillers' concentration to achieve the highest properties for flexural and impact, and preparing hybrid composites at the optimal alumina filler concentration while varying the weight percentage of short fibers. Characterization of the alumina nanoparticles and composites involved several mechanical tests, such as flexural testing, impact testing etc.

Figure 2.9 demonstrates the impact performance of alumina nano-particles. The impact energy rises as the weight fraction of alumina nano-particles within the epoxy matrix escalates, up to a critical concentration, at which point it starts to decline. They came to the conclusion that it represents, the optimum value for impact energy is achieved at a critical concentration of 2 wt%; This shows an 84% improvement over pure epoxy, which then gradually decreases, however, at 5 wt% loading of Alumina Nanoparticles, an extreme reduction in impact energy is seen, still giving a net success of 44% over pure epoxy.

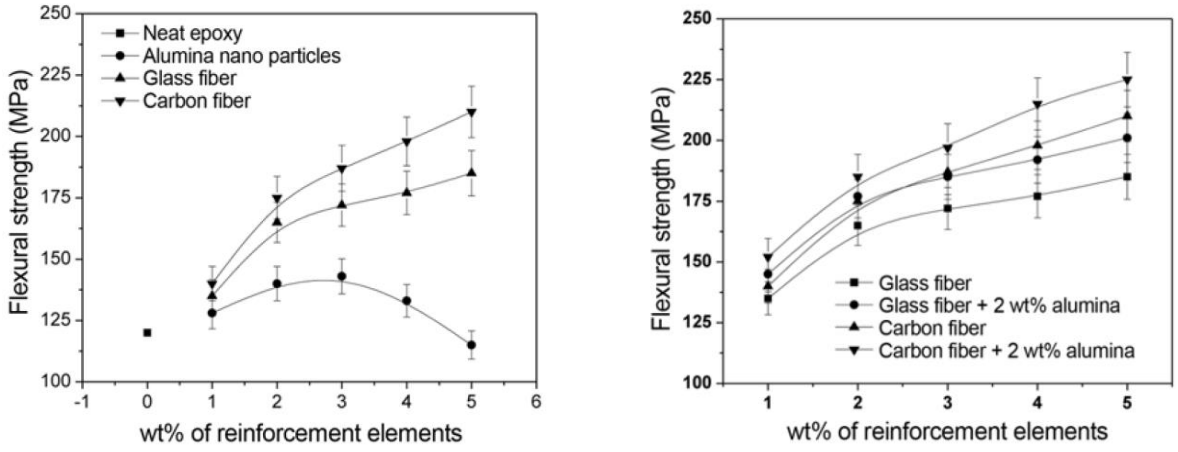


(a) (b)

Figure 2.9. Charpy impact energy results (a) individual, (b) addition to glass/carbon fiber (Mohanty and Srivastava 2015)

Figure 2.10a illustrates the influence of Alumina Nanoparticles on the bending strength of nanocomposites composed of epoxy and alumina nanoparticles. The flexural strength rises with an increase in the weight fraction of alumina nano-particles until reaching a critical concentration, after which it declines for higher concentrations. They achieved a 35% increase over pure epoxy by adding 5% by weight Alumina nanoparticles.

z



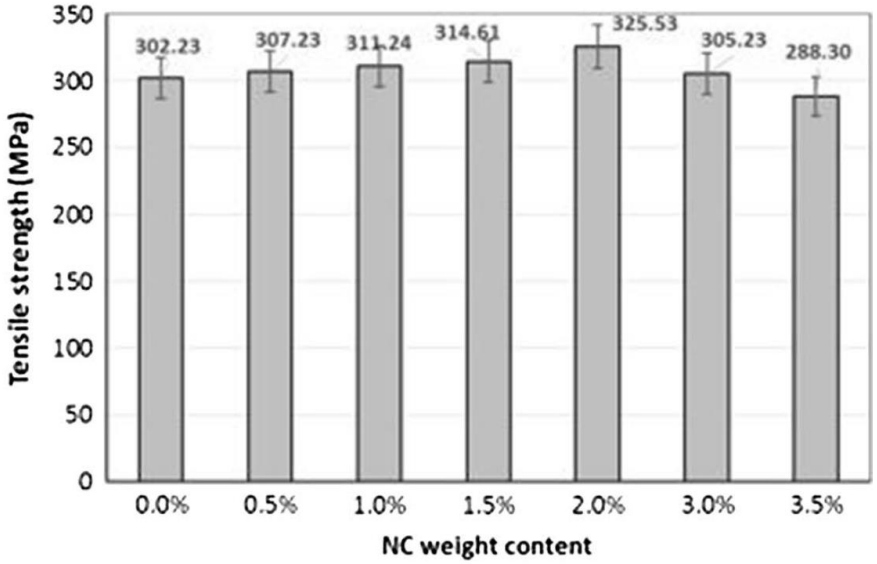
(a) (b)

Figure 2.10. Flexural strength results (a) individual, (b) addition to glass/carbon fiber (Mohanty and Srivastava 2015)

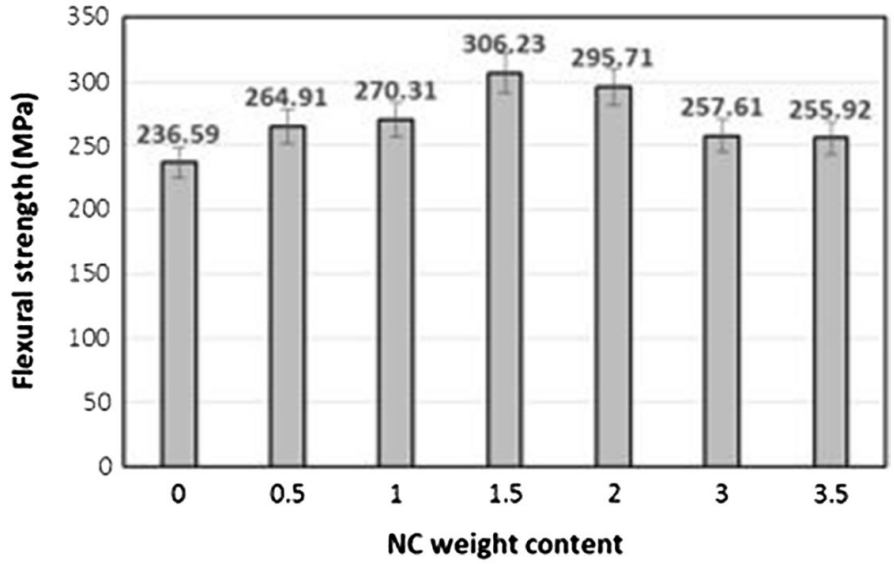
At the optimal alumina nanoparticle concentration (2%wt), nanoscale dispersion of Alumina Nanoparticles is achieved. Nevertheless, with a rise in the alumina nanoparticle content to 5% by weight, it prompts the aggregation of these nano-particles within the epoxy matrix. Additionally, the inclusion of Alumina Nanoparticles bolsters the thermal resistance of epoxy Alumina Nano-composites. In addition, they achieved significant improvements in flexural strength, flexural modulus, and impact strength by adding the ideal concentration of Alumina Nanoparticles (2% wt) to short glass and carbon fiber reinforced epoxy composites.

Bulut et al. (2019), examined the basalt fiber-reinforced polymer (BFRP) composites mechanical and dynamic characteristics, and focusing on their damping properties and natural frequency. The BFRP composites' epoxy resin was modified by incorporating Nanoclay (NC) particles at various (0, 0.5, 1, 1.5, 2, and 3%wt). Mechanical properties that including flexural, tensile and impact properties were conducted.

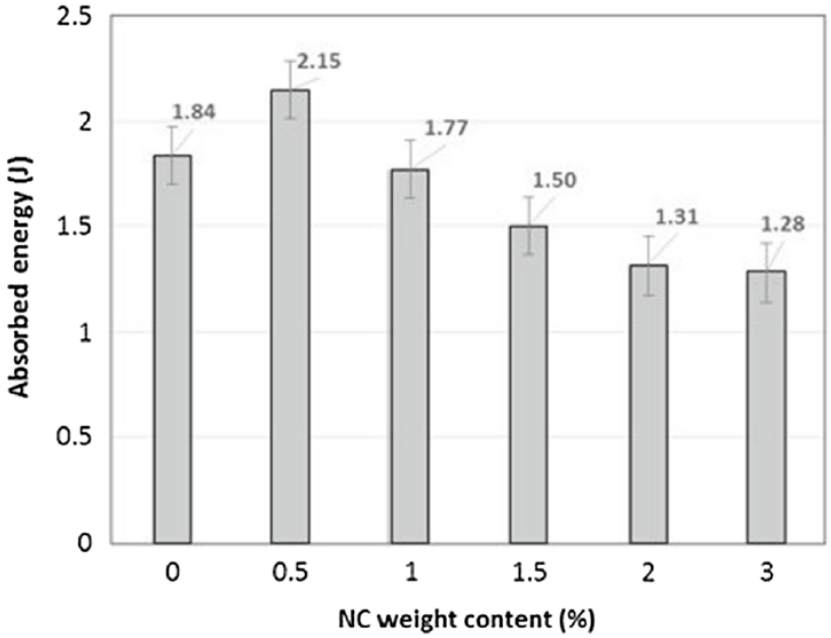
The findings revealed that the inclusion of NC particles resulted in significant improvements in tensile strength, up to 7.61% (Figure 2.11a), flexural strength, raised to 29% (Figure 2.11b), and energy absorption during impact, up to 16.8% (Figure 2.11c) (edgewise impact), achieved at NC contents of 2 wt%, 1.5 wt%, and 0.5 wt%, severally. However, adding further NC particles beyond the optimal concentrations led to a reverse effect, causing reductions in flexural, tensile and impact values due to agglomeration of NC particle. The study suggested that incorporating small amounts of NC particles into the epoxy resin notably enhanced the mechanical and impact properties. In contrast, higher concentrations of NC particles resulted in reduced mechanical and impact properties between epoxy and resin due to the compromised interfacial stress with the bridging effect of NC particles.


Tensile strength (MPa)
350
300
250
200
150
100
50
0
302.23
307.23
311.24
314.61
325.53
305.23
288.30
0.0%
0.5%
1.0%
1.5%
2.0%
3.0%
3.5%
NC weight content

(a)


Flexural strength (MPa)
350
300
250
200
150
100
50
0
236.59
264.91
270.31
306.23
295.71
257.61
255.92
0
0.5
1
1.5
2
3
3.5
NC weight content

(b)



(c)

Figure 2.11. Experimental results of NC modified BFRP (a) tensile, (b) flexural, (c) absorbed energy during impact (Bulut et al. 2019)

Panse et al. (2014), presents findings on the development of epoxy-based hybrid composites reinforced with nano silica for load-bearing structural applications. The composites utilize continuous unidirectional fabric architecture. An ultrasound-assisted method was employed to disperse hydrophobic fumed nano silica in the epoxy resin. The process parameters were carefully optimized to achieve a proper dispersion of the nano silica. Additionally, the impact of nano-filler adding on processing aspects was examined using rheology.

To produce the composites, they combined continuous glass or carbon fibers with unidirectional architecture with epoxy containing dispersed nano silica using a resin film infusion process. An optimized ultrasound-assisted process ensured uniform distribution of nanoparticles in the resin matrix. They discovered that the presence of Nano silica led to a marginal reduction in resin viscosity, while increasing control over the manufacturing process of the composite. Importantly, the glass transition temperature of the epoxy remained unaffected even at low weight fractions of Nano silica.

Table 2.5. Tensile property results of Nano silica reinforced hybrid structure (Panse et al., 2014)

	Carbon/epoxy		Glass/epoxy	
Specimen (wt%)	**Tensile modulus (GPa)**	**Tensile strength (MPa)**	**Tensile modulus (GPa)**	**Tensile strength (MPa)**
Control	123.57± 4.0	2202.4±104.0	42.15±1.9	1068.0±75.5
0.2	122.61±7.2	2216.8±79.2	41.98±3.6	1078.2±55.9
0.4	112.95±8.1	2217.3±152.7	43.06±3.4	1101.2±49.5
0.8	112.51±9.2	2111.3±53.1	43.63±2.4	1092.2±48.6

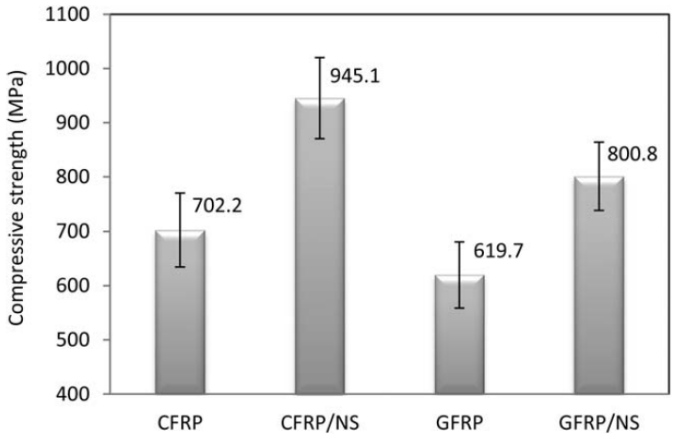


Figure 2.12. Compressive property results of 0.2%wt nano silica reinforced hybrid structure (Panse et al. 2014)

Hybrid CFRP exhibited a significant 35% rise in compressive strength compared to its control CFRP, while GFRP also experienced a notable 30% increase, both achieved with a nano-silica loading fraction of 0.2 wt% as shown Figure 2.12, the compressive and tensile properties of the hybrid composites as represented in Table 2.5.

Caglayan et al. (2018), aims to uncover the impacts how the dispersion and arrangement of CNTs effect on cell foamability and morphology, directly influencing the mechanical properties of sandwich composites and functional foam. The choice of polyurethane (PU) as the polymer foam core is motivated by simplicity manufacturing, availability, and favourable performance-to-cost ratio compared to other materials. To reinforce the PU foam, MWCNTs are incorporated using various methods, incorporate sonication and high shear mixing, to ensure optimal dispersion and arrangement. The sandwich composites are produced VARTM. Three-point bending experiments are conducted on both pristine and sandwich composites with PU foam core and reinforced with CNTs. They supplied PU foam cores in two form PMDI and polyol. Additionally, the procedure for manufacturing and identification of PU foam samples, both neat and CNT-reinforced, is described in Table 2.6. The effects of acid functionalization of carboxylic and MWCNTs aspect ratio of are assessed by analysing both the structure and strength of polymer foams.

Table 2.6. Fabrication and identification of CNTs samples (Caglayan et al., 2018)

Specimen	wt.%	Aspect ratio	Dispersion media	Process
Neat PU	-	-	-	-
R-CNT[a]	0.1	>350–550	Polyol	15 min high shear mixing at 10000 rpm
F-CNT[b]	0.1	~150	Polyol	15 min high shear mixing at 10000 rpm
F-CNT	0.2	~150	Polyol	10 min sonication at 70% amplitude
R-CNT	0.05	>350–550	PMDI	10 min sonication at 70% amplitude
R-CNT	0.1	>350–550	PMDI	10 min sonication at 70% amplitude
R-CNT	0.2	>350–550	PMDI	10 min sonication at 70% amplitude
F-CNT	0.1	~150	PMDI	10 min sonication at 70% amplitude

[a] R-CNT indicate to raw CNT

[b] F-CNT indicate to functional CNTs with carboxylic acid surface modification.

From the data in Table 2.7, they were stated that it is evident that reinforced PU foam with CNT exhibits significantly superior core shear strength compare with the neat foam, attributable to the CNTs toughening effect on the core. The presence of CNTs renders the foam core stiffer and better resists crack propagation, thereby enhancing the load-bearing capability of the sandwich composites. While both pure and CNT reinforced PU foam cores exhibit similar types of failures during bending, a considerable rise in bending failure load is attained with CNT reinforcement.

Table 2.7. Sandwich composites' flexural properties (Caglayan et al., 2018)

Core material	Specific compressive stress (MPa m^3/kg)	Core Shear Ultimate Stress (MPa)	Enh. (%)	Facing Stress (MPa)	Enh. (%)
Neat PU	0.0082 ± 0.0002	0.88 ± 0.09	-	46.5 ± 3.6	-
0.1 wt.% F-CNT/Polyol PU	0.0089 ± 0.0002	1.17 ± NA*	32.9	62.3 ± NA*	33.9
0.1 wt.% R-CNT/PMDI PU	0.0084 ± 0.0001	1.13 ± 0.01	28.4	65.2 ± 0.4	40.2
0.1 wt.% F-CNT/PMDI PU	0.0093 ± 0.0002	1.25 ± 0.08	40.9	78.0 ± 6.2	67.7

* NA: Not Available

In addition, the rigid sandwich composites with PU foam core, both neat and CNT-reinforced, undergo three-point bending tests to assess their bending strength. The results demonstrate that CNT reinforcement leads to a stiffer foam core, significantly improving its resistance to crack propagation. Thanks to customized PU foam with adjustable mechanical properties, researchers have observed that improvements in sandwich composites exceed 30% in both the strength of the coating materials and the shear strength within the core.

Kim et al. (2012), explore the surface treatment of carbon nanotubes (CNTs) using silane to enhance their bonding strength and dispersion with the epoxy matrix. The investigation delves into the impact of this treatment on the bending and mode I fracture characteristics of multi-scale composites comprising CNTs, epoxy, and basalt. Both bending and fracture assessments were conducted on multi-scale composites containing CNTs, basalt, and epoxy, which were subjected to treatment with both acid and silane.

The manufacturing procedure for these multi-scale CNT epoxy basalt composites proceeded as follows: A blend of epoxy resin and hardener (2:1) was formulated, incorporating 1 wt.% of oxidized and silanized CNTs. Subsequently, eight layers of basalt fabric were saturated with the epoxy matrix, and the multi-scale composites underwent curing in an autoclave at 3 kgf/cm² and 130°C for a duration of 2 hours. Figure 2.13 illustrates the process flow.

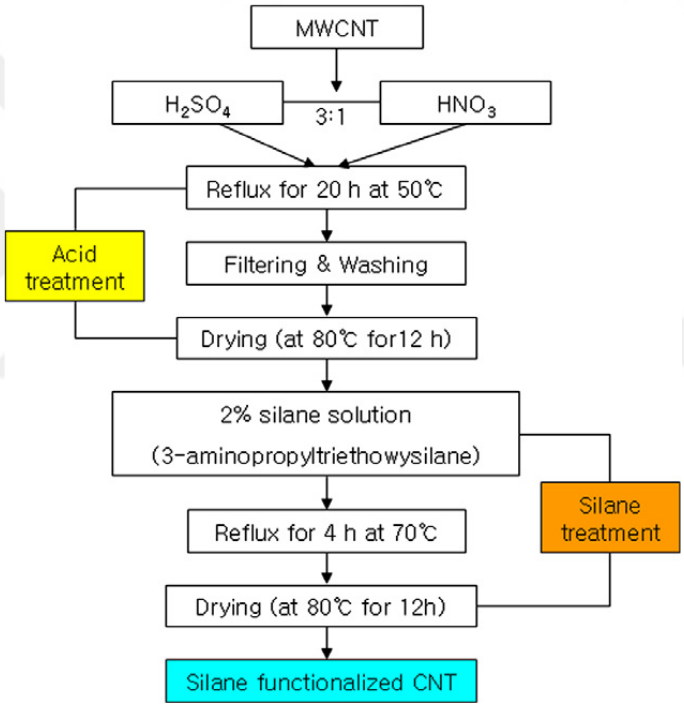


Figure 2.13. Flow chart of CNT functionalized (Kim et al., 2012)

They evaluated the effect of silane treatment on the bending properties of multiscale composites composed of CNTs, epoxy, and basalt by analysing the load-displacement profiles obtained from bending tests. Figure 2.14 illustrates the stress-strain curves for bending in both CNT epoxy basalt multi-scale composites treated with acid and those treated with silane. The bending load exhibited a linear increase with displacement until reaching the maximum bending stress for both composite types. In Figure 2.15, a comparison is drawn between the bending strength of silane-treated CNT epoxy basalt multi-scale composites and that of acid-treated CNT epoxy basalt multi-scale composites. They concluded that the flexural strength and flexural modulus of silane-treated

multiscale composites showed a modest increase of 10% and 14%, respectively, compared to their acid-treated counterparts.

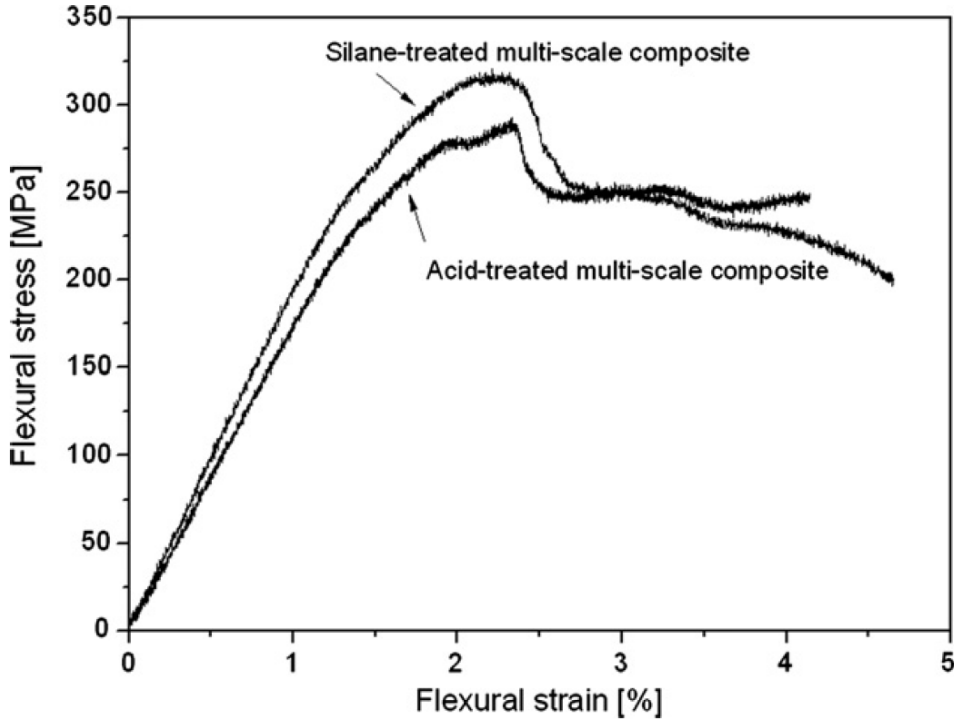


Figure 2.14. Stress–strain curves according to flexural test (Kim et al., 2012)

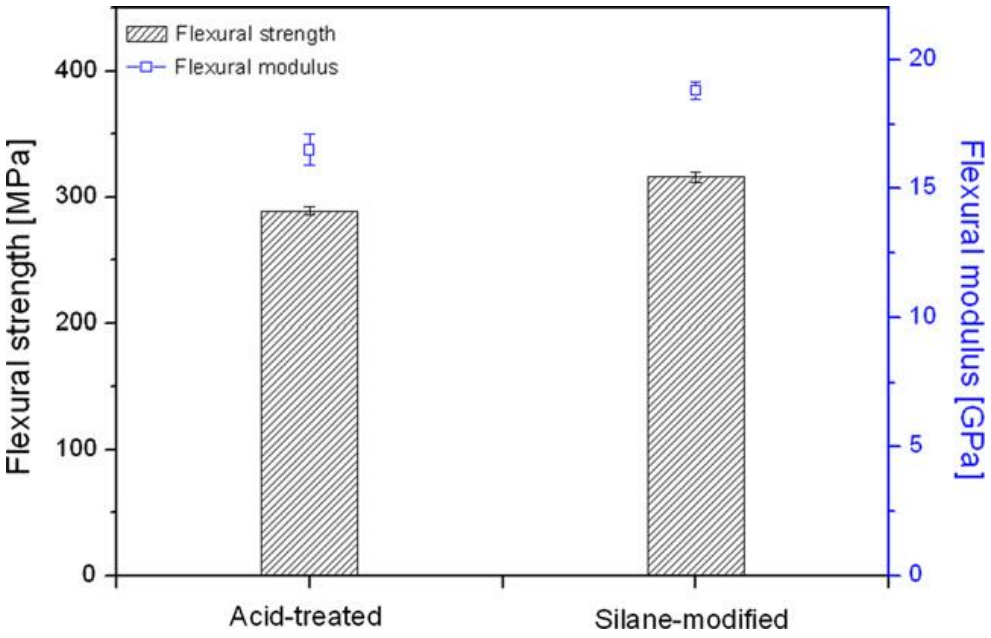
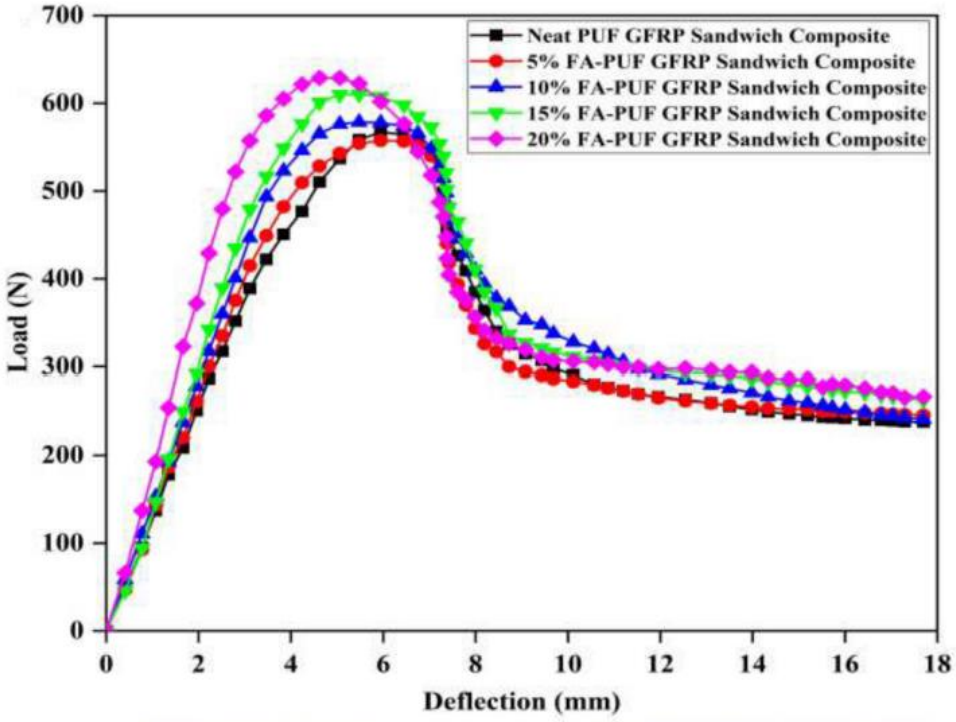


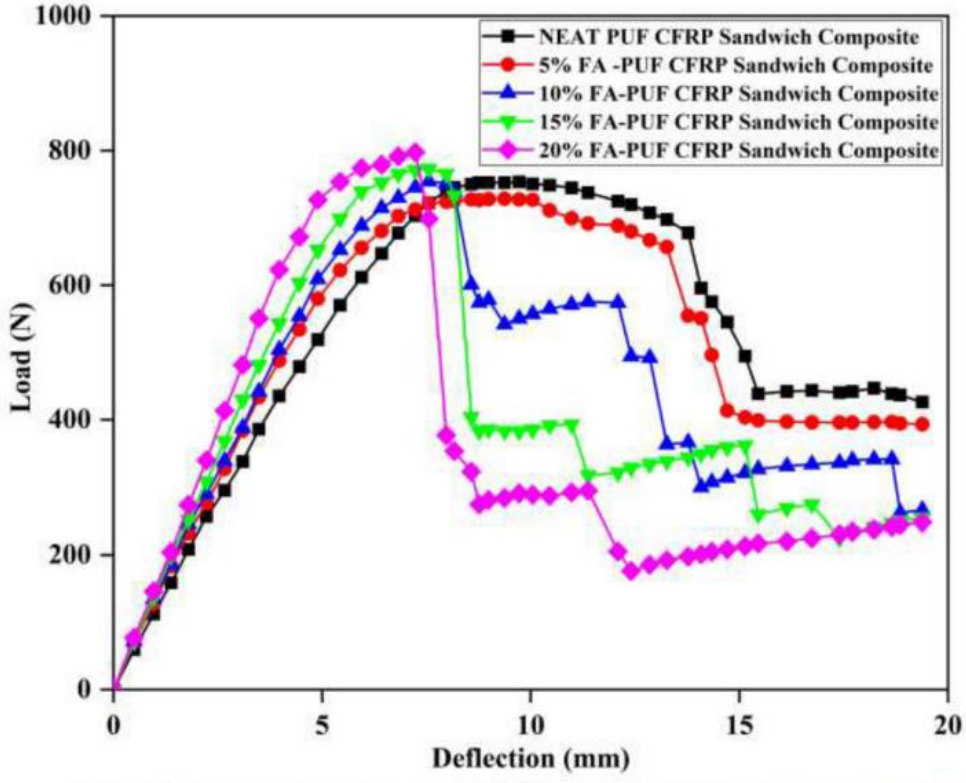
Figure 2.15. Evaluating the differences in Flexural modulus and strength between multi-scale composites treated with acid and those treated with silane. (Kim et al., 2012)

Pareta et al. (2020), conducted a study where they developed a sandwich composite with polyurethane foam (PUF) core and reinforced with fly ash. They investigated its mechanical characteristics when used in conjunction with CFRP and GFRP surface layers. The research explored the flexural and shear performance of both the fly-ash reinforced PU foam (FA-PUF) core and the sandwich laminates. The influence of fly ash weight proportion incorporation, both with and without surface modification, was also ensured, along with a comparison of the mechanical behaviour of neat PUF and PUF with fly ash inclusion, to ensure a comprehensive study. To further validate their findings, the research results were compared with those of other published works, allowing for critical assessment of the observed patterns.

They designed two separate sandwiched composite samples using Woven fabric surface treatment with CFRP and GFRP surface layers and PU foam core. Given that shear and bending are the primary modes of failure in sandwiched composite structures, shear and three-point bending tests were conducted following ASTM standards.



(a)



(b)

Figure 2.16. Load- Deflection curve under bending (a) GFRP (b) CFRP (Pareta et al. 2020)

As they expected, the sandwich composites consisting of a FA-PUF core and CFRP surface layers displayed superior bending strength and stiffness properties when compared to their GFRP

counterparts. Figure 2.16 illustrates a 10% rising in peak force for the 20% FA-PUF GFRP structure compared to the pure PUF GFRP. Conversely, there was a 25% degreasing in deflection at the peak load. Likewise, the 20% FA-PUF CFRP sandwich composites exhibited a 5% rising in peak force and a 25% degreasing in deflection at the peak load when compared to the unmodified PUF CFRP sandwich composites. These findings lead them to interpret that the incorporation of fly ash into the PU foam core has a significantly positive effect on the mechanical properties, as evidenced by the flexural modulus, strength and shear parameters.

3. MATERIAL AND METHOD

3.1. Materials Usage of Sandwich Structure

In this study, sandwich structures with high strength were designed and manufactured. Carbon fiber fabrics are used as the reinforcement material as the surface layer, epoxy resin is used as a matrix and PVC foam is used as the core material of the structure. The additives used in the study were added to the epoxy resin in certain proportions and mixed homogeneously with an ultrasonic homogenizer. The manufacturing of the samples was carried out by hand lay-up method and after vacuum bagging. The prepared epoxy resin was applied to the sandwich structure and placed in a vacuum bag to impregnate the excess resin and cure. Three point bending test and vertical flammability test were performed to obtained specimens.

3.1.1. Carbon Fiber Fabrics

The benefits of the carbon fibers utilized in this investigation encompass remarkably elevated ratios of tensile strength to weight, as well as tensile modulus to weight, an extremely low linear thermal expansion coefficient, robust fatigue resistance, and outstanding thermal conductivity (Zhou et al., 2008). Carbon fibers fabric was obtained from Dost Kimya Inc. in Turkey and Table 3.1 shows the mechanical and physical properties of the carbon fiber fabric used in the sandwich structure in this study.

Table 3.1. Mechanical and Physical Properties of Carbon Fiber Used in Sandwich Structure

Physical and Mechanical Property	**Value**
Fabric Description	Carbon Fiber Fabric 200gr/m2 3K gr Plain
Weave Pattern	Woven plain
Tensile Strength (MPa)	3950
Modulus of Elasticity (GPa)	238
Tensile Strain (%)	1.7
Fiber Diameter (μm)	Warp = Weft = 7
Area Weight (g/m^2)	200
Density (kg/m^3)	1790

Carbon fibers have superior properties from a point of strength compared to glass and aramid fibers. In addition, it provides high stability thanks to the weave structure and ratio used. This type of weave is not suitable for structures with complex contours and generally shows high performance on flat surfaces. The carbon fiber structure is illustrated in Figure 3.1.

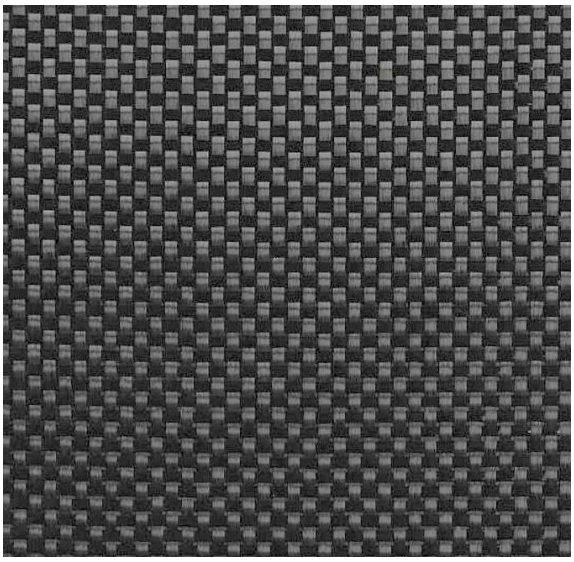


Figure 3.1. Woven-plain carbon fiber fabrics

3.1.2. Core Material

The core material, which forms the basis of the sandwich structure, is located between the two surface layers and a thick structure is obtained. In the thickened structure, the weight gain is kept lower than the thickness increase rate, and at the same time, the moment of inertia of the structure considerably increases.

The core material can be used in different structures (foam, honeycomb, prismatic, etc.) or different materials (metal, balsa wood, polyurethane, etc.). In this study, 10 mm thick closed cell polyvinylchloride, in other words, PVC foam, from Omnis Composite Company in Turkey was used as the core material. Table 3.2 shows the mechanical and physical properties of the core material.

Table 3.2. PVC Foams Mechanical and Physical Properties Used in Sandwich Structure

Physical and Mechanical Property	**Value**
Material Description	Airex C70.48 10mm Plain Panel
Density (kg/m^3)	43-55
Thickness (mm)	10
Areal weight (g/m^2)	480
Compressive Strength Perpendicular to the Plane (MPa)	0.6
Compressive Modulus Perpendicular to the Plane (MPa)	48
Tensile Strength in the Plane (MPa)	0,95
Tensile Modulus in the Plane (GPa)	35
Shear Strength (MPa)	0,55
Shear Modulus (MPa)	16

3.1.3. Polymeric Matrix

The sandwich panels were constructed by laminating surface layers and core material with a polymer matrix around them. The matrix material was created using epoxy resin and the appropriate hardener. Dost Kimya Inc provided the Hexion MGS H160 hardener and Hexion MGS L160 epoxy. The mechanical and physical parameters of the hardener and epoxy resin are listed in Table 3.3. The weight ratio of epoxy resin to hardener was fixed to 100:25 and listed in Table 3.4 giving the mechanical and physical characteristics of a mixed compound.

Table 3.3. Hardener and Epoxy Resins Physical and Chemical Properties

Property	**Epoxy Resin**	**Hardener**
Type	MGS L160	MGS H160
Density (kg/m3)	1130-1170	960-1000
Viscosity (mPas)	700-900	10-50
Epoxy equivalent (g/equivalent)	166-182	-
Epoxy value (equivalent/100 gr)	0.55-0.6	-

Table 3.4. Mechanical and Physical Properties of Hardener and Epoxy Mixture

Property	**Matrix**
Mixed products	MGS L160 / MGS H160
Mixing ratio by weight	100:25
Density (kg/m3)	1180 – 1200
Flexural strength (MPa)	110 – 140
Modulus of elasticity (GPa)	3.2 – 3.5
Tensile strength (MPa)	70 – 80
Compressive strength (MPa)	80 – 100
Elongation at break (%)	5 – 6
Impact strength (KJ/m2)	40 – 50

3.1.4. Additive Materials

Graphene, boron carbide and kaolin particles were added at different rates (2%, 5% and 10%) into the epoxy matrix by matrix toughening method. These materials are in micron size and it is aimed to create a toughed matrix material by obtaining a homogeneous structure with epoxy resin. The physical and mechanical features are given in Tables 3.5 to 3.7.

Table 3.5. Graphene Nanoplatelets' Properties ([1](Lee et al., 2008), [2](Zhang et al., 2014))

Property	**Graphene Nanoplates**
Diameter (μm)	24
Thickness (nm)	6
Surface Area (m^2/g)	120
Purity (%)	99.5
Intrinsic Strength[1] (GPa)	130 ± 10
Modulus of Elasticity[1] (TPa)	1 ± 0.1
Fracture Toughness[2] ($MPa(m)^{0.5}$)	4 ± 0.6

Table 3.6. Boron Carbide's Properties ([1](CES Selector, 2018))

Property	**Boron Carbide**
Particle Size (μm)	0 – 50
Purity (%)	99
Density[1] (kg/m^3)	2490 – 2550
Modulus of Elasticity[1] (GPa)	362 - 380
Tensile Strength[1] (MPa)	261 – 289
Hardness[1] (Vickers)	3990 – 4410
Fracture Toughness[1] ($MPa(m)^{0.5}$)	2.8 – 3.4

Table 3.7. Kaolin's Properties ([1](CES Selector, 2018))

Property	**Kaolin**
Particle Size (μm)	5.5
Purity (%)	99
Density[1] (kg/m^3)	2500 - 2620
Modulus of Elasticity[1] (GPa)	19.6 – 20.4
Tensile Strength[1] (MPa)	45.8 – 50.6

3.2. Method

This section describes the production of sandwich plates and the preparation of samples for testing. The production method and preparation of samples are shown in the diagram in Figure 3.2. For the production of sandwich structures, carbon fibers and PCV foam were cut to specified dimensions. On the other hand, the amount of matrix material was adjusted by the total fiber and foam weight since it is important to distribute the matrix material evenly on each layer. The matrix material, on the other hand, is composed of epoxy and its hardener at a ratio of 100:25. The ratio of additives to be added was adjusted as 2%, 5% and 10% as the weight of the total matrix material. Sandwich structures were produced by hand lay-up after the vacuum bagging method. Fabrication process illustrated in Figure 3.3.

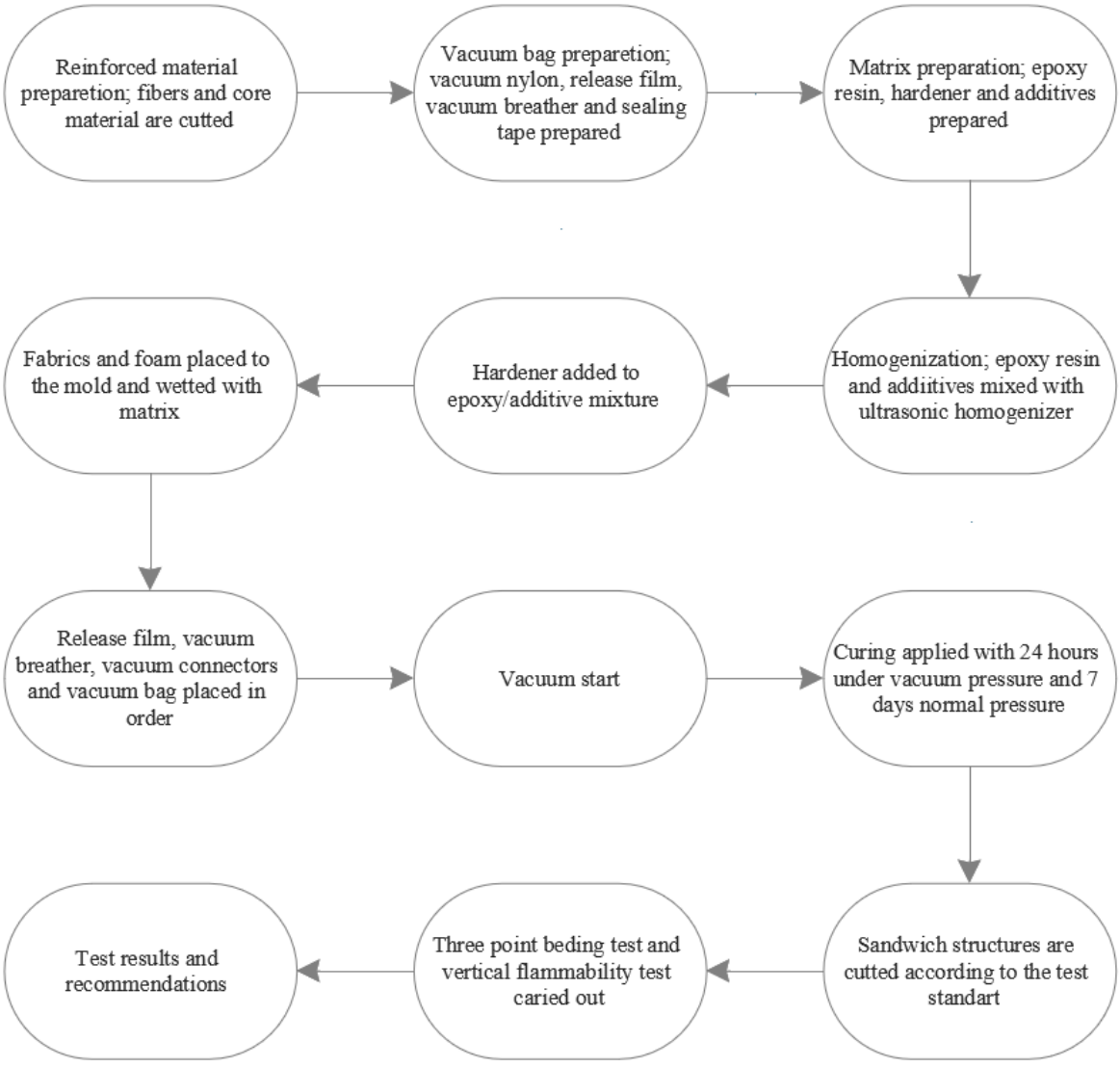


Figure 3.2. Manufacturing and test process of specimens

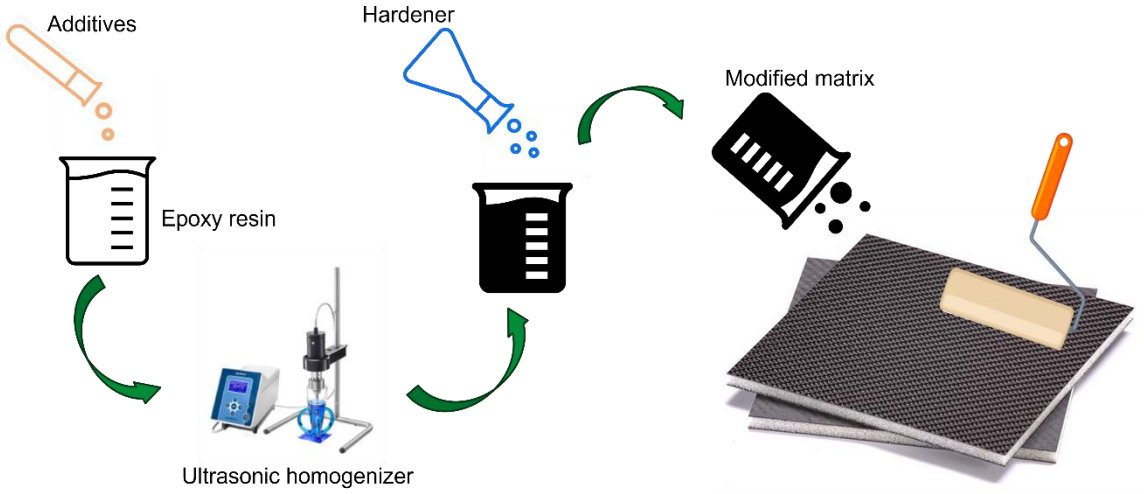


Figure 3.3. Illustration of fabrication process

The cutting plan shown in Figure 3.4 was prepared according to the sample dimensions specified in the test standards. Five samples were prepared each for the three point bending test and the vertical flammability test. Specimen configurations which are the samples of the additives and the control sample are named as shown in Figure 3.5.

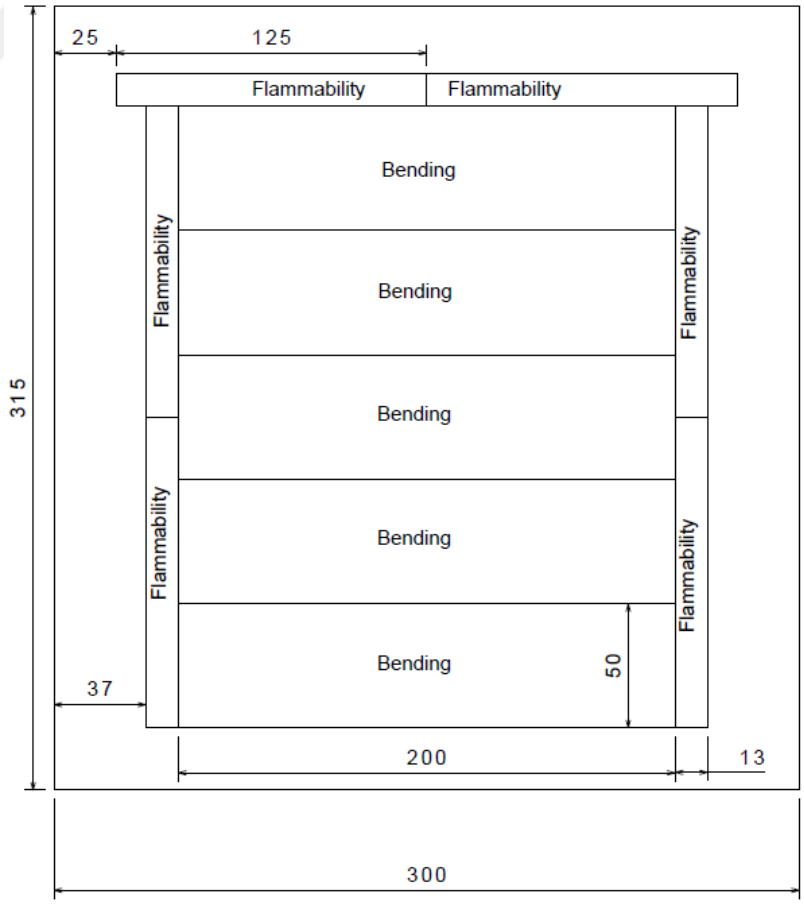


Figure 3.4. Cutting plan of specimens

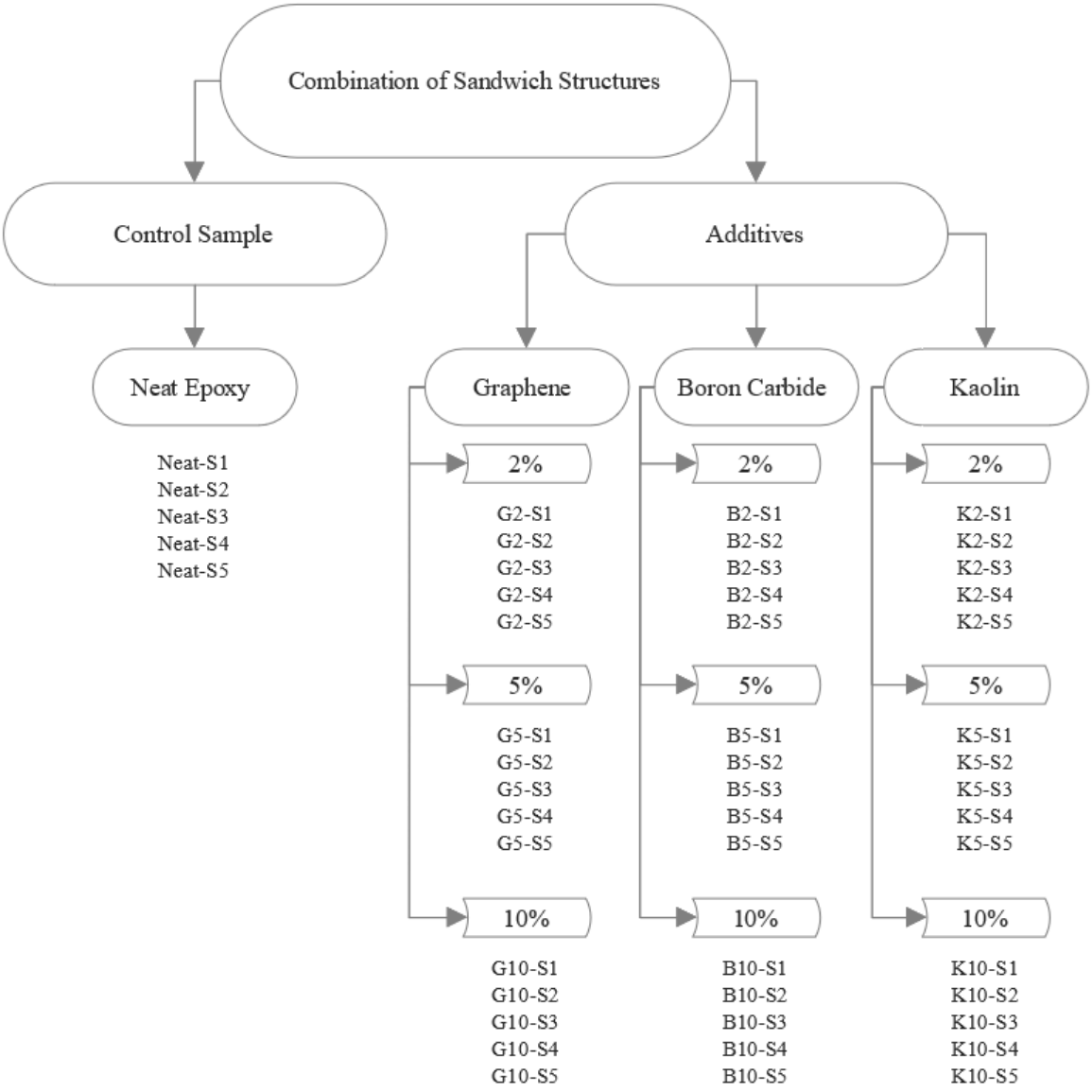


Figure 3.5. Specimen combination

3.2.1. Manufacturing Process of Sandwich Structures

For the production of sandwich structures, the amount of fiber was determined based on the sample sizes specified in the test standard and considering the sample numbers. At the same time, four layers of carbon fiber are used for the sandwich structure as shown in Figure 3.8, and for a total of 10 sets of samples. Approximately 8.64 m^2 of carbon fiber fabric was cut in a smooth quiche as shown in Figure 3.6, and 1.12 m^2 of PCV foam was used.



Figure 3.6. Cutting process of carbon fibers

The next step is to prepare the materials for vacuum bagging while the fibers are ready. At this stage, perforated release film, vacuum breather, vacuum nylon, vacuum connectors and sealing tape are prepared. Sealing tape is bonded on the mold to adjust the production area, then a mold release agent is applied to the production area, which is used to remove the sandwich panel from the mold after curing process completed.

In the matrix material preparation process, after the weight of the fibers is determined, epoxy resin and its hardener are mixed at a ratio of 100:25. In this study, the additives are added to the epoxy resin at different rates. The amounts of additives have been determined as 2%, 5% and 10%, and the epoxy resin has been reduced as much as the additive material to be added so that the total weight of the matrix material is preserved as shown in Figure 3.7a. The additives are mixed for one hour with an ultrasonic homogenizer in order to mix them homogeneously as shown in Figure 3.7b. An important point to be considered here is to prevent the heating of the epoxy resin. Otherwise, since curing will accelerate, an even distribution within the structure cannot be exhibited.



(a) (b)

Figure 3.7. Additive preparation (a) determining the weight of additives, (b) mixing with an ultrasonic homogenizer

For the hand lay-up method and followed by the vacuum bagging method, the weight of the matrix material and carbon fiber with core material must be equal each other. In this method, the fibers are placed on the mold and the matrix material is poured on it and the fiber is rolled until it feeds the matrix material homogeneously. It is important that the matrix material spreads evenly and does not form air bubbles from the composite structure. Because the formation of air bubbles will directly affect the chemical bonding, and because of that lack of bonding can be observed and this will negatively affect the transfer of shear stresses between the surface layer and the core. After all layers are made in this way, perforated release film, breather and vacuum nylon are placed respectively as shown in Figure 3.8 and excess resin is removed with the help of a vacuum pump. In

this setup, the perforated release film ensures that the upper surface of the sandwich structure is properly removed, and the excess epoxy passing through its holes is absorbed by the breather.

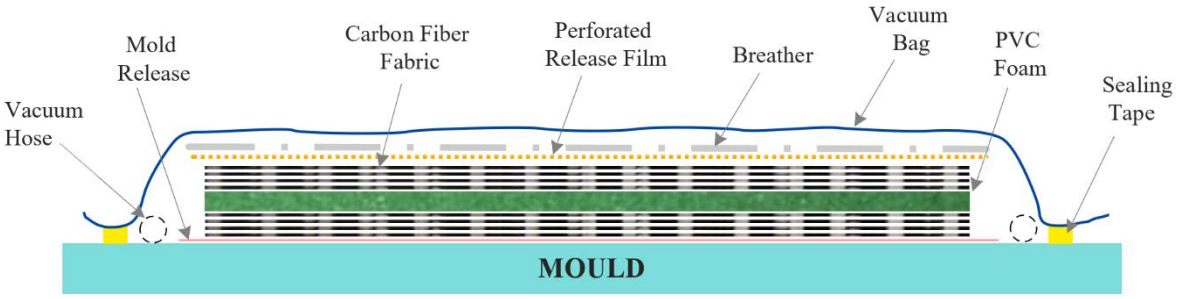


Figure 3.8. Schematic representation of the manufacturing process of sandwich structures

Fibers are placed and wetted with resin. After all layers are completed, the vacuum environment is prepared. Before the curing starts, the pre-cut vacuum equipment is quickly placed in the order indicated in the schematic display and the vacuum is started. Figure 3.9 shows the vacuumed structure. In this way, excess resin is sucked by waiting for 24 hours at room temperature so then air bubbles are removed from the structure. After the curing is completed, the structures are ready to be cut to the appropriate dimensions for test operations. As the disadvantages of hand lay-up and vacuum bag method, it can be said that high labour skills are required. Errors or detects that may occur will directly negatively affect the performance of the final product.



Figure 3.9. Vacuumed structure of sandwich test specimens.

3.2.2. Three-Point Bending Tests

In order to obtain the bending characteristics of the sandwich composites produced in this study, depending on their load-carrying capacity, a three-point bending test was performed according to the ASTM C393 standard. ASTM C393 provides the determination of shear property of sandwich core with regard to core shear yield stress and ultimate strength, and surface tension. During the experiment, the piston head's velocity was adjusted to 2 mm/min. This was done in accordance with ASTM guidelines, which specify that structural failure should ideally initiate or occur within a timeframe of three to six minutes. According to the ASTM C393, core shear stress and facing bending stress of a sandwich can be determined by using Equations 3.1 and 3.2 respectively.

The samples have a length of 200 mm and a width of 50 mm and have been subjected to a three point bending test at a 150 mm span length (opening) as specified in the standard. The three-point bending test is shown schematically in Figure 3.10, and as shown in the image, "t" represents surface layer thickness (mm), "c" is the core thickness (mm), and "d" is the total thickness (mm). The load is applied to the center of the specimens which is half of the span length. A three-point bending test setup is shown in Figure 3.11.

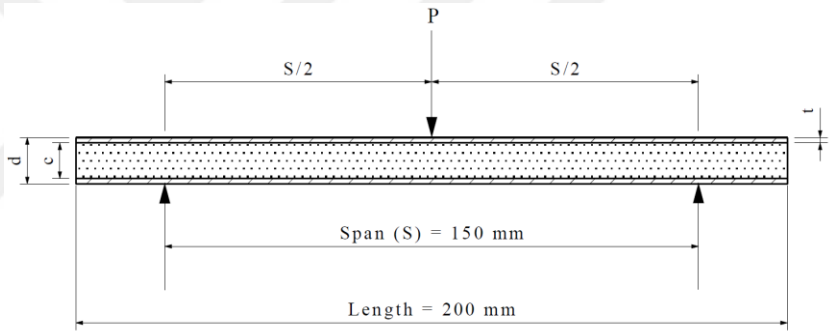


Figure 3.10. Schematic representation of three point bending test

$$\sigma = \frac{P_{max} \cdot S}{2t(d+c)b} \tag{3.1}$$

$$F_s^{ult} = \frac{P_{max}}{(d+c)b} \tag{3.2}$$

Where;

σ = facing stress, MPa,

F_s^{ult} = core shear ultimate stress, MPa,

S = span length, mm,

t = facing thickness, mm,

d = sandwich thickness, mm,

c = core thickness, mm,

b = sandwich width, mm,

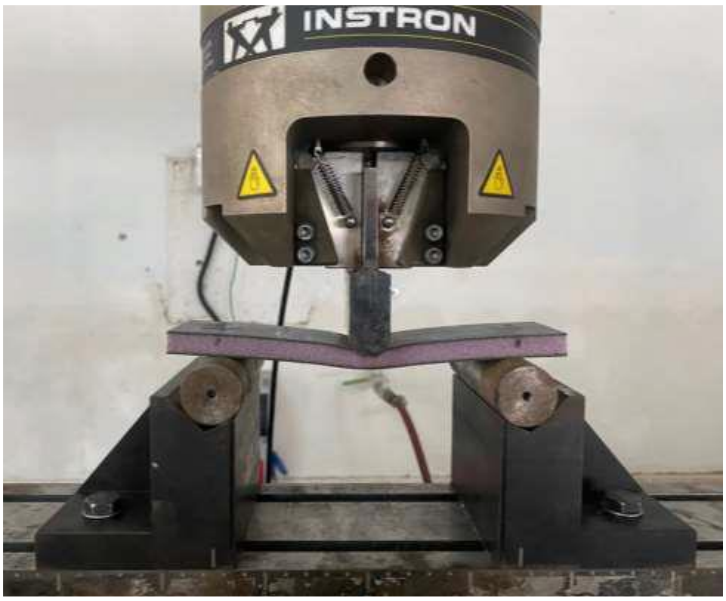


Figure 3.11. Three-point bending test

3.2.3. Vertical Flammability Test

The vertical flammability test is a critical method for evaluating the flammability properties of materials, particularly plastics. This involves subjecting a material to a controlled ignition source in a vertical orientation to assess its ability to resist ignition and halt the spread of flames. Two prominent standards that define vertical flammability tests are the UL 94 and ASTM D3801 standards. A schematic representation is shown in Figure 3.12.

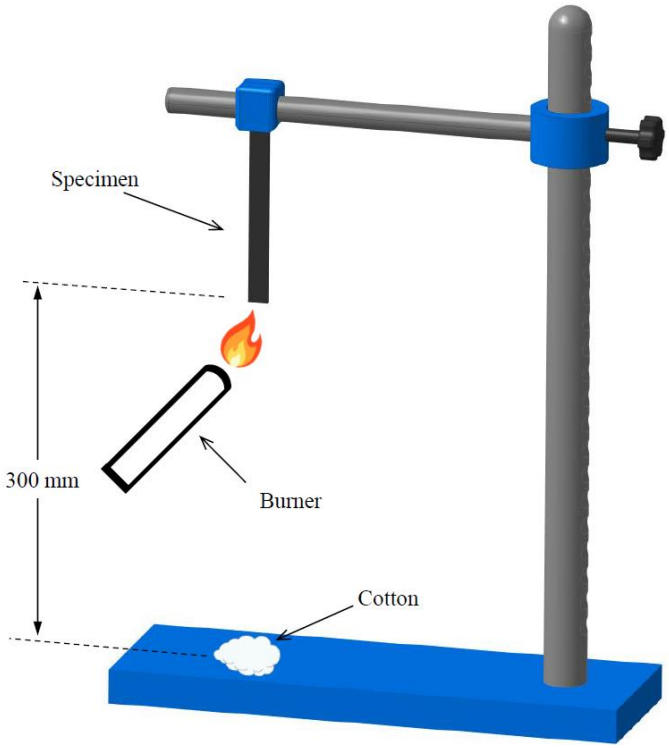


Figure 3.12. Schematic representation of vertical flammability test

The vertical flammability test is important because of its ability to gauge the fire hazard potential of a material. By analysing their behaviour when exposed to fire, this test assists in making informed decisions regarding material selection, ensuring compliance with safety regulations, and designing safer products. It helps to identify materials that exhibit strong flame resistance and self-extinguishing properties, reduce the risk of fire incidents, and enhance overall fire safety measures. Vertical flammability test apparatus shown in Figure 3.13.

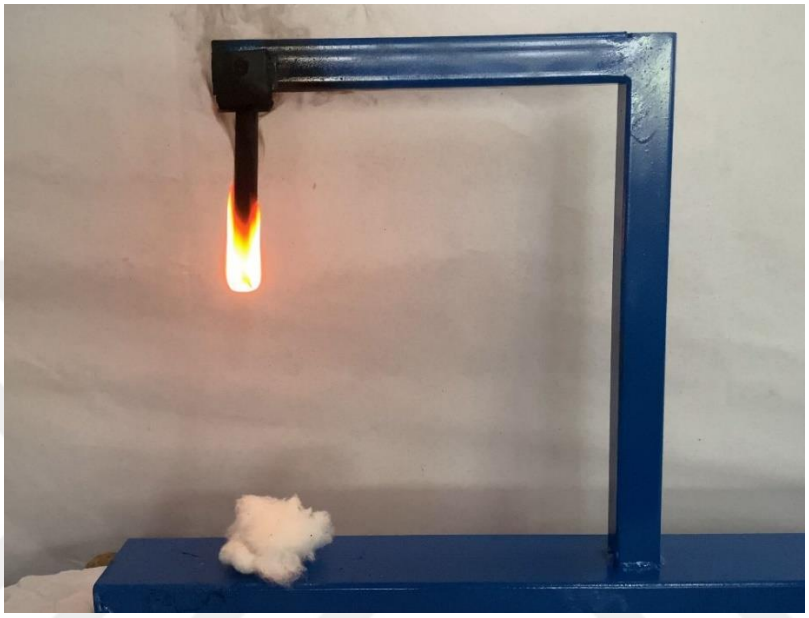


Figure 3.13. Vertical flammability test apparatus

4. RESULTS AND DISCUSSIONS

In this study, the flexural and flammability properties of sandwich structures with carbon fiber reinforced and epoxy matrix surface layer and low-density PCV foam core were subjected to a 3-point bending test and vertical flammability test by adding additives in different proportions of the epoxy matrix. The test results are shown comparatively in the visuals and tables, and the sandwich structure combination that provides the best performance is revealed.

Three-point bending test results are indicated in the load-deflection graph for each combination, Figures 4.1-4.10. The maximum load that the structure will carry without being damaged can be observed in the graph. In addition, the deformation can be seen during the loading until the fracture occurs in the structure. As seen in the graphs, while the loading progresses linearly initially, it reveals a shape that firstly tends to increase gradually up to the maximum point, then decrease gradually, after that a sudden decrease is observed. Uzay et al. (2019) stated the presence of sudden fracture indicates that the structure exhibits brittle behaviour in the surface layer. Comment about the load carrying capacity of the sandwich structure can be made with this decrease. The decrease point is almost half of the maximum load that the structure. From there, it can be results dedicated that even if the sandwich structure is damaged, it can withstand a little more loading. Even if there is a damage in the upper surface layer and the core structure, lower surface layer can carry some more load.

Vertical flammability test results are completed as a result of the necessary measurements and visual inspections as specified in the standard, and the evaluation of the flammability status consisting of V-0, V-1 and V-2 degrees, the results for each material combination are shown in Table 4.7.

The reliability of the production and testing of the sandwich structure was demonstrated by testing five samples from each material combination. One of the biggest problems of production, which is the high cost of polymeric composite sandwich structures, due to high labour skills and the use of quality equipment; is important for the accuracy of the study to show that it is in a problem-free manner. The results show that there is no significant deviation between the samples and the results obtained are close to each other. In other words, the sandwich panels produced by hand lay-up and vacuum infusion showed that the matrix material was dispersed in the structure since they showed the same performance at every point as a complete whole.

4.1. Three-Point Bending Test Results

The three point bending test is performed due to the ASTM C393 standard and reveals the bending characteristics of the sandwich structure. According to the standard, a sandwich structure should have 200 mm in length, and 50 mm in width, and the thickness should not exceed twice the width, and also the span length is determined as 150 mm. Accordingly, the measurement values of the samples produced are shown in Table 4.1. In order to calculate the core shear stress and facing bending stress of the sandwich structure, the thickness of the core material, the thickness of the surface layer, the total thickness, span length, sandwich length and width in the sandwich structure are shown in Table 4.1.

Table 4.1. Dimensions of 3-Point Bending Test Specimens

	Measured Values
Length (L)	200 mm
Width (b)	50 mm
Span Length (S)	150 mm
Core Thickness (c)	10 mm
Facing Thickness (t)	1.25 mm
Sandwich Thickness (d)	12.5 mm

4.1.1. Sandwich Structure with Neat Epoxy

Load-Deflection curve of the Carbon fiber/Epoxy Sandwich composite is shown in Figure 4.1. According to the 3 Point Bending Test results the slope increase linearly up to 506.32 N, after that slope continues nonlinear and the maximum load that the specimens can carry is 583.26 N. After reaching the maximum load, it gradually decreases from a mid-span from a displacement of ∼4.8 mm to ∼10mm. In this section, damage occurs in the core and the upper surface layer carries the load until sudden fracture. Finally, at a mid-span deflection of ∼10 mm, a sudden drop in strength is observed according to the upper surface layer failure.

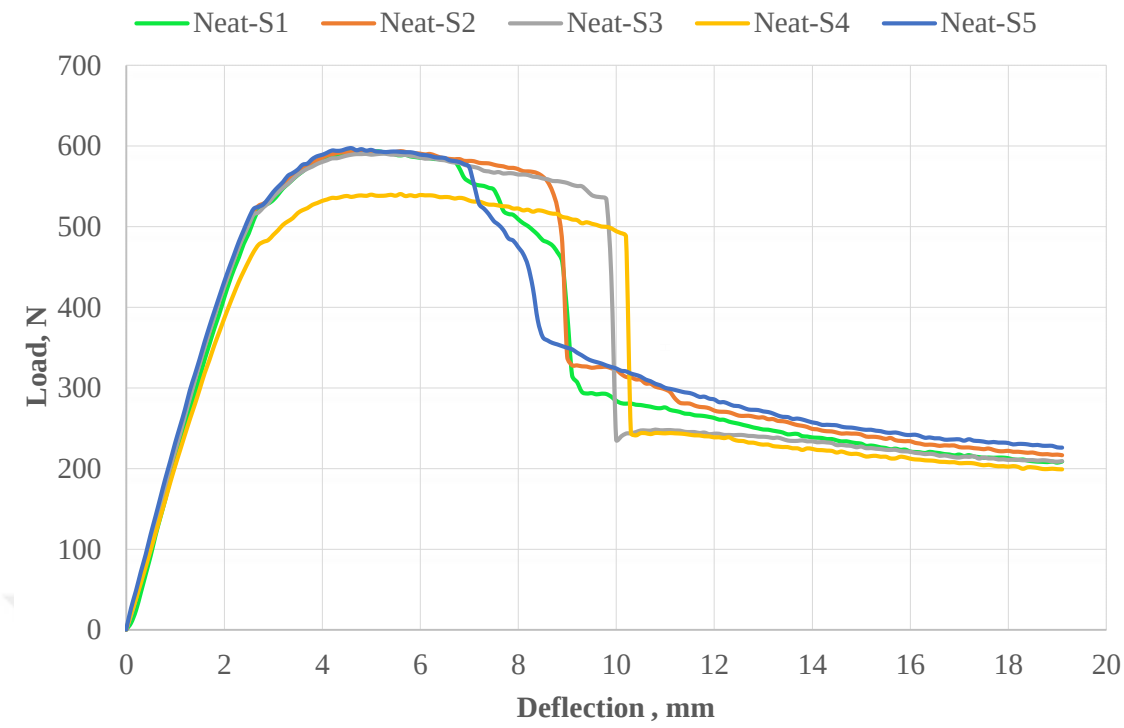


Figure 4.1. Load-Deflection curve for neat epoxy sandwich structure

4.1.2. Sandwich Structure with Different Percentage of Graphene Added

The Load-Deflection curve of the Carbon fiber/Epoxy with 2%, 5% and 10% graphene-added Sandwich composite is shown in Figures 4.2-4.4. According to the Three Point Bending Test results, the slope increase linearly up to 585.21 N, 577.29 N and 580.08 N respectively, after that slope continues nonlinear and the average maximum load that the specimens can carry is 686.92 N, 690.61 N and 696.37 N respectively. After reaching the maximum load, it gradually decreases from a mid-span from displacement of ~6.9 mm to ~11 mm for 2%, ~7.2 mm to ~12 mm for 5% and ~7.6 mm to ~13 mm for 10% graphene ratio. An improvement was observed in the part of the graph where there was a gradual decrease, where the core damage occurred. Additionally, the increase in graphene in the matrix material delayed the core damage that occurred in the sandwich structures. Finally, at a mid-span deflection of ~11 mm, ~12 mm, ~13 mm, respectively for 2%, 5% and 10% graphene, a sudden drop in strength is observed according to the top surface layer failure. Compared to neat-epoxy, an increase in maximum load and mid-span deflection was observed with the increase in graphene in the structure. Qin et al. (2014) and Srivastava et al. (2019) also observed an increase in bending strength with the increase of graphene. However, Hawal et al. (2020) and Kamaraj et al. (2019) found a decrease in bending strength with an increase in graphene in their study. This is due to the agglomeration of the filling material in the matrix. In this study, the bending strength that increases with the increase in the amount of graphene is not seen as much as boron carbide. This may also be caused by agglomeration.

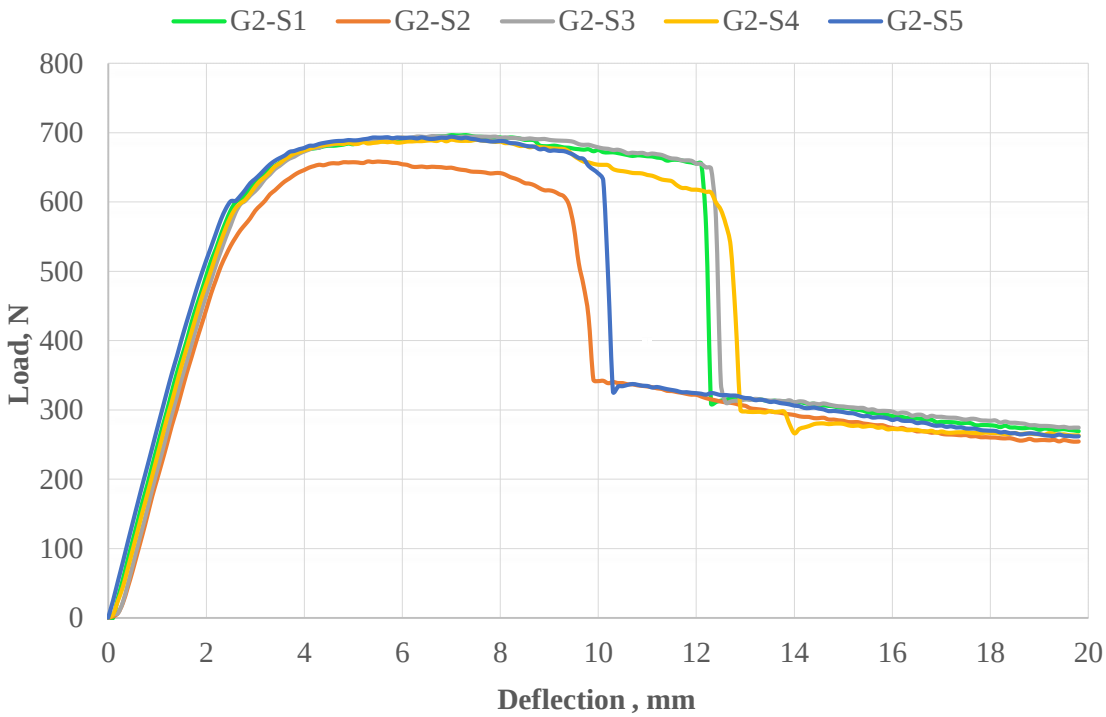


Figure 4.2. Load-Deflection curve for 2% graphene-epoxy sandwich structure

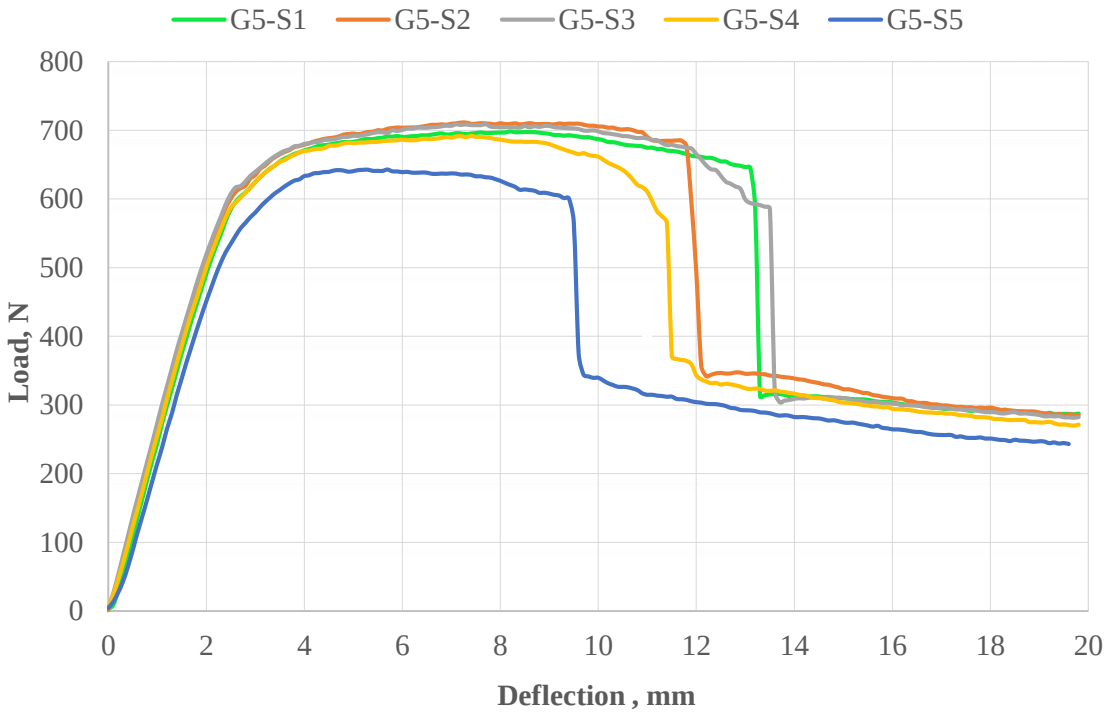


Figure 4.3. Load-Deflection curve for 5 % graphene-epoxy sandwich structure

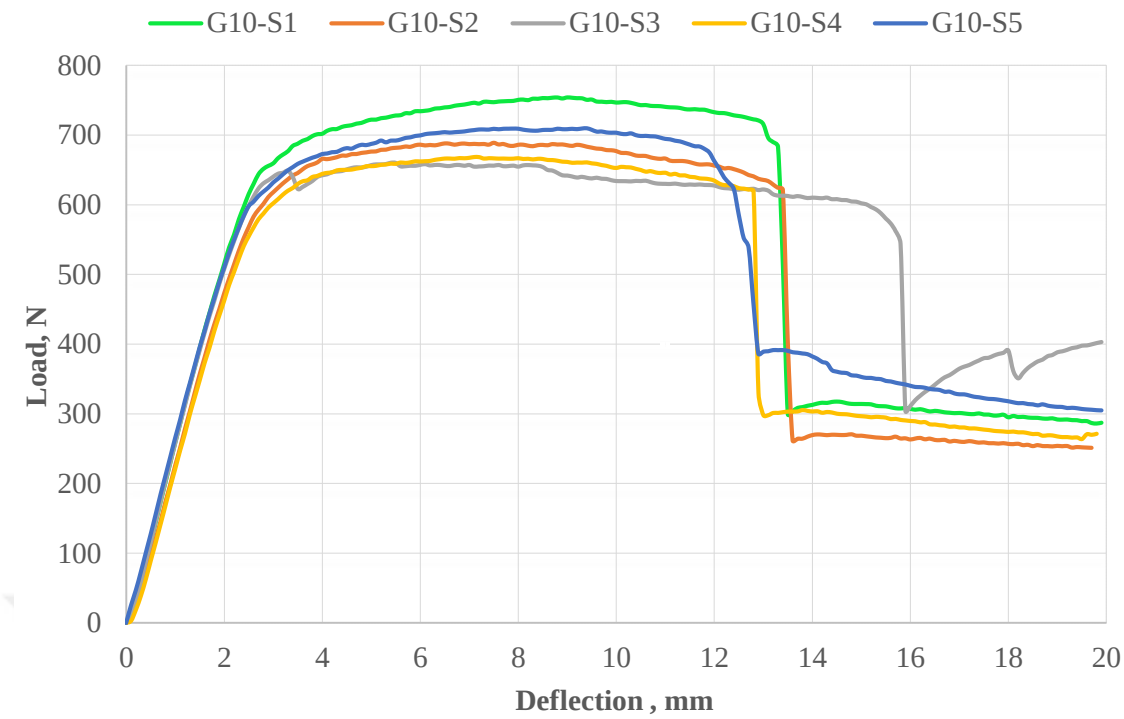


Figure 4.4. Load-Deflection curve for 10 % graphene-epoxy sandwich structure

4.1.3. Sandwich Structure with Different Percentage Boron Carbide Added

Load-Deflection curve of the Carbon fiber/Epoxy with 2%, 5% and 10% boron carbide added Sandwich composite is shown in Figures 4.5-4.7. According to the 3 Point Bending Test results the slope increase linearly up to 493.76 N, 547.17 N and 592.52 N respectively, after that slope continues nonlinear. As seen from the figures, the average maximum load that the specimens can carry is 624.79 N, 668.22 N and 710.85 N respectively. After reaching the maximum load, it gradually decreases from a mid-span from displacement of ~6.4 mm to ~13 mm for 2% boron carbide, ~9.1 mm to ~13.5 mm for 5% boron carbide and ~10 mm to ~12 mm for 10% boron carbide. After reaching the maximum load, the core damage increased with the increase in the boron carbide ratio in the matrix material. Finally, at a mid-span deflection of ~13 mm, ~13.5 mm, and ~12 mm, respectively for 2%, 5% and 10% boron carbide, a sudden drop in strength is observed according to the top surface layer failure. The increase in the boron carbide ratio in the matrix material increased the maximum load and mid-span deflection. Muralidhara et al. (2019) was observed a decrease in bending strength as the boron carbide ratio increased, contrary to the results obtained in this study. Geren et al. (2021) showed in his study that with the increase of boron carbide, the structure withstands high impact loads.

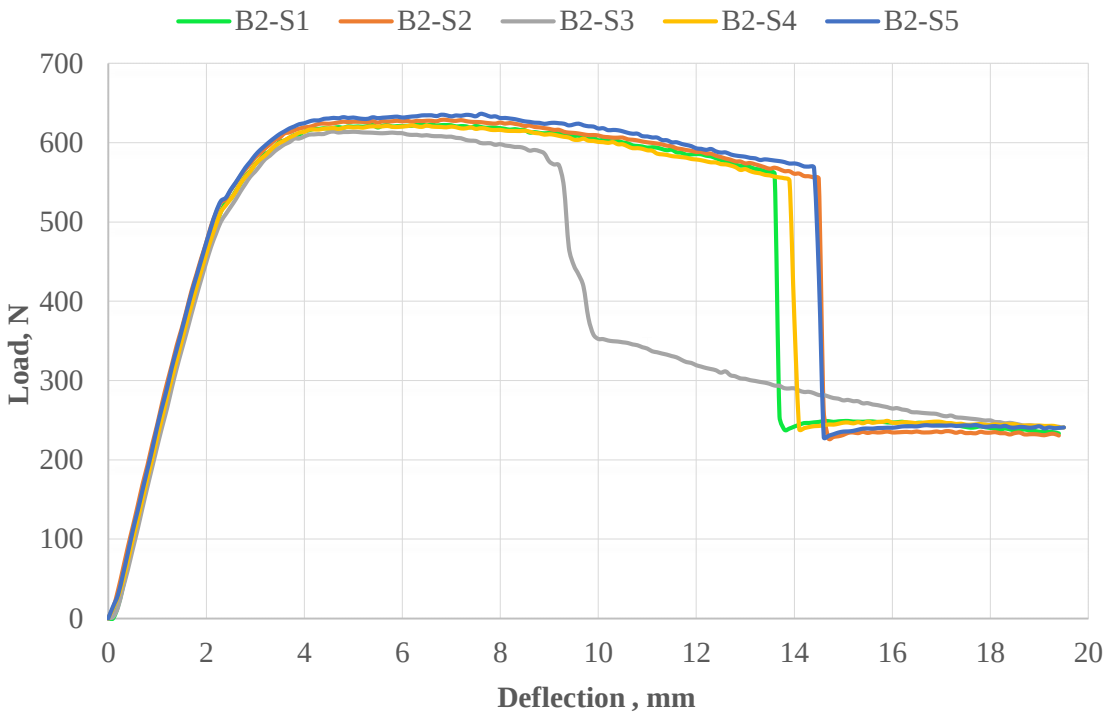


Figure 4.5. Load-Deflection curve for 2% boron carbide-epoxy sandwich structure

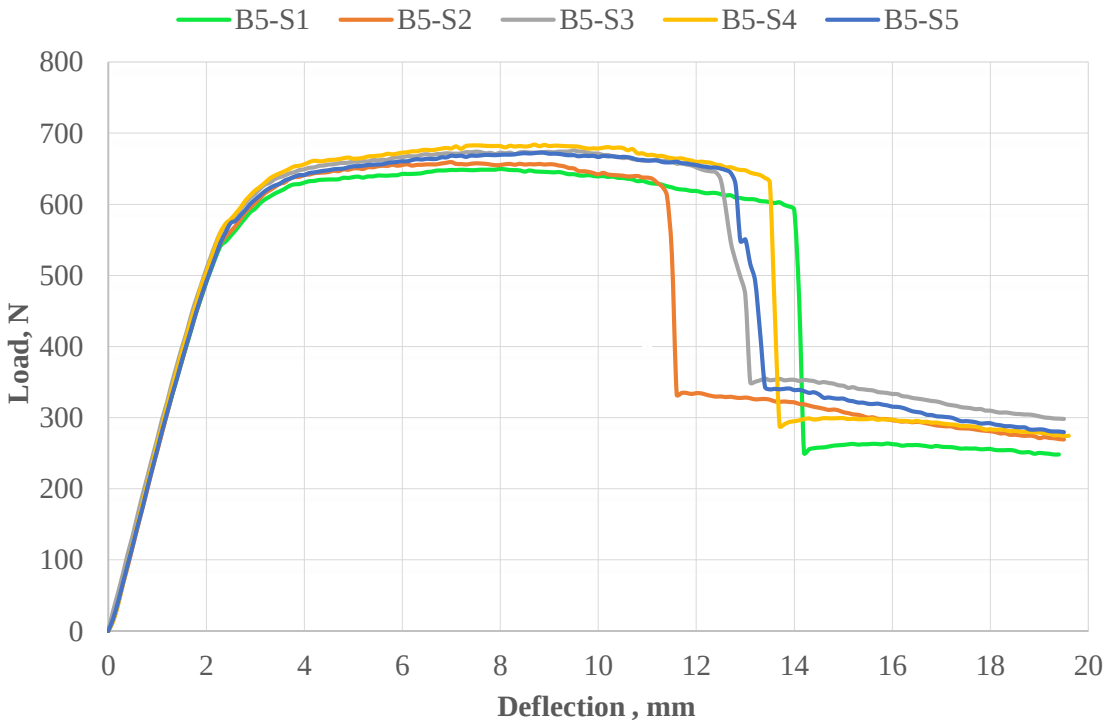


Figure 4.6. Load-Deflection curve for 5% boron carbide-epoxy sandwich structure

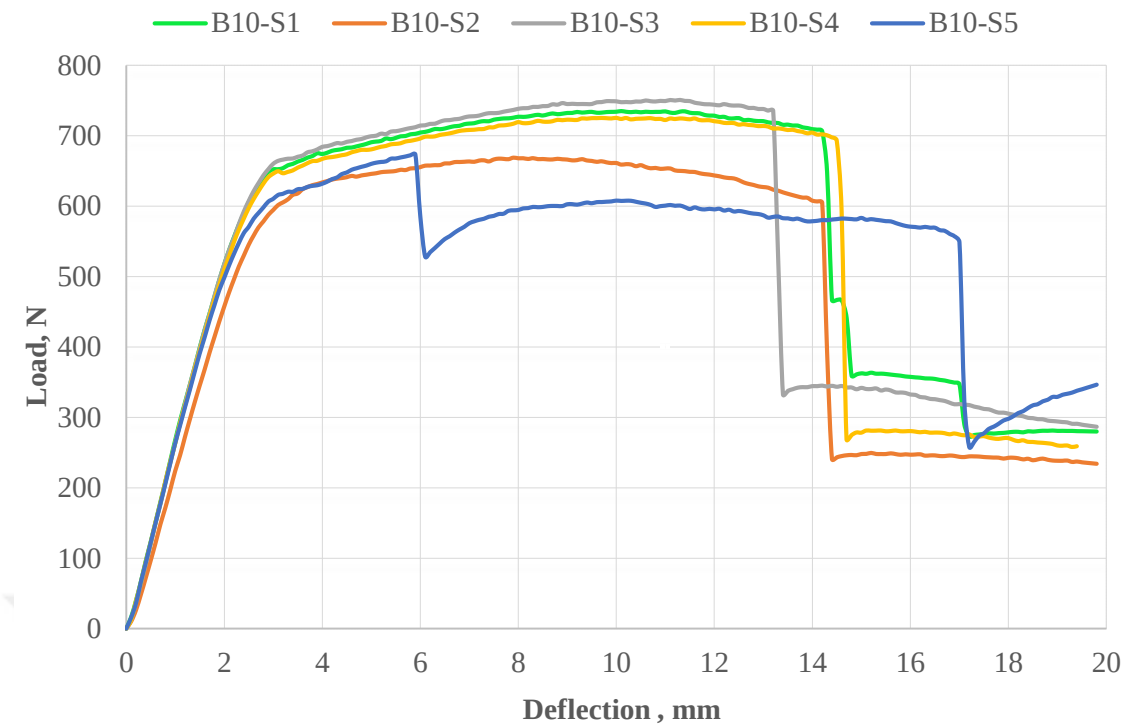


Figure 4.7. Load-Deflection curve for 10% boron carbide-epoxy sandwich structure

4.1.4. Sandwich Structure with Different Percentage Kaolin Added

Load-Deflection curve of the Carbon fiber/Epoxy with 2%, 5% and 10% kaolin added Sandwich composite is shown in Figures 4.8-4.10. According to the 3 Point Bending Test results the slope increase linearly up to 482.69 N, 538.08 N and 528.57 N respectively, after that slope continues nonlinear and the average maximum load that the specimens can carry are 610.71 N, 622.28 N and 627.39 N respectively. After reaching the maximum load, it gradually decreases from a mid-span from displacement of ~5.1 mm to ~10.6 mm for 2% kaolin, ~6.5 mm to ~12 mm for 5% kaolin and ~7.1 mm to ~12.9 mm for 10% kaolin. The damage to the core structure after maximum loading occurred later with the increase in the amount of kaolin in the matrix structure. Finally, at a mid-span deformation of ~10.6 mm, ~12 mm, and ~12.9 mm, respectively 2%, 5% and 10% kaolin, a sudden drop in strength is seen according to the top surface layer failure. With the increase of kaolin in the matrix, the maximum load and mid-span deflection that the structure can withstand increased. Bulut et al. (2019) used Nanoclay, the basic material of kaolin, in their study and observed an increase in the bending strength of the structure with the increase of Nanoclay in the matrix material. However, when the amount of Nanoclay was further increased, a decrease was observed. A similar increase in bending strength with the increase of kaolin has not been seen until boron carbide.

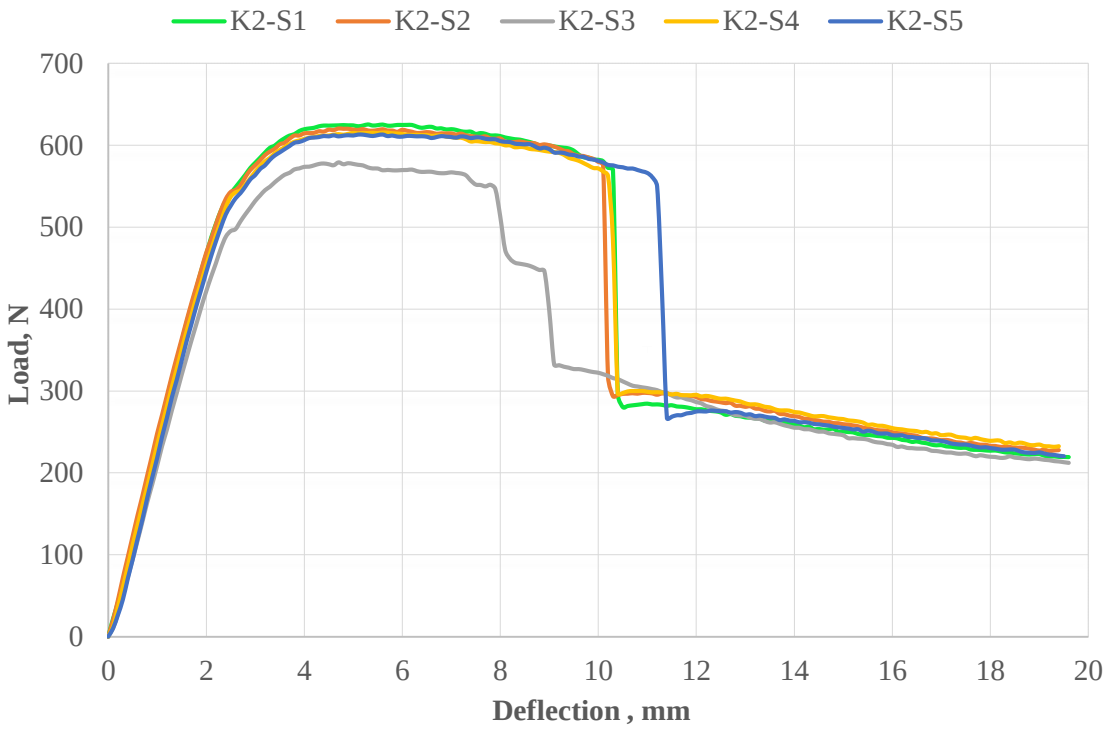


Figure 4.8. Final Evaluation of Flexural and Flammability Properties of Sandwich Structure

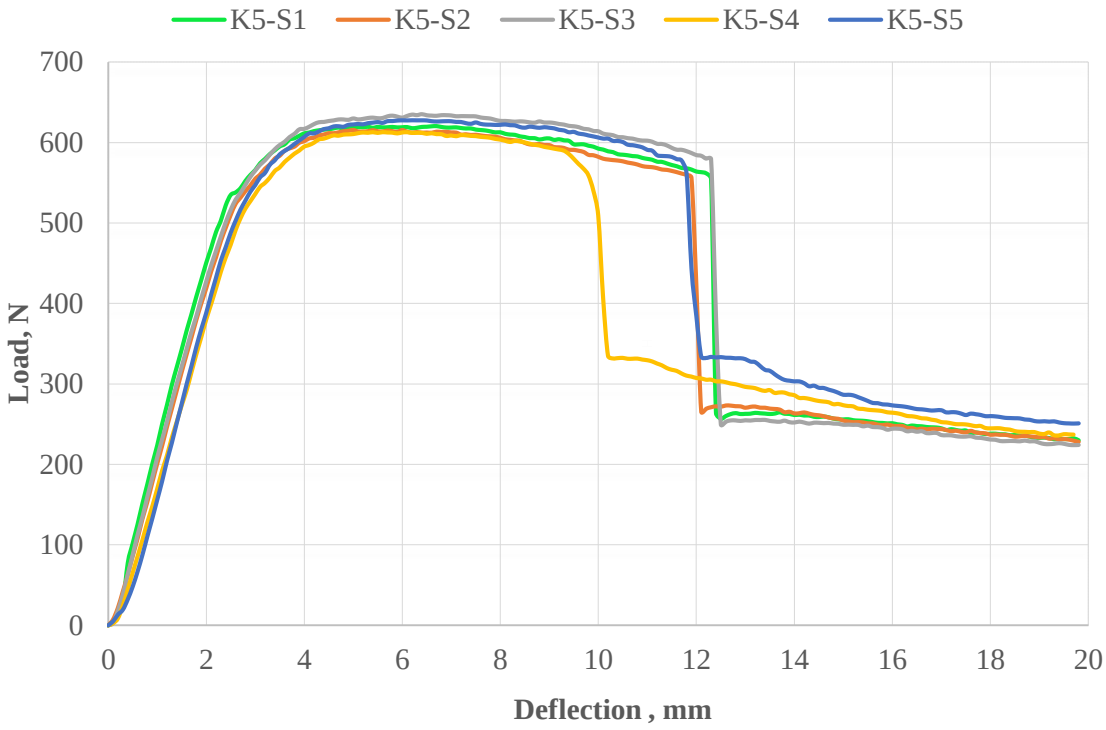


Figure 4.9. Load-Deflection curve for 5% kaolin-epoxy sandwich structure

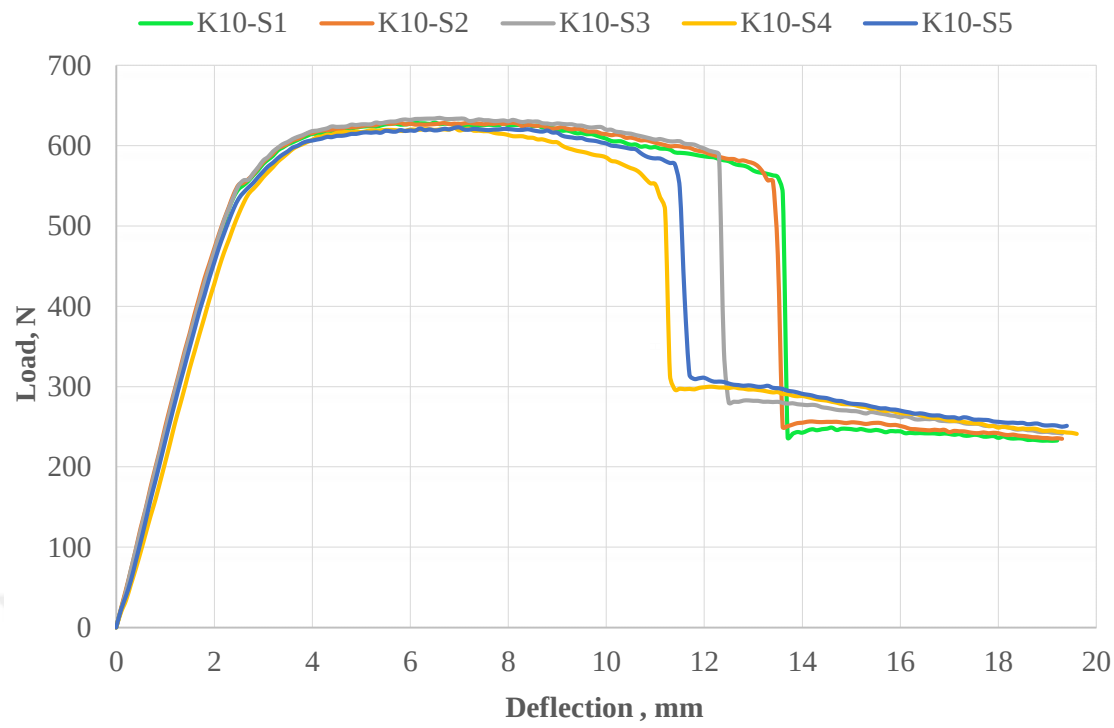


Figure 4.10. Load-Deflection curve for 10% kaolin-epoxy sandwich structure

4.1.5. Comparison of the Additives

When all the sample combinations were evaluated and the average values were taken, it was observed that the bending resistance of the sandwich structure was improved by adding additives to the epoxy structure, and the results are shown in Table 4.2. Addition of 2% graphene to the epoxy increased the bending strength of the structure by 17.6%. This was calculated as 18.2% when 5% graphene was added, and 19.1% when 10% graphene was added. In this case, as a result, the increase of the graphene additive in the epoxy structure increases the flexural strength of the sandwich structure.

Similarly, 2% boron carbide added to the epoxy structure increased the flexural strength by 7%, 5% boron carbide added 14.4% and 10% boron carbide added 19.4% increase in the flexural strength. When the obtained results were compared, it was observed that the flexural strength of the structure increased as the ratio of boron carbide contribution to the epoxy structure increased.

When the effect of kaolin on the sandwich structure is examined; The increase in the kaolin ratio in the epoxy structure increases the flexural strength. The addition of boron carbide at the rates of 2%, 5% and 10%, increased the flexural strength of the structure by 4.7%, 6.7% and 7.6% respectively. The results are visualized in Figure 4.12.

In Table 4.2, the effect of additives, the average of each material combination and the standard deviation values are shown. The low deviation values indicate the consistency of the samples with each other. However, the deviation value in the samples with 10% added boron carbide

was high, and when Figure 4.7 was examined, sample 5 showed a different behaviour compared to the other samples. When the reason for this is examined and sample 5 is visually inspected, as a result of the three-point bending test, as seen in Figure 4.11, separation or debonding was observed in the surface layers of the sample and the core material. Also core crack was observed in sample. In the literature, this situations are defined as "debonding" and "core shear damage" (Çağlayan et al. 2018). When the failure modes analysed core shear damage seen in the compression side and debonding is seen on the tension side after three point bending test. As a result of this situation, when all the remaining samples were examined, such a situation was not observed in the other samples except the sample 3 which 10% graphene added.

After the upper surface layer damage occurred in all materials, the part observed as a sudden drop in the graphs continued to carry the load for some more time before reaching zero value. This is due to the fact that there is no damage to the lower surface plate and it indicates the load-carrying capacity of the material. As can be seen in Table 4.2, no significant change in the decrease in bending strength was observed with the addition of additives into the matrix material.

Table 4.2. Maximum load capacity and mid-span deflection of all combinations of sandwich structure

Specimens	***Average Max Load (N)***	***Standard Deviation***	***Mid-Span Deflection (mm)***	***Reduction in Flexural Load***
Neat-Epoxy	583.26	24.14	5.16	52.63%
G2	686.92	15.92	6.54	54.74%
G5	690.61	27.84	7.3	54.01%
G10	696.37	37.6	7.62	46.18%
B2	624.79	8.4	6.32	50.19%
B5	668.22	13.74	8.7	53.55%
B10	710.85	37.3	9.34	59.22%
K2	610.71	18.33	5.48	47.86%
K5	622.28	9.11	6.1	49.90%
K10	627.39	5.15	7.28	50.34%

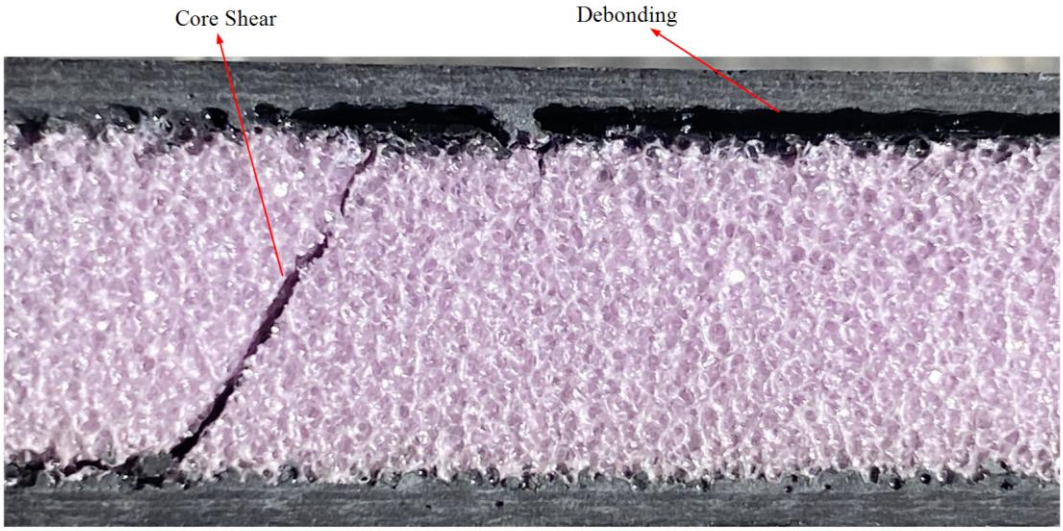


Figure 4.11. Sandwich structure' s failures under three point bending test

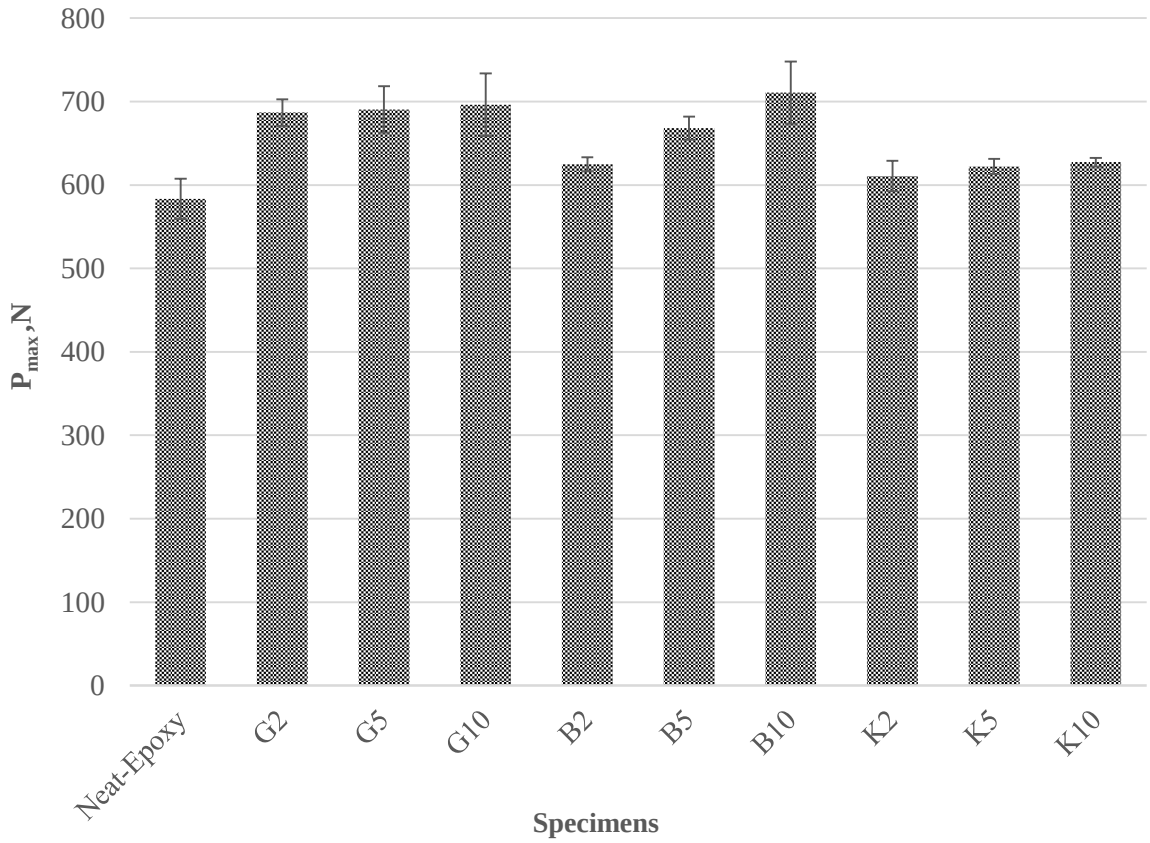


Figure 4.12. Comparison of the average maximum load-carrying capacity of all combinations of the sandwich structures

4.1.6. Facing Bending Stress and Core Shear Stress

The flexural characteristics of the manufactured specimens were determined according to ASTM standards. Facing bending stress and ultimate core shear strength are shown in Equations 3.1 and 3.2 in Chapter 3 (Material and Method). Tables 4.3-4.6 show the maximum load, ultimate core shear strength and facing bending stress values of neat-epoxy, graphene-epoxy, boron carbide-epoxy and kaolin-epoxy specimens after the three-point bending test.

Core shear strength is especially important for composites which are layered structures and sandwich structures. In sandwich structures, it is useful to understand the bonding between the core and the surface layer. According to the results of the three-point bending test; an increase in core shear strength was observed with the contribution of graphene at the rates of 2%, 5% and 10% in the epoxy matrix. When this change is compared with the core shear strength values of the core material (0.55 MPa) of the sandwich structure, it shows that the sandwich structures obtained by the matrix toughening method will be damaged by the core shear failure mode. When compared to other studies in the literature aimed at increasing bending strength (Uzay et al., 2019), it was observed that the surface layers of the sandwich structures produced in this study were improved and were damaged later. An increase in the core shear strength of the structure was observed with the increase of boron carbide additive in the epoxy matrix. Likewise, kaolin additive in epoxy matrix resulted in an increase in core shear strength. In summary, the samples obtained by adding graphene at a low rate to the sandwich structure showed an improvement in core shear strength. On the other hand, the effect of boron carbide showed the highest performance at 10%.

Facing bending stress shows us the maximum stress at the bending point of the material as a result of the three-point bending test. When the samples were analysed, it was observed that graphene additives in the epoxy matrix increased the facing bending stress of the material. 2%, 5% and 10% graphene additives increased the facing bending stress by 17.8%, 18.4% and 19.4% respectively. Similarly, although the addition of boron carbide to the epoxy matrix did not show as much effect as graphene at a low level, facing bending stress increased with the increase of boron carbide. 10%, 5% and 2% boron carbide additives increased facing bending stress by 21.9%, 14.6% and 7.4%, respectively. The addition of kaolin in epoxy did not show a high increase compared to the other two additives. 2%, 5% and 10% kaolin additives increased facing bending stress by 4.7%, 6.7% and 7.6%, respectively. When all the combinations are considered, an increase in flexural properties is observed when the epoxy matrix of the sandwich structure is supported with graphene. The best-performing combination was boron carbide added at 10%. Although the addition of boron carbide at low rates did not show much effect, it was the best-performing additive. The effect of kaolin showed an improvement in the sandwich structures bending properties of the, although not as much as the other two materials. In the study conducted by Selver and Kaya (2019) to improve the bending resistance of sandwich composite structures, an increase in the facing bend stress value of the sandwich structure was observed, as in this study.

Table 4.3. Flexural Properties of Neat-Epoxy Sandwich Structure

Specimen	P_{max}	P_{avg}	F_s, MPa	F_{avg}	σ, MPa	σ_{avg}
Neat-S1	594.42		0.53		31.70	
Neat-S2	593.85		0.53		31.67	
Neat-S3	590.28	583.26	0.52	0.52	31.48	31.11
Neat-S4	540.33		0.48		28.82	
Neat-S5	597.44		0.53		31.86	

Table 4.4. Flexural Properties of Graphene-Epoxy Sandwich Structure

Specimen	P_{max}	P_{avg}	Fs, MPa	F_{avg}	σ, MPa	σ_{avg}
G2-S1	696.31		0.62		37.14	
G2-S2	658.75		0.59		35.13	
G2-S3	695.07	686.92	0.62	0.61	37.07	36.64
G2-S4	690.02		0.61		36.80	
G2-S5	694.45		0.62		37.04	
G5-S1	698.31		0.62		37.24	
G5-S2	711.07		0.63		37.92	
G5-S3	708.82	690.61	0.63	0.61	37.80	36.83
G5-S4	692.11		0.62		36.91	
G5-S5	642.76		0.57		34.28	
G10-S1	754.20		0.67		40.22	
G10-S2	688.98		0.61		36.75	
G10-S3	660.38	696.37	0.59	0.62	35.22	37.14
G10-S4	668.45		0.59		35.65	
G10-S5	709.82		0.63		37.86	

Table 4.5. Flexural Properties of Boron Carbide-Epoxy Sandwich Structure

Specimen	P_{max}	P_{avg}	F_s, MPa	F_{avg}	σ, MPa	σ_{avg}
B2-S1	622.95		0.55		33.22	
B2-S2	628.72		0.56		33.53	
B2-S3	613.89	624.79	0.55	0.56	32.74	33.32
B2-S4	621.92		0.55		33.17	
B2-S5	636.46		0.57		33.94	
B5-S1	649.49		0.58		34.64	
B5-S2	659.28		0.59		35.16	
B5-S3	675.79	668.22	0.60	0.59	36.04	35.64
B5-S4	683.99		0.61		36.48	
B5-S5	672.54		0.60		35.87	
B10-S1	735.04		0.65		39.20	
B10-S2	669.10		0.59		35.69	
B10-S3	751.15	710.85	0.67	0.63	40.06	37.91
B10-S4	725.49		0.64		38.69	
B10-S5	673.47		0.60		35.92	

Table 4.6. Flexural Properties of Kaolin-Epoxy Sandwich Structure

Specimen	P_{max}	P_{avg}	F_s, MPa	F_{avg}	σ, MPa	σ_{avg}
K2-S1	625.42		0.56		33.36	
K2-S2	620.31		0.55		33.08	
K2-S3	579.03	610.71	0.51	0.54	30.88	32.57
K2-S4	615.77		0.55		32.84	
K2-S5	613.01		0.54		32.69	
K5-S1	620.51		0.55		33.09	
K5-S2	615.44		0.55		32.82	
K5-S3	635.08	622.28	0.56	0.55	33.87	33.19
K5-S4	612.77		0.54		32.68	
K5-S5	627.59		0.56		33.47	
K10-S1	628.73		0.56		33.53	
K10-S2	628.43		0.56		33.52	
K10-S3	634.80	627.39	0.56	0.56	33.86	33.46
K10-S4	622.20		0.55		33.18	
K10-S5	622.78		0.55		33.21	

4.2. Vertical Flammability Test Results

The Vertical Flammability test is performed according to the UL 94 and ASTM D3801 standard and reveals the flammability properties of the sandwich structure. According to the standard, sandwich structure should have 125 mm in length, 13 mm in width, and the thickness should not exceed 13 mm. Since the thickness of the sandwich plate was 12.5, samples were in appropriate sizes. Measurement of the flammability test consists of V-0, V-1 and V-2 states as explained in Chapter 3 (Material and Method).

4.2.1. Effect of the Additives on Flammability Properties

According to the UL-94 test results, self-extinguishing was not observed in any laminate structures with graphene, boron carbide and kaolin after being exposed to flame for 10 seconds at the beginning, and all samples were examined as shown in Table 4.7. According to the vertical flammability test, the materials in this combination cannot be called fireproof. In similar studies in the literature, the effect of additives on polymeric composite materials was positive. As mentioned by Kamaraj et al. (2019), graphene reduces heat transfer by forming a layer on the surface of the structure. Poomarimuthukumar and Siva, (2021) revealed that with the increase of boron carbide filler in basalt fibre-epoxy laminate, better flame retardant properties. When the samples were examined as a result of the fireproofing test in this study, delamination was observed in the laminated structure, as shown in Figure 4.13. The matrix material burned and disappeared, only the fibers remained. Additives in powder form added into the matrix material had no effect. This is due to the low temperature working conditions of the resin and hardener used. Epoxy, which does not have fireproof properties, could not be given flame retardant properties by adding additives.



Figure 4.13. Specimen after Vertical Flammability Test

Table 4.7. Flammability test results

Matrix Material	Additive Ratio	Extinguish Time	UL 94 Status	Dripping
Neat-Epoxy	0	Not	N/A	No
Graphene-Epoxy	2%	Not	N/A	No
	5%	Not	N/A	No
	10%	Not	N/A	No
Boron Carbide-Epoxy	2%	Not	N/A	No
	5%	Not	N/A	No
	10%	Not	N/A	No
Kaolin-Epoxy	2%	Not	N/A	No
	5%	Not	N/A	No
	10%	Not	N/A	No

4.3. Evaluation of SEM Analysis

Thanks to the Scanning Electron Microscope (SEM) analysis, it will be possible to observe the distribution of micron-sized powder additives added into the sandwich structure, while it will be possible to examine whether a homogeneous mixture can be obtained with the epoxy resin. The images obtained from the SEM analysis are shown in Figure 4.14-4.17. When the images are examined, the distribution of powder additives within the structure is not clearly visible. According to the results in the literature, the most common problem was the agglomeration of additives in the structure (Hawal et al., 2020 and Kamaraj et al., 2019). However, the results in this study show that the additives were distributed homogeneously in the matrix and did not show any strength losses that may occur as a result of agglomeration. However, as the amount of graphene and kaolin increases, the increase in bending strength is lower than that of boron carbide. This may be an indication that the increase in graphene and kaolin in the matrix may cause agglomeration.

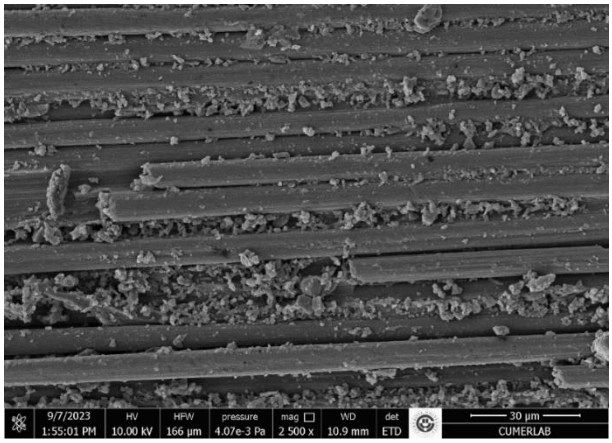
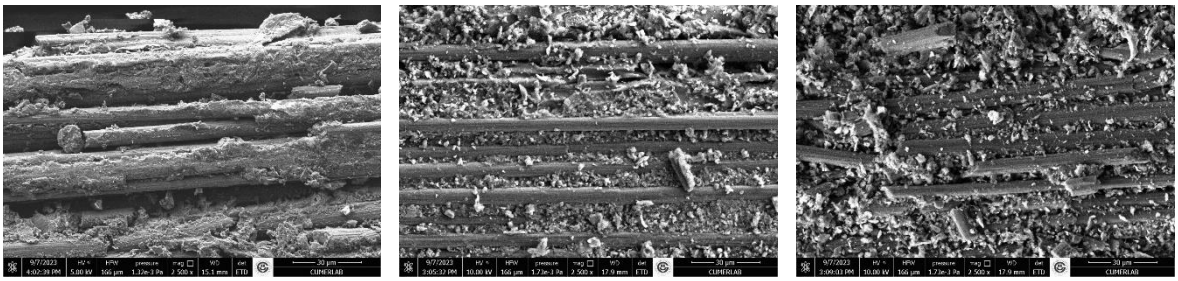
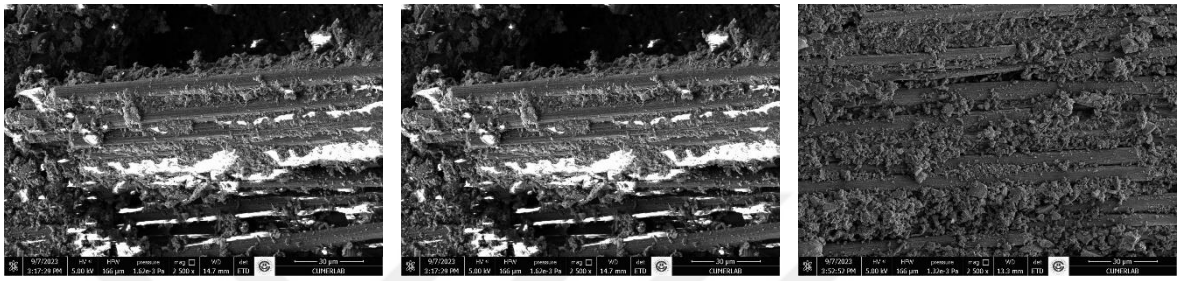


Figure 4.14. SEM results of Neat-Epoxy Sandwich Structure



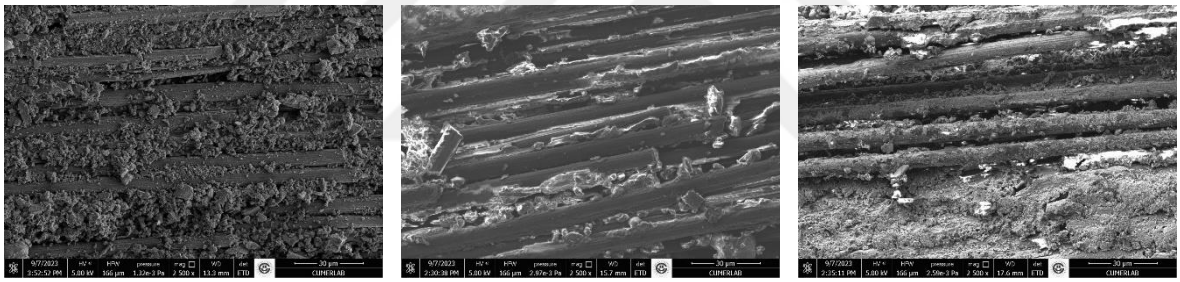
(a) (b) (c)

Figure 4.15. SEM results of Graphene-Epoxy Sandwich Structure (a) 2%, (b) 5%, (c) 10%



(a) (b) (c)

Figure 4.16. SEM results of Boron Carbide-Epoxy Sandwich Structure (a) 2%, (b) 5%, (c) 10%



(a) (b) (c)

Figure 4.17. SEM results of Kaolin-Epoxy Sandwich Structure (a) 2%, (b) 5%, (c) 10%

4.4. Final Evaluation for All Properties

According to the three point bending test results, the addition of graphene, boron carbide and kaolin into the matrix structure of carbon fiber reinforced epoxy matrix sandwich composites has shown that the sandwich structure increases the bending strength and resists to deformation, that is, the structure can be more exposed to bending load without any failure. In addition, even if the structure breaks, it continues to carry a load that is almost half of the maximum load it carries. The additives improves the load it carries. They even carry load after the breakage. When the additives added at 2%, 5%, and 10% were compared, the best performance was shown when graphene and boron carbide were added at 10%. Although there was a slight difference between graphene and boron carbide, boron carbide showed slightly better results. On the other hand, when the cost of graphene and boron carbide are compared, a sandwich structure produced by adding 10% boron carbide will be cheaper than adding graphene. In addition, when the vertical flammability test results

were evaluated, the effect of the additives in the powder form added into the matrix on the flame retardant properties of the carbon fiber laminated structure has not been observed. In the structure exposed to flame, the matrix material completely disappeared, only the fibers remained and delamination occurred. Table 4.8 shows the flexural property and flammability property improvements comparing the cost of the structures.

Table 4.8. Final Evaluation of Flexural and Flammability Properties of Sandwich Structure

Matrix Material	**Additive Ratio**	**Max. Bending Load Improvement**	**Flammability Improvement**	**Cost**
Neat-Epoxy	-	Control	Control	Control
Graphene	2%	17.6%	No	+48%
	5%	18.2%	No	+120%
	10%	19.1%	No	+240%
Boron Carbide	2%	7%	No	+17%
	5%	14.4%	No	+42%
	10%	19.4%	No	+83%
Kaolin	2%	4.7%	No	+0.08%
	5%	6.7%	No	+0.2%
	10%	7.6%	No	+0.4%

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5. CONCLUSIONS

In this study, sandwich plates were produced, whose surface layer consists of carbon fiber reinforcement and epoxy matrix, and the core is PVC foam. By adding the additives, in a powder form, into the epoxy matrix, bending resistance and flammability properties were investigated. As additives, Graphene, Boron Carbide and Kaolin at the rate of 2%, 5% and 10% by the weight of the matrix were added to the epoxy resin and a homogeneous matrix was obtained by using an ultrasonic mixer, and plates were produced by hand lay-up method and then vacuum bagging method. In order to examine the bending resistance and flammability properties of the produced plates, Three Point Bending Test and Vertical Flammability test were applied.

The following flexural properties of the sandwich structure and flame retardant properties of composite laminates were achieved from the results of Three Point Bending Test and Vertical Flammability Test.

- The effect of additives added into the epoxy matrix on the Flexural characteristics of the sandwich structure was unveiled with regard to facing stress, core shear stress and maximum bending load capacity.
- The facing stress value of sandwich structures increases as the rate of addition of the additive into the epoxy matrix increases. At the highest rate of 10%, all samples gave the highest value among themselves. These values for Boron Carbide, Graphene and kaolin are 21.9%, 19.4% and 7.6% respectively. Samples with 10% Boron carbide additive give the highest results.
- When we look at the core shear stress values of sandwich structures, they increase with the increase in the amount of additives. The sample with 10% Boron carbide added gave the highest value with an increase of 17.4%. In graphene, the three contribution ratios are very close to each other. The increase is at the lowest level in kaolin-added samples.
- When looking at their effects on the maximum load capacity carried by sandwich structures, it is seen that the addition rates in the matrix increase for all three additives. For Graphene, this increase is higher than for other additive materials, even when added at a low level. This is similar to studies in the literature. (Qin et al., 2014 and Srivastava et al., 2019) However, as the proportion of graphene increased, Boron Carbide did not increase as much as carbide. Since the increase in the additive may cause agglomeration in the matrix material, the increase rate decreases.
- The maximum carrying capacity, which increases with the increase in the amount of Kaolin, has not increased as much as Boron Carbide, but there is still an increase. There are similar results in similar studies in the literature (Bulut et al., 2019).

- Adding Boron Carbide into the matrix material showed the highest performance. This has been beneficial in increasing the bending resistance without increasing the weight of the sandwich structure by using the matrix toughening method.
- The contribution of boron carbide, graphene and kaolin added into composite laminated structures did not show the expected results, contrary to the literature. No improvement in flame retardant properties was observed in any of the samples. The matrix material of the laminate structure was completely destroyed by ignition.

When all materials are compared and the results are evaluated, Boron Carbide is the additive material that exhibits the best performance when a structure that is exposed to bending resistance. Also Graphene added sandwich structures show a great bending performance. However when the costs are evaluated in the foreground, it will not be the best option.

- In this study, the flexural strength of the material with additives was revealed with a 150 mm span length. When the bending tests are repeated by using the same additives in the same proportions by changing the sample sizes, that is, by increasing the span length to 200mm, the properties of the sandwich structure such as flexural stiffness, sandwich beam deflection and core shear modulus can be calculated.
- Samples were produced by adding additives to the epoxy resin. Considering the interfacial interactions of the additives in the fiber-matrix, the additives can be sprayed with an air brush on the structure and the results can be compared to examine the flexural strengths. This method can be further developed and the additives can be applied in a dispersion with alcohol, and then the sample can be heated to the evaporation temperature of alcohol to remove alcohol from the structure. Also this type of surface coating may increase the flammability properties of composite structure.
- Matrix toughening is one of the important methods to improve mechanical properties. Comparisons can be made by applying other additives used in similar applications in the literature to the same sandwich structure.
- Only 10 mm thick low density PVC foam was used in this study. The effects of core materials that can be used in different thicknesses, densities or forms can be examined.
- In this study, carbon fiber was used as the surface layer. A comparative study can be done using other fibers such as glass fiber, aramid fiber, etc.

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