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INVESTIGATING THE IMPACT OF GLASS AND KEVLARFIBER VOLUME FRACTIONS ON MECHANICAL PROPERTIES OF EPOXY COMPOSITES

Elias Louka[1], Loucas Papadakis[2] and Jianping Xuan[1]*

[1]School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China;
[2]Department Mechanical Engineering, Frederick University, Nicosia, Cyprus;

ABSTRACT

This study aimed to investigate the impact of the proportion of glass and Kevlar fibers in epoxy composites on their mechanical properties. To achieve this, we employed different combinations of layer counts, non-impregnated fiber mass, and reinforcing materials to fabricate the specimens. As a result, specimens with varying thicknesses and total composite mass were generated, thereby altering the volume fraction accordingly. The specimens made use of fiber glass and Kevlar, which were prepared through the vacuum banging technique with epoxy resin serving as the matrix material. Subsequently, the mechanical characteristics of the specimens were evaluated through uniaxial tension and three-point bending tests, focusing on stiffness and strength. It was observed that factors such as the number of layers,fiber properties, sample thickness, and mass of fibers and the overall composite played a significant role in designing a composite that exhibits optimized stiffness or strength-to-weight ratio.

KEYWORDS

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

1. INTRODUCTION

With the advancements in technology witnessed in recent decades, there has been an increasing demand for versatile and lightweight materials across various industries [1]. This demand stems from the need to meet new requirements and replace traditional metal-based materials, thereby driving the development of novel polymer-matrix composites that offer enhanced performance [2]. High-performance and functional fibers, characterized by their exceptional strength, stiffness, heat resistance, wear resistance, and impact resistance,have played a pivotal role in this regard [3]. The utilization of composite materials has found widespread application in the manufacturing of diverse products, including automotive and aircraft components, structural elements, sports equipment, and biomedical devices, owing to their remarkable structuralproperties [4, 5].

Examples of commonly employed reinforcing materials in composite manufacturing include carbon fibers, aramid fibers, ultra-high molecular weight polyethylene (UHMWPE) fibers, polyphenylene sulfide (PPS) fibers, and polybenzoxazole (PBO) fibers [6-8]. Composite materials typically consist of two or more components that do not dissolve in each other, namely the matrix and the reinforcing phase. While the reinforcing materials primarily contribute to the strength and hardness of the composites, the matrix imparts corrosion resistance, toughness, and ductility [9]. The chemical, physical, and mechanical properties of

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composite materials are greatly influenced by factors such as the shape, type, size, and volume fraction of both the matrix and reinforcing materials [10]. Among the commonly used reinforcing materials with polymer matrices are graphite/carbon, glass, aramid, and boron fibers. Polymer matrix materials are preferred over metal and ceramic matrices due to their low melting temperature, ease of fabrication, low density, and favorable molding properties. Moreover, composite materials offer advantages such as reduced energy consumption in ground, sea, and air transportation vehicles due to their low density, high stiffness-to-weight and strength-to-weight ratios, as well as excellent corrosion resistance. Additionally, they provide effective acoustic and thermal insulation. By minimizing air pollution resulting from exhaust emissions, composite materials contribute to mitigating the adverse environmental impact [11].

Aramid materials have garnered significant interest, primarily due to their exceptional strength and heat resistance. Aramid fibers, known for their high elastic modulus and tensile strength, have gained a substantial market share owing to their affordability when compared to other ultra-high strength fibers [12– 14]. Consequently, these functional aramid fibers have found applications in various sectors, including industrial materials, aircraft development, marine fisheries components, bulletproof and protective shielding, as well as civil construction structures [15].

Recent research efforts have focused on the development of lightweight, high-performance, and cost- effective polymeric composites. One approach involves incorporating reinforcing fibers into the resin matrix, allowing for the enhancement of performance in thermosetting or thermoplastic composites [16]. Numerous studies have been conducted to improve properties such as tensile strength, impact resistance, and flexural strength [17–19].

On the contrary, glass fibers possess remarkable strength, durability, and stiffness characteristics. The reinforcing phase and the matrix both play vital roles in ensuring the strength of a composite material. Typically, the reinforcing component possesses attributes such as low density, high strength, stiffness, and thermal stability [20]. In polymer matrix composites, fibers serve as the primary means of reinforcement. Glass fibers, in particular, exhibit notable technical features combined with their low density. As a result, polymer materials reinforced with glass fibers have demonstrated superior strength-to-weight ratios [21]. Pihtili et al. conducted research on glass fabric and aramid fiber-bonded composite materials [22]. The weight reduction achieved with aramid fiber-reinforced epoxy composites (AFRC) was found to be relatively modest compared to glass fabric-reinforced composites (GFRC) [21].

Various manufacturing processes are commonly employed for epoxy matrix composite materials, including hand lay-up, spraying, and vacuum bagging. The hand lay-up process involves applying resin onto fibers in a mold using brushing or rolling techniques. It is crucial to minimize porosity in this process to ensure the quality and effectiveness of the composite materials. The impregnated fibers are then cured either at ambient temperature and atmospheric pressure or at different pressures and temperatures, depending on the desired thickness. In the vacuum bagging method, resin-impregnated fabrics are stacked to achieve the desired thickness and enclosed within a vacuum bag. Curing occurs under vacuum pressure at the designated temperature [10]. The vacuum bagging method enables the production of high-quality composite products.

In recent times, significant research efforts have been dedicated to examining the impact of the number of layers in composite structures. Reference [23] conducted a study investigating the effect of varying the number of layers on the mechanical response of a multilayer composite plate subjected to axial compression, while keeping the total thickness constant. The findings shed light on how the mechanical behavior changes as the number of layers increases. Moreover, the mechanical properties of woven fiber-reinforced composites can be influenced by the number of layers and fiber distribution, thereby influencing the manufacturing process [24]. The number of layers, along with the properties of the fibers and the thickness of the samples, can affect the volume fraction.

Therefore, this study aimed to investigate the impact of glass and Kevlar fiber volume fractions of specific mechanical properties of epoxy composite. Understanding the impact of fiber volume fractions on mechanical properties is crucial for optimizing the performance of composite materials across various applications.

To generate the specimens, various configurations involving different numbers of layers and total mass of non-impregnated fibers and reinforcing materials were employed. This led to the production of specimens with varying thicknesses and total masses of the composite. The volume fraction of the composite was adjusted based on these parameters. The total fiber mass represents the combined areal weight of the fibers prior to the application of epoxy. Five different cases were considered for the total fiber mass: 1kg, 2kg, 3kg, 4kg, and 5kg with the number of layers determined by the specific material's areal weight. Vacuum bagging was utilized to prepare specimens using fiber glass and Kevlar, with epoxy resin serving as the matrix material. The mechanical properties of the specimens were evaluated through uniaxial tension and three-point bending tests, with a specific focus on stiffness and strength. The findings highlighted the significant influence of the number of layers and material selection on designing composites with optimized stiffness or strength-to-weight ratios.

2. EXPERIMENTAL

Materials Preparation

The composites were prepared by using fiber glass and Kevlar with different areal weight, grams per meter square (gr/m^2). A woven reinforcement with plain weaving at 0 and 90 was 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	Kevlar
Weight (gr/m^2)	200	170
Weave	Plain	Plain
Thickness (mm)	0.16±0.02	0.27±0.02

Table 2 Properties 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 Kevlar and fiber glass with mass per unit area 170 gr/m^2 and 200 gr/m^2, respectively. Five different fiber total masses (FTM) were investigated in this study, FTM for 1kg, 2kg, 3kg, 4kg and 5kg. 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 thefinal samples were produced with different volume fraction. The specimens type abbreviations correspondto the varying fiber mass and the details for the samples are listed in Table 4. The laminating structure of specimens about the number of layers and details about total thickness, weight and volume fraction ofsamples are shown in Figure 1 and 2, respectively.

Table 3 Number of the layers

Number of the layers	Type of Fiber	
	Fiber Glass 200 gr/m^2	Kevlar 170 gr/m^2
Fiber Mass 1kg	5	6
Fiber Mass 2kg	10	12
Fiber Mass 3kg	15	18
Fiber Mass 4kg	20	24
Fiber Mass 5kg	25	30

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

Abbr.	'ype ofFiber	Weight (gr/m^2)	Numberof layers	Mass of Fibers (gr)	Total Thicknessof sample (mm)	Total Weightof sample (gr)	Volume Fraction
1k200f	F. Glass	200	5	1000	0.8	3.6	0.095
2k200f	F. Glass	200	10	2000	1.5	7.7	0.101
3k200f	F. Glass	200	15	3000	2.3	11.9	0.099
4k200f	F. Glass	200	20	4000	3.1	15.1	0.097
5k200f	F. Glass	200	25	5000	4	18.2	0.094
1k170k	Kevlar	170	6	1020	1.5	4.7	0.098
2k170k	Kevlar	170	12	2040	3.1	9.3	0.105
3k170k	Kevlar	170	18	3060	4.9	17.8	0.098
4k170k	Kevlar	170	24	4080	6.8	22.2	0.096
5k170k	Kevlar	170	30	5100	8.8	27.5	0.095

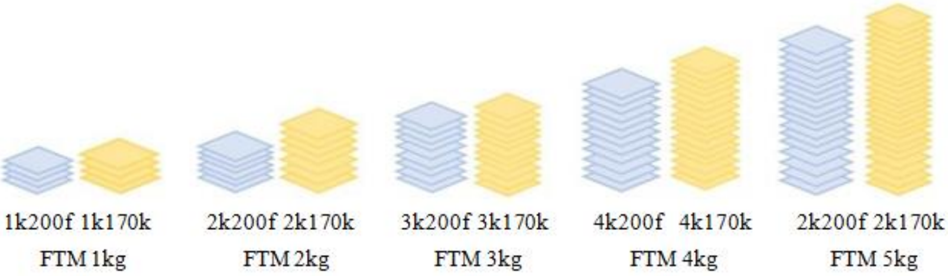

Figure 1. Details of the specimens with varying fiber total mass (FTM) and the laminating structure

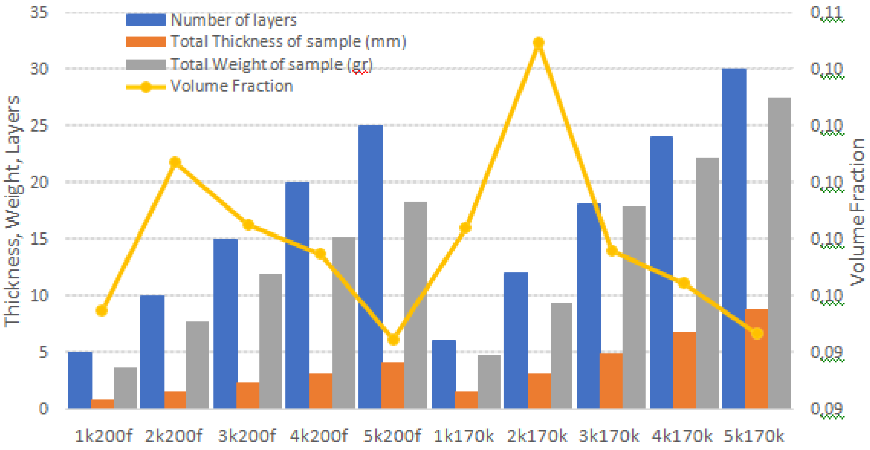

Figure 2. Number of the layers, weight of samples and total thickness in relation to volume fractions

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.

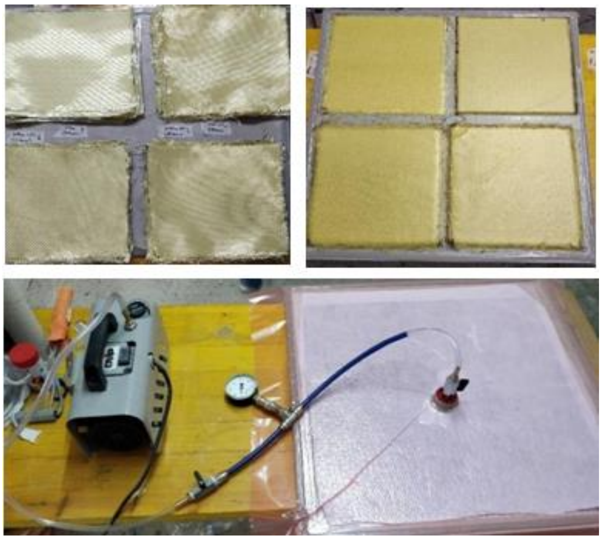

Figure 3. Reinforcing fibers before and after epoxy impregnated, Vacuum bagging method

The specimens were constructed using a hand-layup method involving a vacuum pump, vacuum bagging, spiral tubing, and sealant tape. The spiral tubing ensured a uniform vacuum distribution to prevent epoxy pooling and maintain consistent facesheet thickness. The hand-layup technique produced high-quality specimens with minimal defects [25]. The process involved applying epoxy and fabric layers, ensuring proper epoxy application and spreading. The specimens were covered with vacuum bagging to avoid wrinkles that could affect the surface finish. Trapped air and excess epoxy were removed using a rubber squeegee. The composites were fabricated using the vacuum bagging method for one hour and then cured for two days at room temperature. Additional details can be found in Figure 3.

Specimens and tensile tests

The composite material plate, fabricated using the vacuum bagging technique, underwent machining to create the specimens. Tensile specimens were then cut to the dimensions specified by the ASTM D638 standard [26]. A total of six samples were prepared for each type of specimen. Further information regarding the specimens can be found in Figure 4. The tensile tests were conducted at room temperature, with a cross head speed of 2 mm/min. From the tensile test results, parameters such as ultimate tensile strength, modulus of elasticity, strain, and strain energy were determined.

Figure 4. Tensile specimens of fiber glass and Kevlar, Tensile test

3. RESULTS AND DISCUSSION

Tensile behavior of Kevlar and fiber glass composite

To determine the mechanical properties of the composites, tensile tests were conducted on the fiber glass and Kevlar epoxy matrix composites. Load and displacement 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. Energy absorption and elongation are shown in Figure 5. 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. Energy is proportional to the fiber total mass.

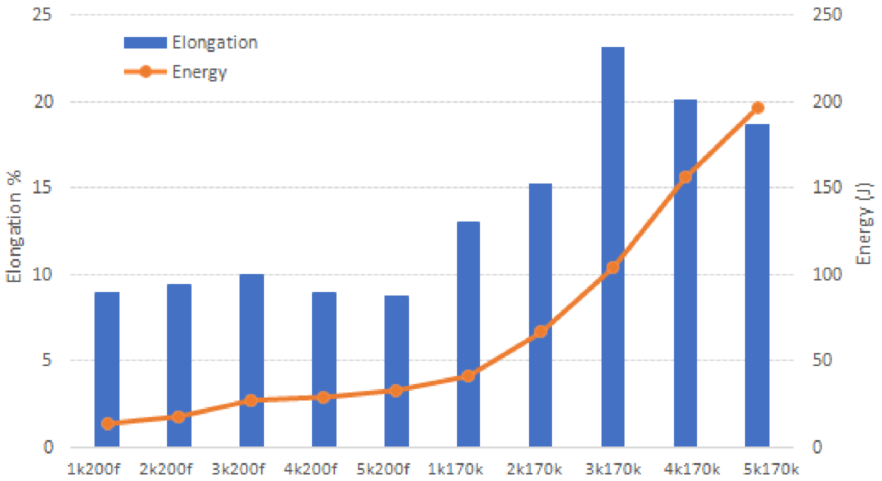

Figure 5. Energy (J) and elongation % with the different type of specimens

Figure 6 shows the elastic modulus with the different fiber total mass of specimens. Fiber glass samples, have smaller total thickness and lower total weight comparing to Kevlar samples. A comparison between the two reinforcing materials showed significant different about stiffness. Samples produced by fiber glass had higher modulus of elasticity comparing to the samples produced by Kevlar, in almost all different FTMs. Solely, the FTM 1kg showed lower value for fiber glass compare to Kevlar. Both materials showed higher stiffness in cases of FTM 2kg and FTM 3kg, while cases of FTM 4kg and FTM 5kg showed slightly lower.

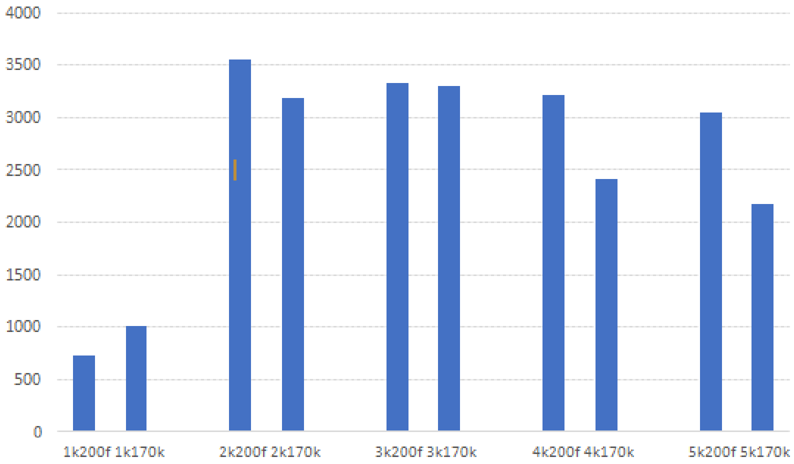

Figure 6. Stiffness of the different fiber mass

The lowest values, which exhibited a significant difference, were obtained by FTM 1kg for both types of reinforcing materials. The highest modulus of elasticity value was observed in the fiber glass samples produced with FTM 2kg, while for the Kevlar samples, it was achieved with FTM 3kg. In addition, for FTM 3kg, the two reinforcing materials exhibited the least disparity in their values.

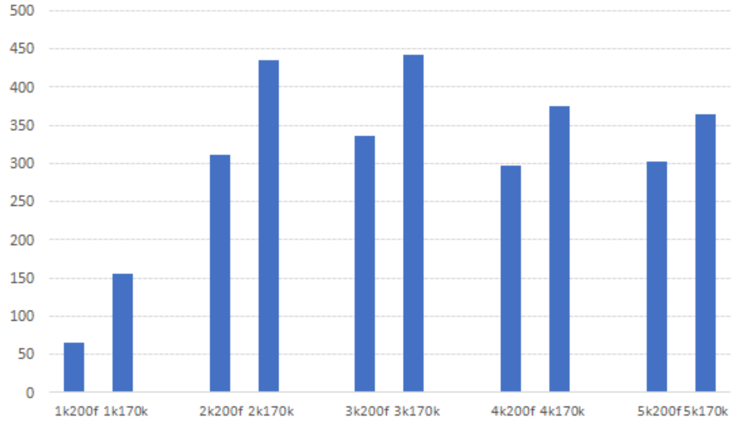

Figure 7. Ultimate tensile strength with the different fiber mass

Figure 7 shows the ultimate tensile strength per fiber total mass. The samples produced by Kevlar showed higher tensile strength in all different fiber masses compare to fiber glass samples. Both materials showed higher strength in cases of FTM 3kg, while cases of FTM 2kg showed slightly lower. Similar with stiffness, FTM 1kg samples showed the lowest values for both materials. 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 have lower ductility but higher elastic modulus, in most of the cases where have been investigated.

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 mm to 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. 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 the depth of samples, respectively. The bending strength of the samples was calculated for the maximum load Fmax at break.

Figure 8 shows the bending and tensile strength with all specimens with varying fiber masses. The bending strength of the samples, fiber glass and Kevlar, was distributed in the range of 290 – 510 MPa, but samples of FTM 1kg were below the 160 MPa. In contrast to the tensile strength, samples produced by fiber glass for the cases of FTM 2kg, FTM 4kg and FTM 5kg showed higher bending strength, compare to corresponding of Kevlar. On the other hand, Kevlar showed higher bending strength for the cases of FTM 1kg and FTM 3kg compare to fiber glass. The highest values for bending strength were obtained by FTM 3kg for both reinforcing materials.

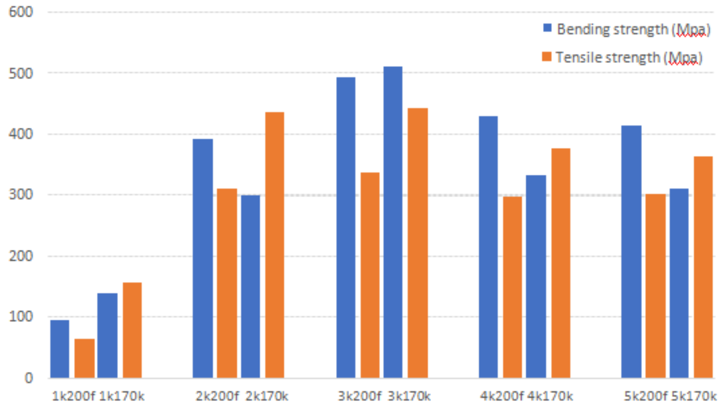

Figure 8. Bending and Tensile strength

Stiffness- and Strength to weight ratio

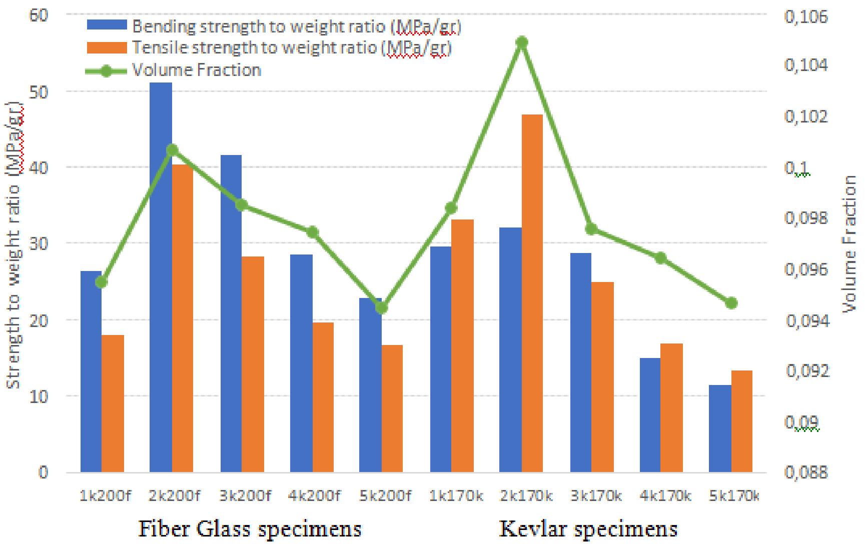

Figure 9. Bending and tensile strength-to-weight ratio in relation of volume fraction

Details for the strength-to-weight ratio and volume fraction are shown in Figure 9. Analysis of tensile and bending test results showed that samples of FMT 2kg reach higher strength-to-weight ratio compared to the other fiber masses, for both materials. The lowest values for strength-to-weight ratio were obtained by FTM5kg for both materials. From the figure it can be observed that strength-to-weight ratio is proportional to the volume fraction. In particular, with decreased fiber volume fraction, the strength-to-weight ratio drops.

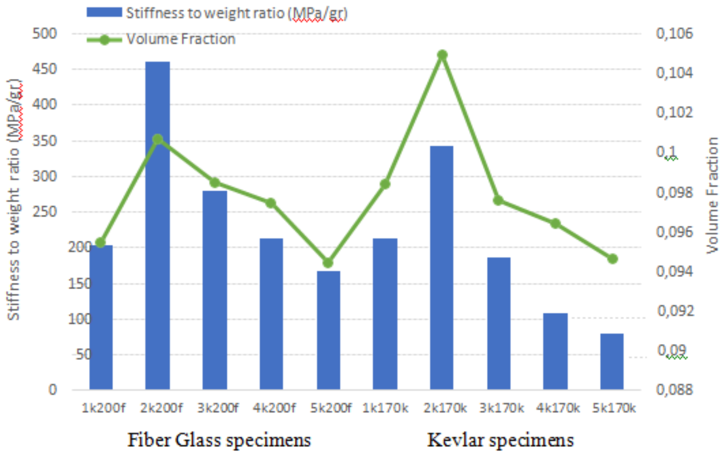

Figure 10. Stiffness-to-weight ratio in relation of volume fraction

Figure 10 shows the stiffness-to-weight ratio in relation of volume fraction. Here, stiffness defines the tensile modulus of elasticity. Samples of FTM 2kg show the highest stiffness-to-weight ratio for each material, while samples of FTM 5kg demonstrate the lowest values. The increase of fiber mass and the associated increase 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 FMT 3kg, 4kg and 5kg and due to this, less epoxy fraction. Samples produced by fiber glass showed higher stiffness-to-weight ratio compared to Kevlar for almost all cases, except FTM 1kg, which the difference between them is insignificant. The highest stiffness-to-weight ratio was obtained by sample 2k200f. Similar with strength, the stiffness-to-weight ratio is proportional to the volume fraction. Additionally, with increased fiber volume fraction, the stiffness-to-weight ratio proves to be higher as expected.

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 of masses of fibers. Five cases of fiber total mass were examined in this research. Fiber masses of 1kg, 2kg, 3kg, 4kg and 5kg. Specimens of fiber glass and Kevlar were prepared and epoxy resin used 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 were produced. The mechanical properties resulting from the varying fiber 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 fiber masses. Fiber glass showed better results of their stiffness with higher modulus of elasticity comparing to Kevlar for the fiber masses 2kg, 3kg, 4kg and 5kg, but not in cases of 1kg. Samples of FTM 2kg proves the highest value of modulus of elasticity for fiber glass, while for Kevlar, it was achieved by 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 has lower ductility but higher elastic modulus. The bending test showed that the samples produced by fiber glass have higher bending strength for the masses of FTM 2kg, FTM 4kg and FTM 5kg, comparing to Kevlar. Highest bending strength is observed by the sample of FTM 3kg produced by Kevlar and the lowest was obtained by sample FTM 1kg produced by fiber glass.

Analysis of strength-to-weight ratio showed that the samples of FTM 2kg have higher values comparing to the other masses, for bending and tensile strength, for both materials. 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 decreased fiber 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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AUTHORS

Elias Louka: He is currently pursuing the Ph.D. degree in School of Mechanical Engineering at Huazhong University of Science and Technology, China. His research direction focuses on the composite materials.

Jianping Xuan earned his Ph.D. degree in Mechanical Engineering from Huazhong University of Science and Technology (HUST) in 1999. After postdoctoral work ended, he joined the Mechanical Engineering faculty, HUST, in 2002. From February 2013 to February 2014, he was a visiting scientist in Department of Mechanical Engineering, Massachusetts Institute of Technology, USA. Currently, he is a Professor with the Department of Mechanical Engineering, HUST. His research interests include Intelligent Manufacturing, Digital Manufacturing for Difficult-to-machine Materials and Structures; Big Data Based Intelligent Maintenance Systems; PHM for Structures, Machinery, CNC systems and Machine Tools. He has published more than 80 journal papers.

Loucas Papadakis: He was awarded with both the Diploma and the Doctor Title in Mechanical Engineering at the Technische Universität München, Germany (TUM) in 2003 and 2008 respectively. He has been with the Frederick University in Cyprus since fall 2008 and currently holds the position of Associate Professor in the Mechanical Engineering Department. His major research interest is the development of simulations chains for supporting the product design, manufacturing and quality prediction of lightweight structures.