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THE EFFECT OF GLASS AND KEVLAR FIBER VOLUME FRACTION ON THE MECHANICAL PROPERTIES OF EPOXY COMPOSITES

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ABSTRACT

The effect of glass and Kevlar fiber volume fraction on the mechanical properties of epoxy composites, was investigated in this study. Different number of layers, total mass of the non-impregnated fibers and reinforcing materials were used to create the specimens. As a result of the different number of the layers, specimens with varying thickness and total composite mass were produced. Volume fraction was changed, depends on these parameters. Specimens of fiber glass and Kevlar were prepared using the vacuum banging method and epoxy resin as the matrix material. The mechanical behaviors of the specimens were tested under uniaxial tension and three-point bending. Specifically, the samples' stiffness and strength, were examined.The aspects of varying layers, fiber properties, thickness of sample and mass of fibers and total composite, i.e. volume fraction was found to play an important role for the design of a composite with an optimized stiffness or strength-to-weight ratio.

KEYWORDS

Fiber glass, Kevlar, volume fraction, composite materials, epoxy resin

1. INTRODUCTION

With the development of technology in recent decades, more and more multi-purpose and lighter materials are needed in a wide range of industries[1]. Every year the demand for advanced materials with better performance increases, which aim to meet new requirements or replace existing materials such as metal-based ones. These efforts have greatly contributed to the development of new polymer-matrix composite materials, enabling significant design improvements[2].High performance or high-functional fibers offer the advantages of high strength, high stiffness, heat resistance, wear resistance and impact resistance[3].The use of composite materials has found wide application in the manufacture of various products, including automotive and aircraft components, structural components, sports equipment and biomedical devices due to their excellent structural properties[4,5]. Typical reinforcingis carbon fiber, aramid fiber, UHMWPE fiber (ultra-high molecular weight polyethylene), PPS fiber (polyphenylene sulfide), and PBO fiber (polybenzoxazole)[6-8]. Composite materials consist of at least two or more different components that do not dissolve in each other. One component is called matrix and the other is calledthe reinforcing phase. The strength and hardness of composite materials are mainly obtained from the reinforcing materials, while the matrix provides corrosion resistance, toughness and ductility[9].The shape, type, size and volume fraction of the matrix and reinforcing materials have a significant influence on the chemical, physical and mechanical properties of composite materials [10]. The most common reinforcing materials used primarily with polymer matrices are graphite/carbon, glass, aramid and boron fibers.Because of their low melting temperature, simplicity of manufacture,low density and benefits for molding, polymer matrix materials are preferred among the matrix materials over metal and ceramic matrices. Because of their low density, high stiffness- and strength-to-weight ratios, and excellent corrosion resistance, composite materials greatly minimize the amount of energy used in the ground, sea, and air transportation vehicles. They additionally provide effective acoustic and thermal insulation. By decreasing air pollution from exhaust gases, composite materials contribute to minimize the negative impact on the environment[11].

Aramid material has gotten a lot of attention, in particular because of its high strength and heat resistance. Aramid fiber has a sizable market share due to its affordable price when compared to other ultra-high strength fibers, due to its high elastic modulus and tensile strength[12–14]. Functional aramid fibers have thus been used in industrial materials, aircraft development, marine fisheries parts, bulletproof and protective shielding, and civil construction structures[15]. Making lightweight, high-performing, and inexpensive polymeric composites has recently received a lot of research attention. By adding and reacting reinforcing fibers to the resin matrix, thermosetting or thermoplastic composites can be used to increase performance[16].Many studies have been reported to improve the tensile strength, the impact, and flexural strength properties [17–19].

On the other hand, glass fibers have a high level of strength, durability, and stiffness. In order for a composite to be strong, both thereinforcing phaseand the matrix are crucial. Typically, the reinforcing component has low density, strong, stiff and thermally stable[20]. In polymer matrix composites, fibers serve as the main reinforcement. Glass fibers also show significant technical characteristics associated with low density. Because of this, polymer materials reinforced with such fibers have demonstrated the highest strength-to-weight ratio[21]. Glass fabrics and composite materials bonded with aramid fibers were also the subject of research by Pihtili et al.[22]. In comparison to glass fabric reinforced composites GFRC, the weight reduction of aramid fiber reinforced epoxy composites AFRC was shown to be quite low[21].Hand lay-up, spraying, and vacuum bagging processes are a few of the typical manufacturing processes for epoxy matrix composite materials.

The hand lay-up process is based on brushing or rolling resin onto fibers in a mold. For the quality and effectiveness of composite materials, it is crucial in this procedure to reduce porosity. Impregnated fibers are cured at ambient temperature and atmospheric pressure, or at different pressuresandtemperatures, depending on the required thickness. Using the vacuum bagging method, the resin-impregnated fabrics are placed on top of each other to the desired thickness and covered with a vacuum bag. Curing takes place using vacuum pressure at the curing temperature[10].Good quality products can be obtained using vacuum bagging method.

Recently much research effort has been devoted to investigate the effect of number of the layers in the composite structure. Refs.[23]has investigated the effect of varying the number of layers for a fixed total thicknessand the change of the mechanical response of a multilayer composite plate loaded in compression in the axial direction when the number of layers increases. The influence of the number of layers and fiber distribution have effective role on the mechanical properties of woven fiber-reinforced composites by changing the number of layers or the manufacturing process [24].The volume fractionis affected by varyingthe number of layers, fiber properties and thickness of the samples.

In this study therefore, the effect of glass and Kevlar fiber volume fraction on the mechanical properties of epoxy composites, was investigated. Understanding the effect of fiber volume fractions on mechanical properties is crucial for optimizing the performance of composite materials in various applications.

Different number of layers, total mass of the non-impregnated fibers and reinforcing materials were used to create the specimens. As a result of the different number of the layers, specimens with varying thickness and total composite mass were produced. Volume fraction was changed, depends on these parameters. The fiber total mass refers on the sum of areal weight of the fibers before the epoxy was applied. Three cases of total fiber mass were used, masses of 2kg, 3kg, and 4kg, with different number of layers was used depends on the areal weight of the specific material. For masses 2kg and 4kg two different combinations were examined, while for fiber mass of 3kg four different combinations.Specimens of fiber glass and Kevlar were prepared using the vacuum banging method and epoxy resin as the matrix material were examined. The mechanical behaviors of the specimens were tested under uniaxial tension and three-point bending. Specifically, the samples' stiffness and strength, were examined. The number of layers and the material selection was found to play an important role for the design of a composite with an optimized stiffness or strength-to-weight ratio.

2. EXPERIMENTAL

2.1. Materials Preparation

The compositeswere prepared by using two types of fiber glass and two types of Kevlar with different areal weight, grams per meter square (gr/m^2). A woven reinforcement with plain weaving at 0 and 90was used and epoxy resin as the matrix material, more specifications are given in Table 1. Table 2 shows the characteristics of the epoxy resin.

Table 1 Specifications of composite materials

Fiber	Fiber Glass 1	Fiber Glass 2	Kevlar 1	Kevlar 2
Weight (gr/m^2)	80	200	61	170
Weave	Plain	Plain	Plain	Plain
Thickness (mm)	0.08±0.02	0.16±0.02	0.12±0.02	0.27±0.02

Table 2Properties of epoxy resin (EC 130LV).

Viscosity at 25°C (mPas)	1200 ± 400
Hardener	W340
Curing	24 h TA + 15 h 60°C
Tensile strength (MN/m^2)	75
Compressive strength (MN/m^2)	85
Flexural strength (MN/m^2)	115

(*) TA = laboratory room temperature (23±2°C), h = hours

To examine the volume fraction of the specimens created by the different number of layers for fiber total mass of the non-impregnated fibers were used two types of Kevlar and two type of fiber glass with mass per unit area 61 gr/m^2, 170 gr/m^{2}and 80 gr/m^2, 200 gr/m^2, respectively. Three differentfiber totalmasses (FTM)were investigated in this study, FTM for 2kg, 3kg and 4kg. For the cases of the FTM 2kg and FTM 4kg, specimens of Kevlar 170 gr/m^2 and fiber glass 200 gr/m^2 were prepared. In contrast to the case of FTM 3kg where all type of composite were used. Due to their different mass per unit area, different number of the layers was needed to prepared the required fiber masses. More details about the number of the layer are shown in Table 3. Different thicknesses and different masses resulted for each sample when the epoxy was applied and the final samples were produced with different volume fraction.The specimens type abbreviations correspond to thevarying fiber mass and the details for the samples are listed in Table 4. The laminating structure of specimens about the number of layersand details about total thickness, weight and volume fraction of samples are shown in Figure 1 and2, respectively.

Table 3Number of the layers

Type of Fiber	Number of the layers		
	Fiber Mass 2kg	Fiber Mass 3kg	Fiber Mass 4kg
Fiber Glass 80 gr/m^2	-----	38	-----
Fiber Glass 200 gr/m^2	10	15	20
Kevlar 61 gr/m^2	-----	50	-----
Kevlar 170 gr/m^2	12	18	24

Table 4Details about the different weight of reinforcing materials, the total thickness and weight of the samples created

Abbr.	Type of Fiber	Weight (gr/m^2)	Number of layers	Mass of Fibers (gr)	Total Thickness of sample (mm)	Total Weight of sample (gr)	Volume Fraction
2k200f	F. Glass	200	10	2000	1.5	7.7	0.1007
3k200f	F. Glass	200	15	3000	2.3	11.9	0.0985
3k80f	F. Glass	80	38	3050	2.9	13.7	0.1120
4k200f	F. Glass	200	20	4000	3.1	15.1	0.0974
2k170k	Kevlar	170	12	2040	3.1	9.3	0.1049
3k170k	Kevlar	170	18	3060	4.9	17.8	0.0976
3k61k	Kevlar	61	50	3050	4.7	15.5	0.1226
4k170k	Kevlar	170	24	4080	6.8	22.2	0.0964

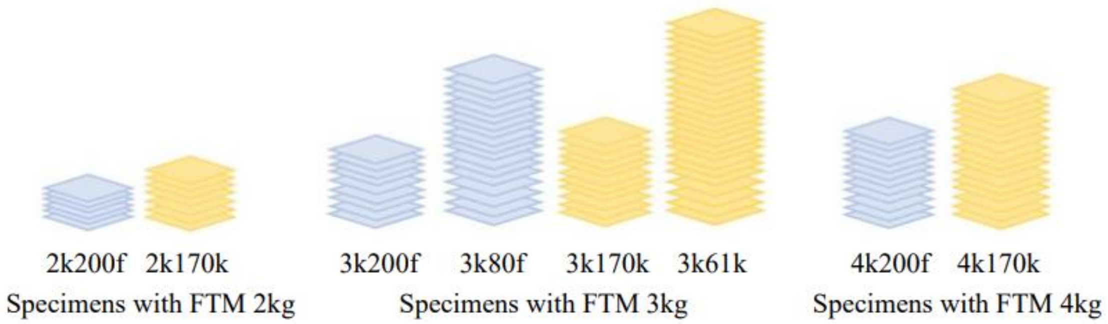


Figure1.Details of the specimens with varyingfiber total mass (FTM)and the laminating structure

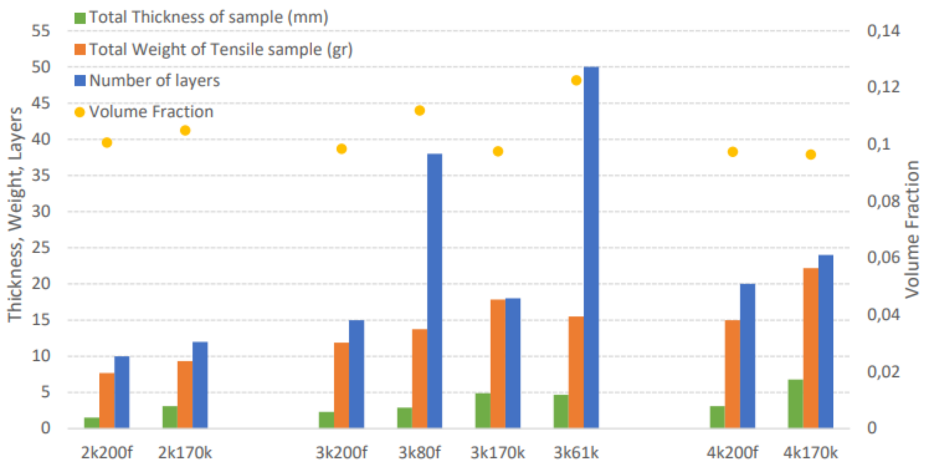


Figure2. Total thickness, weight of samples and volume fractions in relation to the number of layers

2.2. Sample Construction

Specimens were prepared as sheets with multiple internal layers. First, reinforcing fibers were uniformly cut into 250 x 250 mm pieces. Eight types of paired specimens were prepared with different laminations, as it shown in Table 4.

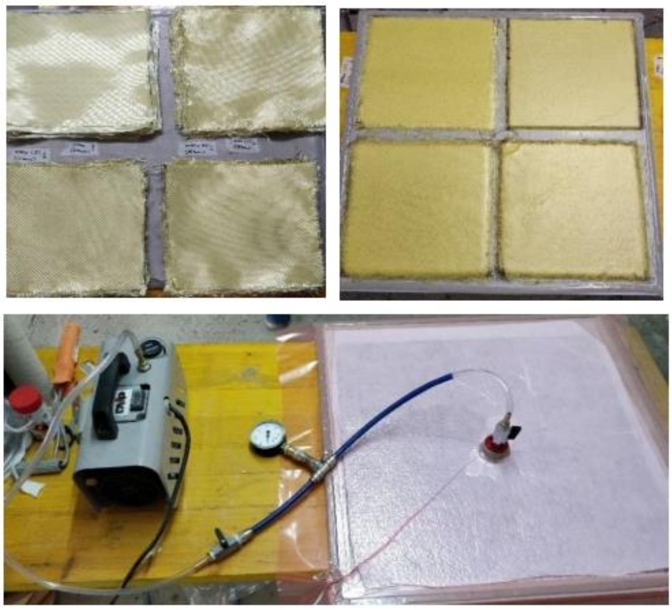


Figure3.Uniformly cut reinforcing fiber before and after epoxy impregnated, Vacuum bagging method

A hand-layup method was used to construct the specimens. This method consists of a vacuum pump, vacuum bagging, spiral tubing, and sealant tape. The spiral tubing creates uniform vacuum across the sample, preventing epoxy from collecting on the side of the sample where there is less vacuum.Epoxy pooling makes thefacesheet thickness not uniform.The hand-layup technique produced high quality specimens with less defects[25].To create the specimens, a layer of epoxy was applied firstand then each layer of fabric was placed. Hereby, the necessary amount of epoxy was appliedand the spread-out procedure was performedspecial care. After all the layers were placed, the specimen was carefully covered with the vacuum bagging to ensure that no wrinkles would occur when the vacuum was applied. The surface finish of the specimen is affected if there are any wrinkles on the vacuum bagging.Trapped air and the extra epoxy were removed using a rubber squeegee. The composites were fabricated by using the vacuum bagging method for one hour. Specimens were then cured at room temperature for two days. Details about the preparation of the samples are shown in Figure3.

2.3. Specimens and Tensile Tests

The plate of composite material produced by vacuum bagging was machined to produce the specimens. Tensile specimens were cut to the size according to the ASTM D638 standard[26].Six samples were prepared for all different types of specimens. Details of the specimens are shown in Figure4. Cross head speed of 2 mm/min was used. All the tests were done at room temperature. Ultimate tensile strength, modules of elasticity, strain and the strain energy were determined from the tensile test results.

Figure4. Tensile specimens of fiber glass and Kevlar, Tensile test

3. RESULTS AND DISCUSSION

3.1. Tensile Behavior of Kevlar and Fiber Glass Composite

To determine the mechanical properties of the composites, tensile tests were conducted on the fiber glass–epoxy matrix composites and Kevlar–epoxy matrix composites. Force (load) and displacement (ΔL) were the collected data from the tensile experiment. Ultimate tensile strength, modules of elasticity, strain and the strain energy were determined according to the collected data.Figure5 shows a typical stress – strain curve obtained for the fiber glass and Kevlar samples laminated with different number of the layers according to the requested fiber total mass.

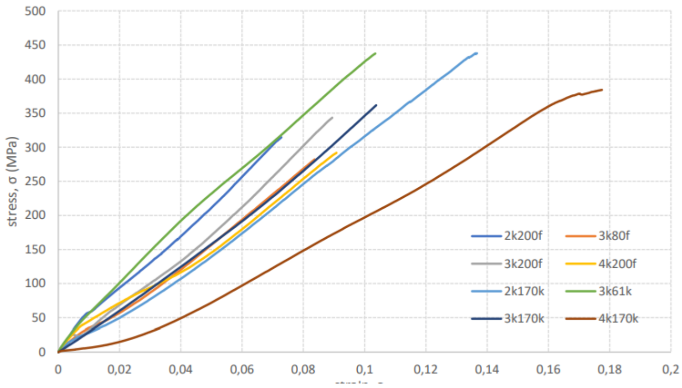


Figure5. Stress and strain curves of specimens laminated by fiber glass and Kevlar

Kevlar laminated showed slightly higher stress in stress – strain curve than the fiber glass laminated samples. Energy absorption and elongation are shown in Figure6. Similar behavior of elongation at break and energy absorption are obtained for fiber glass samples. Kevlar samples have significant higher thickness than the corresponding glass fiber, which leads to higher elongations at break and thus, more energy absorption.

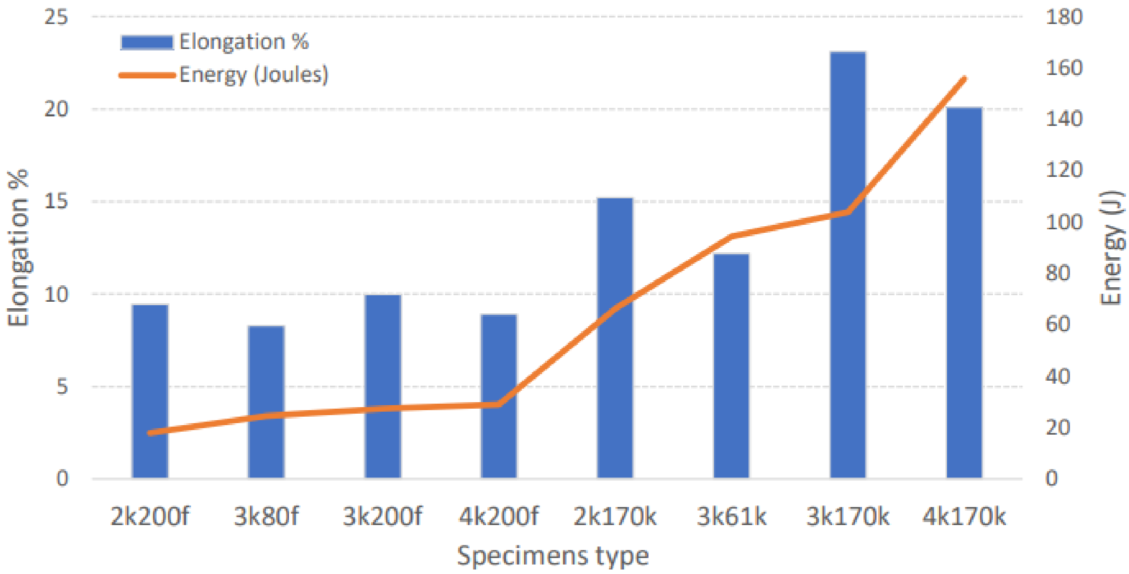


Figure6.Energy (J) and elongation % with the different type of specimens

Figure7 shows the elastic modulus with the different fixed fiber mass of specimens. A comparison in cases of FTM 2kg and FTM 4kg, showed that the samples 2k200f and 4k200f produced by fiber glass had higher modulus of elasticity comparing with 2k170k and 4k170k produced by Kevlar.

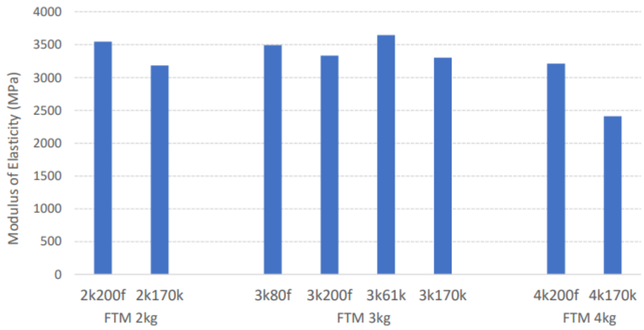


Figure7.Stiffness of the different fiber mass

Fiber glass samples, have smaller total thickness and lower total weight comparing to Kevlar samples. Both materials for FTM2kg showed higher modulus of elasticity than FTM 4kg samples. Sample 2k200f showed the highest modulus of elasticity from fiber glass samples. For the specimens with 3kg, four different combinations were investigated, two fiber glass and two Kevlar. A comparison between the two reinforcing materials showed significant different about stiffness. Sample 3k80f has greater total thickness and total composite weight, lower weight per fiber and higher number of the layer than 3k200f. Sample 3k61k has smaller total thickness, lower total composite weight, lower weight per fiber and higher number of the layer than 3k170k.However, samples 3k80f and 3k61k have higher volume fractionand they showed higher modulus of elasticity comparing with 3k200f and 3k170k, respectively. The highest stiffness was obtained by 3k61k sample.

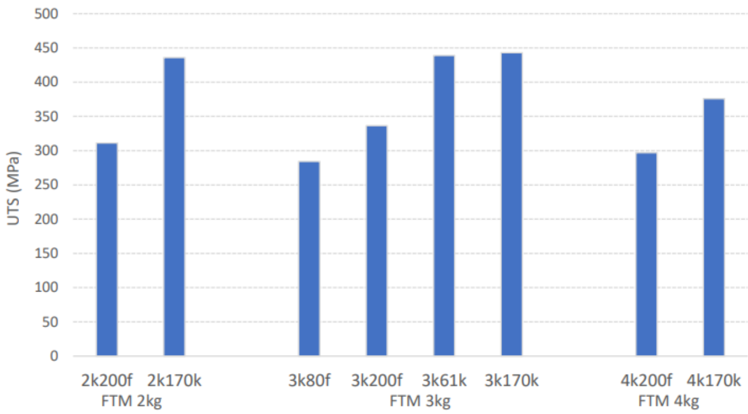


Figure8.Ultimate tensile strength with the different fiber mass

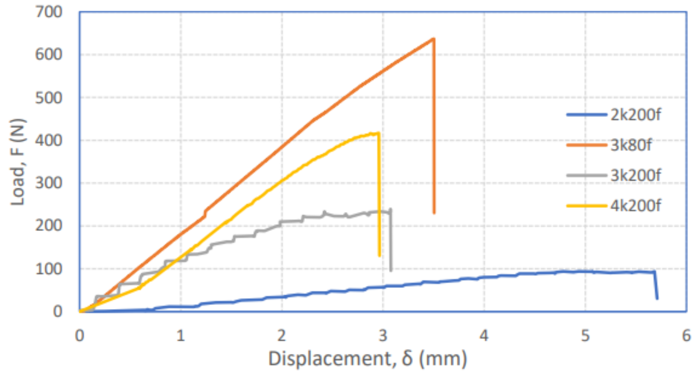
Figure8 shows the ultimate tensile strength per fiber total mass. The samples produced by Kevlar showed higher tensile strength. The highesttensile strength was observed by 3k170k, with sample 3k61k and 2k170k showed slightly lower, while the lowest were obtained by 3k80f sample.Both materials showed high strength for samples of FTM 3kg. It can also be observed that samples of Kevlar have better toughness and ductility than the samples produced by fiber glass.Samples produced by fiber glass havelower ductility but higher elastic modulus, in most of the cases where have been investigated.

3.2. Bending Strength of Kevlar/ Fiber Glass Composite

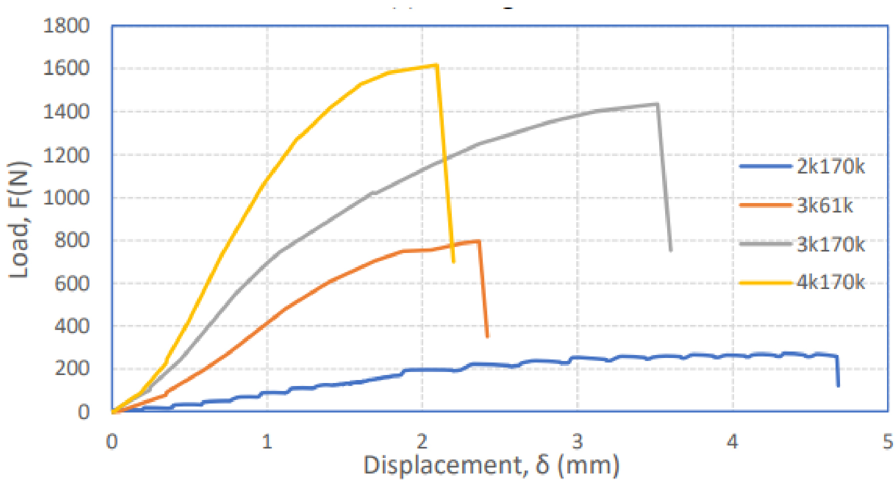
The plate of composite material produced by vacuum bagging were machined with dimensions of 80 mm x 12.7 mmto create the specimens for the bending test. Six specimens were tested and their average values are determined in this study. The bending tests, using a universal testing machine, were conducted according to ASTM D790 with 2 mm/min cross-head speed.Figure 9 shows the curvesof the load-displacement of the composite materials with different fixedtotal mass under bending load. The bending strength was calculated using the following equation, Eq. (1):

$$\sigma_b = \frac{3FL}{2bt^2} \tag{1}$$

where F, L, b and t represent bending load, support span, width of the specimen and thedepth of samples, respectively. The bending strength of the sampleswas calculated for the maximum load Fmax at break.



(a) Fiber glass



(b) Kevlar

Figure9.Load – displacement curves for samples produced by fiber glass (a) and Kevlar (b)

Generally, all specimens exhibit initially a linear load increase followed by a parabolic increase due to local crack initiation and a final failure. Solely the sample 3k80f shows purely linear behavior prior to an abrupt failure. The specimens with mass of 2kg have the highest displacement and the lowest carried load. The samples 3k80f and 4k170k have the highest carried load for samples of fiber glass and Kevlar, respectively.

Figure10 shows the bending and tensile strength with all specimenswith varying fiber masses. The bending strength of the samples, fiber glass and Kevlar, was distributed in the range of 300 – 510 MPa, but 3k80f samples were a level of more than 700 MPa. In contrast to the tensile strength, samples produced by fiber glass showed higher bending strength for almost all cases, except sample 3k170k. Comparing the different materials by their samples, the lowest values of bending strength were observed by the samples of FTM 2kg. It can be seen that FTM 4kg had higher tensile strength but lower bending strength comparing to FTM 2kg. In particular, 2k200f and 2k170k showed the lowest bending strength for samples produced by fiber glass and Kevlar, respectively. Samples with FTM 3kg showed the highest values for the bending and tensile strength, except sample 3k200f showed the lowest value for tensile strength.

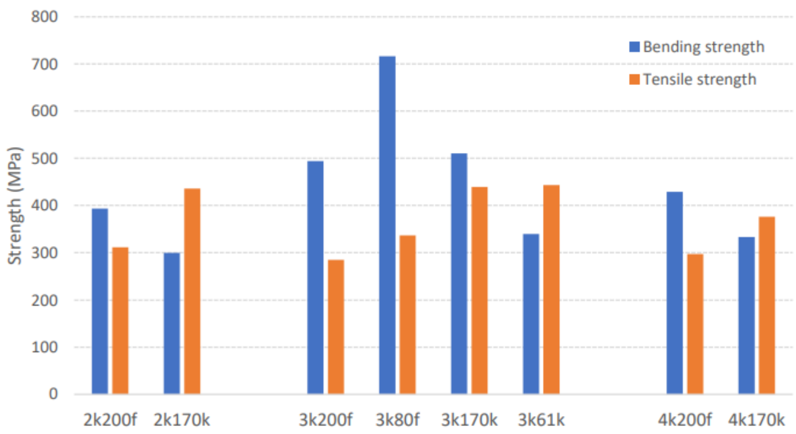


Figure10. Bending and Tensile strength

3.3. Stiffness- and Strengthtoweight Ratio

Analysis of tensile test results showed that samples of 2kgfiber massreach higher strength-to-weight ratio compared with 3kg and 4kg, for both materials,Kevlar sample 2k170k demonstrates the highest tensile strength-to-weight ratio. On the other hand, fiber glass samples of FTM 3kg exhibits slightly higher bending strength-to-weight ratio compared with FTM 2kg, while the FTM 4kg shows lower strength. In particular, sample for 3k80f and 2k200f higher bending strength-to-weight ratio are observed, with marginal difference. Details for the strength-to-weight ratioand volume fraction are shown in Figure 11.

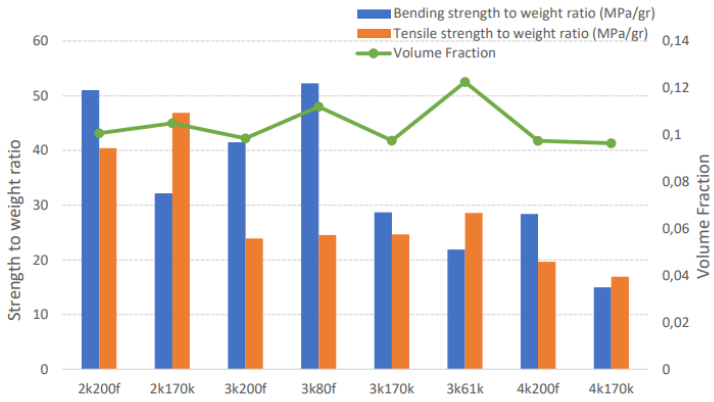


Figure 11.Bending and tensilestrength-to-weight ratio in relation of volume fraction

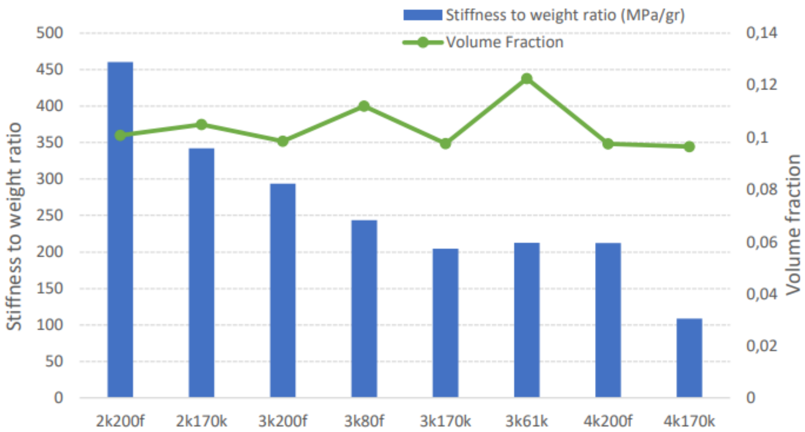


Figure 12.Stiffness-to-weight ratio in relation of volume fraction

Figure 12 shows the stiffness-to-weight ratioin relation of volume fraction. Here, stiffness defines the tensile modulus of elasticity. Samples of fiber mass 2kg show the highest stiffness-to-weight ratio for each material, while samples of FTM 4kg demonstratethe lowest values.The increase of fiber mass and the associatedincrease of number of the layers play an important role, since the thickness and the total weight of the sample increase as well. FTM 2kg samples have smaller total thickness and lower total weight compared to the rest samples and due to this, less epoxy fraction. Samples produced by fiber glass showed higher stiffness-to-weight ratio compared to Kevlar for all three fiber masses. The highest stiffness-to-weight ratio was obtained by sample 2k200f. Even though a general reduction of stiffness-to-weight is observed with increase of the fiber layers, it is worth mentioning that for 3kg fiber mass for Kevlar, even though the number of layers increases for 3k61k compared to 3k70k, here a slight increase of stiffness-to-weight is observed.

4. Conclusion

The effect of varying fiber mass and consequently different volume fraction and number of the layers of the non-impregnated glass and Kevlar fibers was investigated in this study. The fiber mass refers on the sum of areal weight of the fibers before the epoxy was applied. Different number of layers was used depending on the areal weight of the specific material, to achieve varying groups ofmasses of fibers. Three cases of total fiber mass were examined in this research. Fiber masses of 2kg, 3kg, and 4 kg. For fiber masses 2kg and 4kg two different combinations of glass fibers were examined, while for the fiber mass of 3kg four different combinations of both glass and Kevlar fibers were examined. Specimens of fiber glass and Kevlar were prepared using the vacuum banging method and epoxy resin as the matrix material. The samples were manufactured efficiently using vacuum banging method. As a result of varying the fiber mass and the number of fabrics layers, specimens with different thickness and different total composite mass wereproduced. The mechanical properties resulting from the varyingfiber mass were investigated using tensile and bending test.The results from this research can be summarized as follows.

The tensile test showed that the Kevlar has higher strength than fiber glass for all material combination and the different fibermasses. Fiber glass showed better results of their stiffness with higher modulus of elasticity comparing to Kevlar for the fiber masses 2kg and 4kg. Kevlar 3k61k samples proves the highest value of modulus of elasticity. It can also be observed that samples of Kevlar have better toughness and ductility than the samples produced by fiber glass. Samples produced by fiber glass has lower ductility but higher elastic modulus.The bending test showed that the samples produced by fiber glass have higher bending strength for all different masses comparing to Kevlar. Highest bending strength is observed by 3k80f.

Analysis of strength-to-weight ratio showed that the samples of FTM 2kg have higher values comparing to masses of 3kg and 4kg, for bending and tensile strength, with an exception of sample 3k80f. Similarly, stiffness-to-weight ratio shows that the highest values were obtained by fiber mass of 2kg. Samples with smaller number of the layers and lower thickness need less epoxy resin and showed higher strength and stiffness to weight ratio. This leads to the conclusion that with decreasedfiber volume fraction, i.e., higher epoxy fraction, the probability for a crack initiation is more likely this is why the strength-to-weight ratio drops. Additionally,with increased fiber volume fraction, i.e., lower epoxy fraction, the stiffness-to-weight ratio proves to be higher as expected. The aspects of varying layers, fiber properties, thickness of sample and mass of fibers and total composite, i.e. volume fraction was found to play an important role for the design of a composite with an optimized stiffness or strength-to-weight ratio.

Future studies on the design of a composite with an optimized stiffness or strength-to-weight ratio, based on the role of volume fraction, in hybrid composite and short fiber composite would be worthwhile.

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