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Study the Effect of Reinforcing Kevlar Fibers with Carbon Fibers and Glass Fibers on the Performance of the Athletic Prosthetic Foot

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Abstract

In this research, the mechanical properties were studied from the experimental, theoretical, and numerical aspects of the sports prosthetic foot for the purpose of providing a sporty prosthetic limb with high performance, easy to use and an appropriate financial cost to use by amputees who have lost their lower limbs (amputation below the knee) in practicing their sports activities and overcoming physical disability. The dimensions of the blades were calculated based on side profiles from European patent specifications. The chosen fibers have high strength, are light in weight, and can be purchased for a lower price than the materials that are used in the production of the sports prosthetic feet that are already on the market and are produced by specialized companies such as Ottobock and Ossur. Six laminates of the composite material consisting of matrix orthocryl lamination 80:20 pro reinforced with different fibers (Kevlar fibers, carbon fibers, glass fibers, and perlon fibers) were fabricated in the form of rectangles using the vacuum system and then cut to the required dimensions using a CNC machine. The density and volume fraction of the samples and the use of the rule of mixtures to calculate the mechanical properties of the laminates were calculated and entered into the ANSYS program. Then the boundary conditions were applied to the athlete's prosthetic foot and the total deformation, and the total strain energy was calculated to find out the best laminates in the athlete's foot industry. It was noticed that the laminates reinforced with carbon fibers were better than the laminates reinforced with glass fibers in terms of Young's Modulus, as well as deformation. The best laminate obtained is (12 K + 4 C).

Keywords: Athletic prosthetic, Kevlar, Carbon fiber, Glass fiber, Total deformation, Strain energy.

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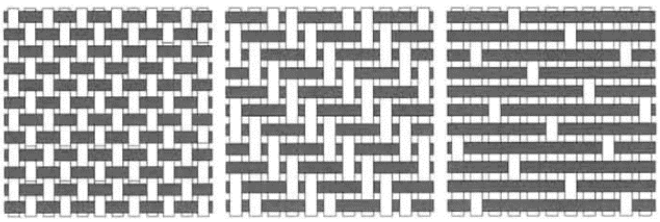
1. Introduction

Nowadays, and not so long ago, composite materials have been widely used in many fields due to the good advantages they provide, such as ease of formation, lightweight and good mechanical specifications, in addition to the availability of fibers in different types, as the fibers are available in the form of particles, Discontinuous, Continuous and Nano each has its uses. Woven fabric is a type of fiber that consists of continuous fibers of two types, the first extending in a longitudinal way and called (warp) and the other in a transverse way that intersects with the longitudinal fibers and is called (weft) and as shown in Fig. 1 [1].



(a) **(b)** **(c)**

Fig. 1 Examples of fabric woven styles: **(a)** plane weave, **(b)** 2 × 2 twill, and **(c)** eight harness satin weaves [1].

The use of composite materials at the present time is widely spread in various fields due to their good mechanical properties, and therefore it requires studying and testing composite materials to determine their specifications and behavior and to choose the best [2]-[4]. Ebrahimnezhad-Khaljiri et al. [5] studied the tensile and flexural behavior of epoxy materials that were reinforced with Kevlar fibers, carbon fibers, and glass fibers to determine the mechanical properties of the hybrid layers and noticed that the type of reinforcement and the number of layers used in the hybridization influenced the results of the tests and the behavior of the composite materials.

The manufacture of artificial limbs is one of the fields in which composite materials have been used, to help amputees to practice their normal lives and participate in various activities, including sports [6]. Where recent scientific developments in the manufacture of artificial limbs have allowed helping people with amputations in their lower limbs to run for long distances, as well as to perform jumps to reasonable heights [7]. The Flex foot is the first prosthetic foot that has a distinctive design and is shaped like the letter *J* that was used in running competitions [8]. Despite the fact that the prosthesis does not comparable to the foot of a healthy person in all characteristics, it must play its role in the process of running or walking, by conducting examinations and tests and taking changes that occur in the boundary conditions during use [9]. Hobara et al. [10] conducted tests on nine volunteers who use the athletic prosthetic foot belonging to special teams in track and field competitions as runners specialized in the

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100 m race and the long jump, and they compared the results they obtained with the performance of the healthy limb. They noticed that running speed affects leg stiffness which depends on the force of the ground reaction, as well as the amount of distortion that occurs during the running process. Hase et al. [11] proposed a mathematical parametric model for mathematical prosthetics based on the force of the ground reaction and its representation in the form of a spring using finite elements to reduce the computational cost. The results of distortion in the process of take-off and long jump were somewhat close to the actual phenomenon. LeMoyne [12] suggested that the transformation in the development of a prosthetic limb lies in increasing its ability to transfer energy during the stance phase of gait, either by making a limb that has sufficient flexibility to absorb energy and return it, or by operating the limb with an energy source. Nielsen [13] noticed that the use of the flexible foot during walking was better than the traditional foot.

Rigney et al. [14] suggested a model that combines empirical analysis and numerical analysis to calculate the stored energy in the athlete's prosthetic foot. He conducted the study on four models used in running sports manufactured by Ossu Company and Ottobock Company, and he worked on repeating the experiments several times. The results indicated that the energy stored in the athlete's foot varies according to the type of foot and the material manufactured for it, as it is inversely proportional to the amount of stiffness and the value of the deformation that occurs during running.

Ismail et al. [15] prepared a study and numerical analysis of three different designs of artificial feet that are used for running (Flex-Sprint Blade, Ottobock 1E90, Ossur Flex-Foot Cheetah). Where they worked on changing the thickness of the athlete's prosthetic foot for the purpose of obtaining a prosthetic athlete's foot (below the knee) at an appropriate cost that allows it to be used by people with disabilities in Indonesia. An epoxy polymer reinforced with carbon fiber was used. Models were drawn using the SolidWorks program and simulations were carried out using the ANSYS program. The results showed that the Ossur Flex-Foot Cheetah design was the best, with a thickness of 10 mm.

The effect of the number of layers on the behavior of the prosthetic foot was also studied by Ouarhim et al. [16], who used two types of glass fibers, the first in the form of a woven and the second in the form of chopped strand mat, in addition to the polyester matrix. the results indicated that the increase in the volume fraction of the fibers inside the laminate with the same thickness increases and improves the mechanical specifications of the composite material. also worked on manufacturing a sports prosthetic foot and conducting experimental tests and numerical analysis using the ANSYS program, and the experimental results were close to the results that appeared in the numerical analysis with a difference of 10%.

The effort is required to study and develop the sports prosthetic foot from the technical and manufacturing side and compare it with theoretical and numerical studies. Therefore, the properties of several layers consisting of a matrix and reinforced with different fibers (Kevlar, carbon, glass fiber, and Perlon) were studied with the application of the boundary conditions during the running process in the ANSYS program.

2. Materials

The materials used in this study are as follows:

1. The woven fabrics made of Aramid 1414 and Kevlar 49 were purchased from Yixing Huaheng High-Performance Fiber Textile Co. Ltd in China.
2. Carbon woven fabrics are the most popular type of composite fiber, and they are available in a wide range of shapes and mechanical characteristics, depending on the manufacturing process used to create them. In addition to being good in mechanical properties, it is expensive compared to other fibers.
3. The most common type of fabric is glass-woven fabric. Great strength, low cost, high chemical resistance, and good thermal insulation properties are just a few of the advantages of using these materials. Reduced elastic modulus, poor adhesion to polymers, abrasion sensitivities (which can affect tensile strength), and limited fatigue strength are just a few of the disadvantages of using this material [17], [18].
4. Perlon woven fabrics stockinet white.
5. Resin orthocryl lamination 80:20 pro.
6. Hardening powder (Ottobock health care 617P37).
7. A polyvinyl alcohol (PVA) (Ottobock health care) is used in two layers, the first was below the woven fabric layers for the purpose of isolating the layers of the fiber from the gypsum mold, as well as to provide a smooth and flat surface for the manufactured laminate, and the second layer of it was added over the laminate to ensure the distribution of the matrix within the layers of the woven fabric.
8. Jepson mold is made of gypsum material in the form of a rectangle with dimension (10 × 35 × 27) cm^3, used for the purpose of pouring fiber layers on it.

And since most companies such as Ottobook and researchers are working on the manufacture of sports prosthetic feet from carbon fiber and the fact that carbon fibers are expensive, we worked in this study on the use of Kevlar fibers because the mechanical specifications are close to carbon fibers and are inexpensive. Table 1 shows the mechanical properties of the materials used.

Table 1. The mechanical properties of materials [30], [31].

Materials	Tensile Strength (MPa)	Young Modulus (GPa)	Density (g/cm^3)	Poisson's Ratio
Kevlar	3600	120.3	1.44	0.35
Carbon	3800	230	1.4	0.2
Glass	3450	72.5	2.48	0.23
Perlon	78	3.43	1.083	0.39
Resin	53.8	2.5	1.19	0.38

3. Experimental work

The fiber was cut to the required dimensions where it must be cut in dimensions so that it can be brushed on the gypsum mold using special scissors and the weight of the fibers was calculated after cutting by a sensitive scale as shown in Fig. 2. The gypsum mold was installed on the vacuum system device and a special (PVA) bag was installed on it to obtain a smooth surface and prevent the adhesion of the fibers and matrix on the gypsum mold. It also helps to smooth the vacuum process and then start arranging the layers of the fiber. Where the first layer of fibers was added and then the matrix is distributed manually using the brush, as is the case with the rest of the layers then a (PVA) bag was placed on the layers of the fiber and tightly tightened with worked two ports, the first from the top is used to pour the matrix and the other from the bottom for the purpose of inserting the tube of the vacuum system device and withdrawing the excess matrix material as shown in Fig. 3. Waiting for 48 hours at room temperature to obtain the required laminates, as shown in Table 2. Thus, laminates with dimensions of (25 × 30) cm were obtained, and then a CNC cutting machine was used to cut the specimens according to the required dimensions.

Table 2. The different types of laminations used in this study's laminated composite specimens.

Composite lamination system	No. of layers	Layer's symbol
Laminate 1	8	6K + 2C
Laminate 2	10	8K + 2C
Laminate 3	16	12K + 4C
Laminate 4	8	6K + 2G
Laminate 5	10	8K + 2G
Laminate 6	16	12K + 4G

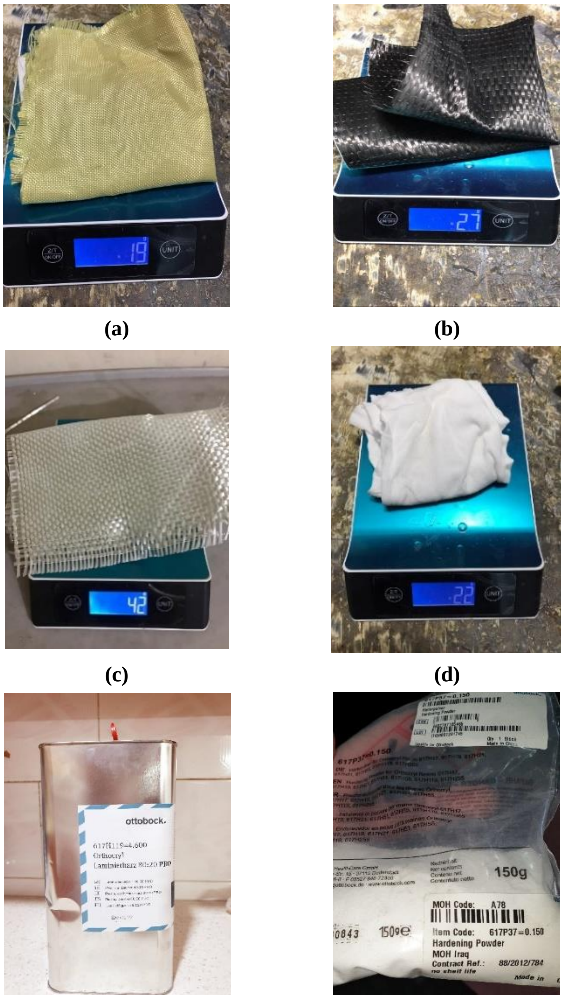

Fig. 2 Materials used in the current study: **(a)** Kevlar woven fabrics, **(b)** Carbon woven fabrics, **(c)** Glass woven fabrics, **(d)** Perlon woven fabrics, **(e)** orthocryl lamination 80:20 pro, and **(f)** Hardening powder.

Fig. 3 Composite laminates manufacturing.

4. Theoretical analysis

The density of the laminate (ρ_c) was calculated according to ASTM Standards (D 792) by using the density tester Radwag PS 360/C1 Precision Lab Balance, Compact Scale 360 g × 0.001 g, 1800 × 0.005 ct as shown in Fig. 4, where the weight of the specimen in the air was calculated, then the weight in the water was calculated, and then used the equation below [19]:

$$SP(\text{gr}) = \frac{a}{a-b} \quad (1)$$

$$\textit{Density of composite, } \rho_C = SP(\text{gr}) \times 997.5 \quad (2)$$

Where: a = apparent mass of the specimen, without wire or sinker, in air, b = apparent mass of specimen (and of sinker, if used) completely immersed and of the wire partially immersed in liquid.

As the density is important in calculating the volume fraction, which is the basis for calculating the mechanical properties of the laminate (Longitudinal).

Young's modulus E_1, Transverse Young's modulus E_2, Major Poisson's ratio ν_{12}, transverse Poisson's ratio ν_{23}, in plane shear modulus G_{12} and out of plane elastic properties E_3, G_{13}, ν_{13}) using the rule of mixtures, as follows [20]:

$$w_c = w_f + w_m \quad (3)$$

$$W_{f,m} = \frac{\omega_{f,m}}{\omega_c} \quad (4)$$

$$V_m = W_m \frac{\rho_C}{\rho_m} \quad (5)$$

Where $\omega_{f,m}$ the weights of the fiber and matrix, respectively (kg), W_f, W_m, and W_C are the weights fraction of the fiber, matrix, and composite, respectively, and V_f, V_m, and V_C are the volume fraction of the fiber, matrix, and composite, respectively.

The mechanical specifications of the composite material manufactured from woven were calculated according to their respective equations, and there is a difference in the mechanical specifications of the layers manufactured from the unidirectional fibers [21]:

$$E_3^{UD} = E_2^{UD}, \qquad G_{13}^{UD} = G_{12}^{UD}, \qquad v_{13}^{UD} = v_{12}^{UD}$$

$$E_1^{WF} = E_2^{WF}, \qquad G_{13}^{WF} = G_{23}^{WF}, \qquad v_{13}^{WF} = v_{23}^{WF}$$

Fig. 4 the density tester.

5. Numerical model

Numerical simulation is one of the best techniques to obtain results that are close to reality and help shorten time and cost, and nowadays it is widely used [5]. In this research, simulation of composite materials using the ANSYS ACP Workbench 19 program was used. The mechanical specifications of the manufactured laminates obtained on the theoretical side were entered in engineering data and then the prosthesis model was drawn in geometry by taking the lateral dimensions of a European patent model Fig. 5 [23].

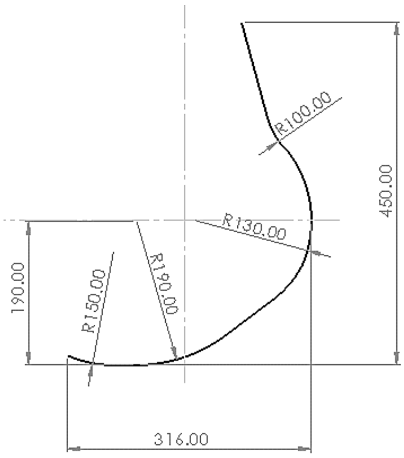

Fig. 5 Athlete's artificial foot.

To apply finite element analysis, the object to be simulated is divided by making a mesh for it, and the smaller the divisions, the better the results. Where the artificial sports foot was divided into (7185) nodes and (6915) elements as shown in Fig. 6.

The force of the ground reaction resulting from the running of the person wearing the foot is approximately 2.29 - 2.26 times of body weight and a person weighing 67.9 kg running at a speed of 3 m/s was chosen [24]. Therefore, a force of 1554.91 N will act on the prosthetic foot from the bottom and it will be fixed through two holes located at the top as shown in Fig. 7.

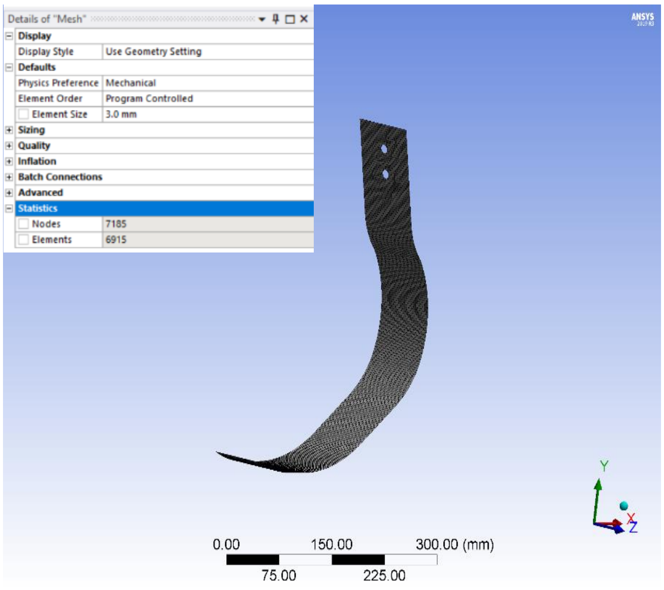

Fig. 6 Mesh Athlete's artificial foot.

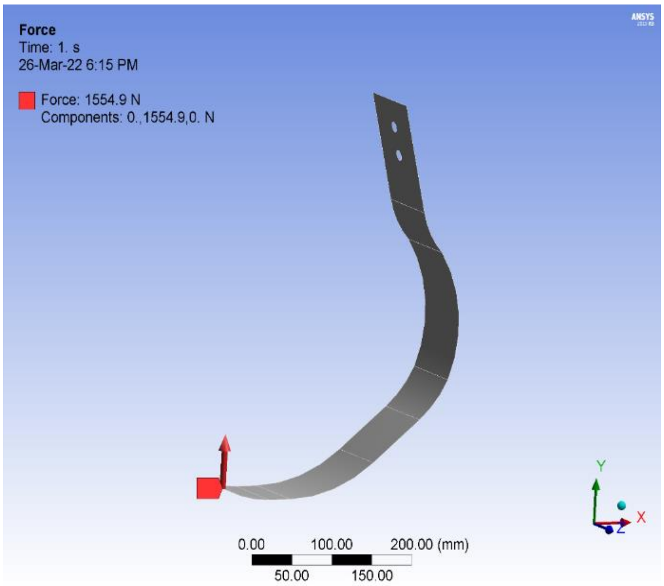

Fig. 7 Apply boundary conditions.

6. Results and Discussion

Figure 8 shows the volume fraction values of the laminates consisting of the resin orthocryl lamination 80:20 pro, Kevlar fibers, carbon fibers, and glass fibers. Where the results showed that the value of the volume fraction increases, albeit slightly, by increasing the number of layers of Kevlar fibers, and also that the increase was clear between the laminates that contain carbon fibers and the laminates that contain glass fibers. This is due to the nature of the fibers and their ability to absorb the matrix material, as well as the manufacturing method [25].

Figure 9 shows the theoretical values of the Young's Modulus, and it is shown that the laminates increase the values of Young's Modulus by increasing the number of layers of Kevlar fibers. In general, the laminates that contain layers of carbon fibers were higher than the laminates that contain glass fibers. The reason for these different results is due to the volume fraction of the fibers inside the laminates as well as the type of reinforced fibers. The increase in the volume fraction of the fibers increases and improves the mechanical properties of the laminates because the fibers have higher mechanical properties than the mechanical properties of the matrix [26], [27] as for the type of reinforcing material used, carbon fibers have higher mechanical specifications than glass fibers, thus raising the modulus for the laminates that make up them.

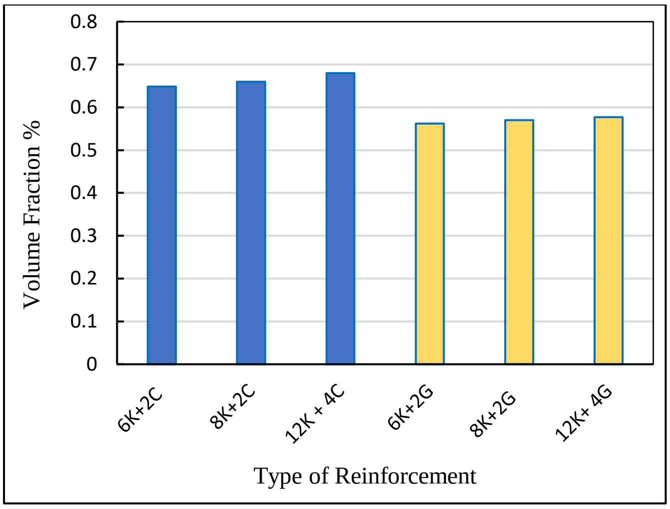

Fig. 8 Variation of volume fraction of different types of reinforcing material.

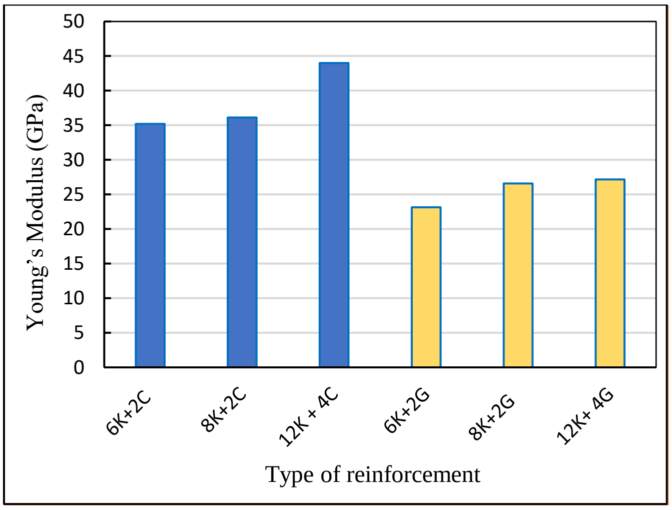

Fig. 9 Effect of different types of reinforcing on Young's Modulus.

Figure 10 shows the amount of deformation of the prosthetic foot for the different laminates, and it is shown that the deformation value decreases with the increase in the number of layers, and the deformation in the laminates that contain layers of carbon fibers is less than the deformation found in the laminates that contain layers of glass fibers when comparing laminates that consist of the same number of layers. The reason for the decrease in the value of the deformation is due to the increase in the number of layers because the increase leads to an increase in the Young's Modulus and the deformation value is inversely proportional to the value of the deformation as shown in table 3 as well as the type of reinforced material is evidence of the value of the deformation because carbon fibers have the ability to withstand external load is higher than glass fibers because they have It has good mechanical specifications. The Laminate 3 was the best in terms of the value of the deformation because the manufacturers suggest that the amount of distortion should be between 1 to 2 inches [28].

Table 3. Comparison of Young's Modulus and deformation of athletic prosthetics foot for different types of composite materials.

Composite lamination system	Young modulus (GPa)	Total deformation (mm)
Laminate 1	35.182	169.82
Laminate 2	36.135	107.02
Laminate 3	44.005	58.992
Laminate 4	23.14	240.27
Laminate 5	26.587	150.58
Laminate 6	27.168	90.508

Figure 11 shows the total strain energy, where it was noticed that the strain energy value decreases with the increase in the hardness of the sports prosthesis, as the laminates containing carbon fibers had less energy than the laminates containing layers of glass fibers and it was positively proportional to the deformation. The lower the deformation, the lower the value of the strain energy, and this corresponds to the law of strain energy [29].

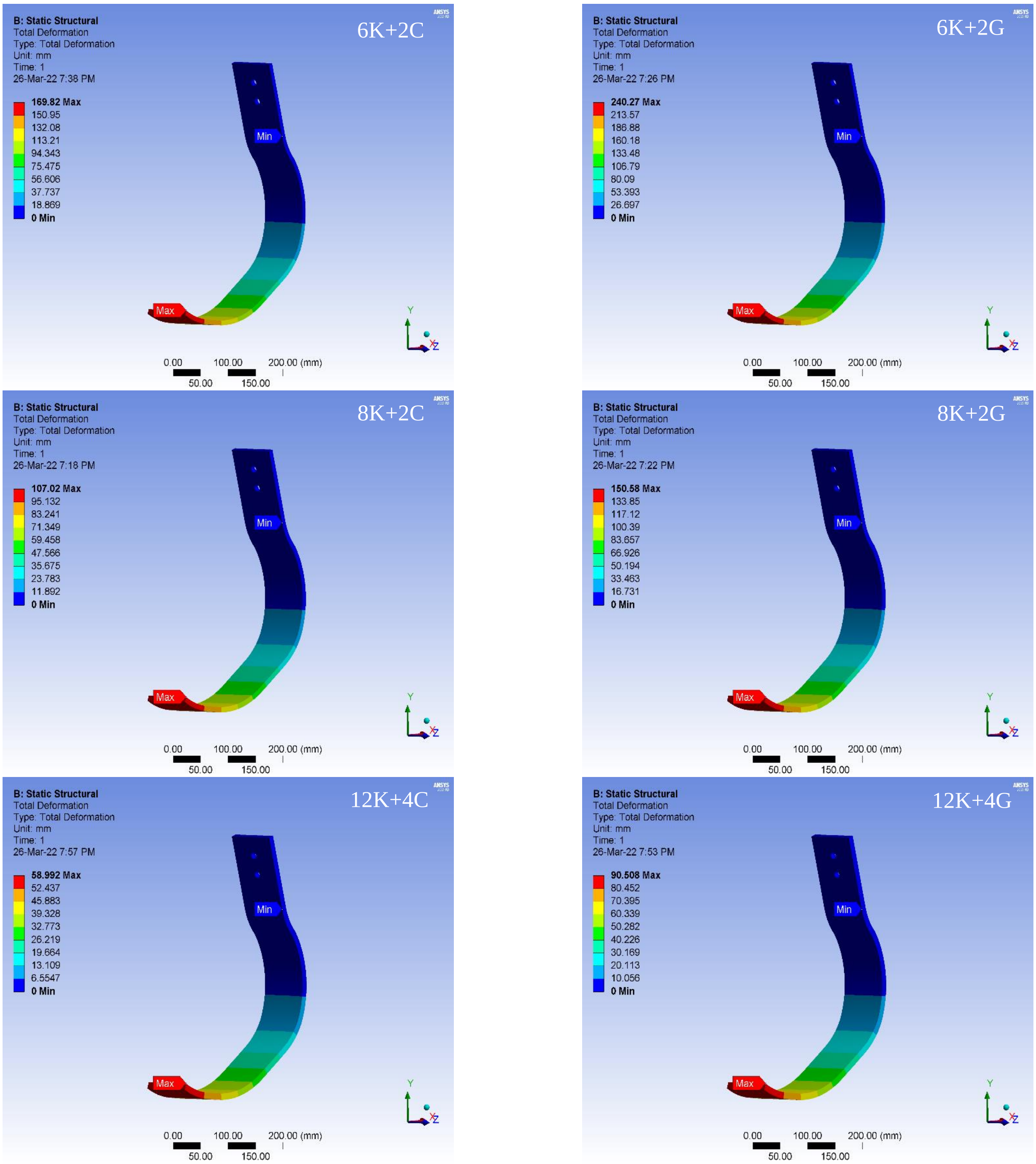

Fig. 10 Effect of different types of reinforcing on total deformation.

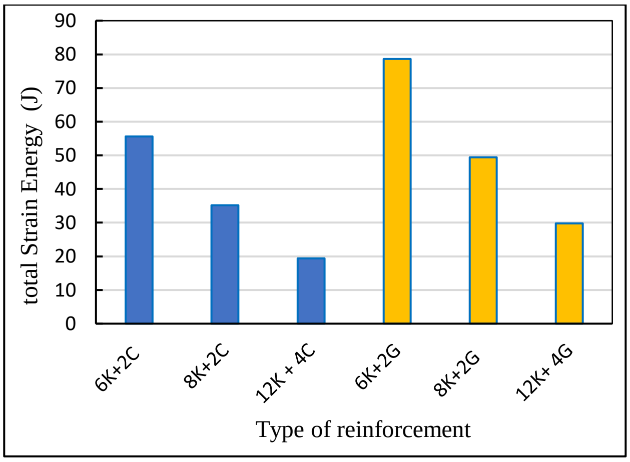

Fig. 11 Effect of different types of reinforcing on Total Strain Energy.

7. Conclusions

The mechanical properties of six laminates the composite material manufactured from different fibers (Kevlar fibers, carbon fibers, glass fibers, and perlon fibers), and the matrix (Resin orthocryl lamination 80:20 pro) were studied and used in the ANSYS program for purpose of conducting basic tests and calculations. A prosthetic foot in the shape of the letter *J* and the selection of the appropriate laminate in the manufacture of the prosthesis. It has been observed that the following:

1. The increase in the volume fraction of fiber leads to an increase in the mechanical properties of the laminate, as it appeared that the value of the modulus is positively proportional to the value of the volume fraction of the fibers.

2. The value of the deformation in the sports prosthetic foot depends mainly on the strength of the composite material it is manufactured for. The higher the strength, the lower the deformation value, and the stronger laminate 3 and in which the value of deformation was less than the rest of the layers.
3. The value of the total strain energy of the sports prosthetic foot is directly proportional to the value of the deformation, as laminate 3 was the least value in the amount of deformation, and it is also the least in the value of the total strain energy.

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