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DEVELOPING FUNCTIONAL COMPOSITE MATERIALS AND TOPOLOGY OPTIMIZATION FOR STRUCTURAL APPLICATION OF CLIMBING ROBOTS

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ABSTRACT

Weight reduction is a major key to energy conservation. To achieve this goal, a composite material has been designed and topology optimization has been done to estimate the optimal topology of the climbing robot maintaining the minimum weight. Epoxy matrix containing carbon nanofibers with contents of 0, 0.2, 0.4, 0.6 and 0.8 wt. % (EPC0, EPC0.2, EPC0.4, EPC0.6, EPC 0.6, and EPC0.8) have been firstly fabricated and mechanically tested. Epoxy-glass fibers composites with different layers numbers have been fabricated using lay-up technique as the second group of materials and tested. Epoxy-carbon fiber composite material (2-layers) has been fabricated and tested. The results revealed that epoxy-carbon fiber composite showed the best mechanical performance and the lowest weight concurrently. The results proved that using epoxy-carbon fiber composite as a structural material for the climbing robot could decrease the weight by 42.3% when compared with the aluminum frame. Topology optimization technique could offer an additional weight reduction of the robot frame by 29.3%.

KEYWORDS

Composite materials, carbon nano-fibers, carbon fibers, glass fibers, topology optimization, polymers.

INTRODUCTION

The fast progress of the recent application requires a new generation of materials that could fulfill these requirements. Composite materials have been proposed as promising candidates to overcome many problems related to the weight, strength, corrosion resistance, etc. Polymer matrix is commonly used for lightweight structures, in addition to the vibration damping characteristics. Moreover, polymeric composites have been chosen as an efficient alternatives due to the low fabrication costs, [1]. Epoxy/carbon fibers composite has been used for structural elements owing to the distinction mechanical properties and preserving lower weight to volume ratio at the same time, [2-4]. Epoxy has been selected as a polymeric matrix for many structural elements [spindles, bearing races, enclosures, etc.] by many researchers in the last few years due to the its thermal and the environmental stability, relative high strength and relative wear resistance, [5]. Carbon fibers has been selected as a reinforcement material due to the distinction mechanical properties, [2, 6-8].

The weight and the costs of the mechanical components affects dramatically on the performance of those elements. Moreover, preserving the energy is a persistent need. Topology optimization is considered as an effective approach used for further decreasing for the weight and costs maintaining the performance of the structural element concurrently, [9-12].

It is well known that the weight is a critical requirement for the climbing robot's frames. So that, the recent study shows a successful approach to develop a new approach using polymer-based composites and topology optimization - compared to aluminum frames - to enhance the performance of climbing robots.

EXPERIMENTAL

Three composite materials have been suggested as possible alternatives for the aluminum as mentioned below:

a. Carbon nano-fibers composites.
b. Glass Fiber + Epoxy.
c. Carbon Fiber + Epoxy.

Epoxy-Carbon Nano-fiber composite

Epoxy resin [Solvent free, non-pigmented liquid] [supplied by CMB international (Egypt)] and carbon nano-fibers (CNFs) [average length of 10- 25 µm, average diameter of 200-400 nm, and > 90% p`urity was supplied by XFNANO, INC., China] were mixed mechanically at mixing speed of 150 RPM for 30 min. The epoxy and CNFs mixture were left in a vacuum environment for 24 hrs. to get rid of the air bubbles. After that, the hardener was added to epoxy CNFs mixture with a volume percentage of 1:2. CNFs-epoxy and hardener mixture were mixed mechanically at 100 RPM for 3 min, in a water bath according to the material data sheet. The samples were left for 24 hrs. in a vacuum oven at temperature of 35 °C. The samples were prepared with CNFs contents of 0 wt.%, 0.2 wt.%, 0.4 wt.%, 0.6 wt.%, and 0.8 wt.% which are referred as EPC0, EPC0.2, EPC0.4, EPC0.6, and EPC0.8 respectively.

Epoxy- Glass fiber composite

Two patterns of [woven glass fiber, and random glass fiber] glass fibers reinforcements have been used as shown in Fig. 1.

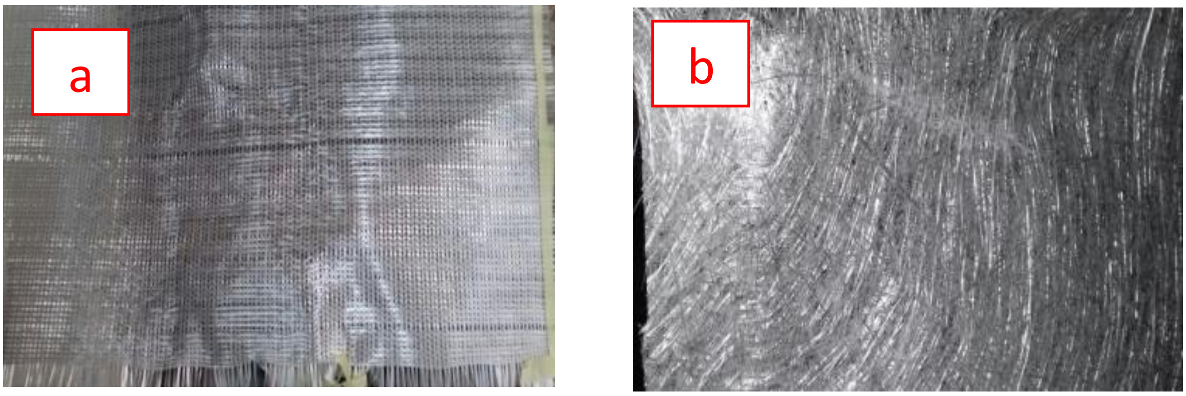


Fig. 1 Glass fibers; (a) woven glass fibers, (b) random glass fibers.

Nano-Carbon fiber composite

Carbon 3K twill weave has been used as reinforcement material for epoxy-based composites. The carbon fibers are shown in Fig. 2.

Fig. 2 Carbon 3K twill weave.

The frame fabrication

The steps of robot's frame fabrication is based on lay-up technique and it could be summarized as follow:

a) **Preparing the die, as shown in Fig. 3(a).**
b) **Cutting the fiber sheet into desired size and insert it inside the die**
c) **Mixing epoxy with hardener with ratio 2:1, Fig. 3(b)**

Fig. 3 (a) Preparing the die, (b) Mixing epoxy with hardener.

Fig. 4 Epoxy and fiber inside the die.

d) **Pouring the mix inside the die**
e) **Insert another layer of fiber in the die then repeating step (4), Fig. 4.**

The same fabrication technique has been used for both of epoxy-glass fiber and epoxy-carbon fibers composites.

RESULTS AND DISCUSSION

Tension test results

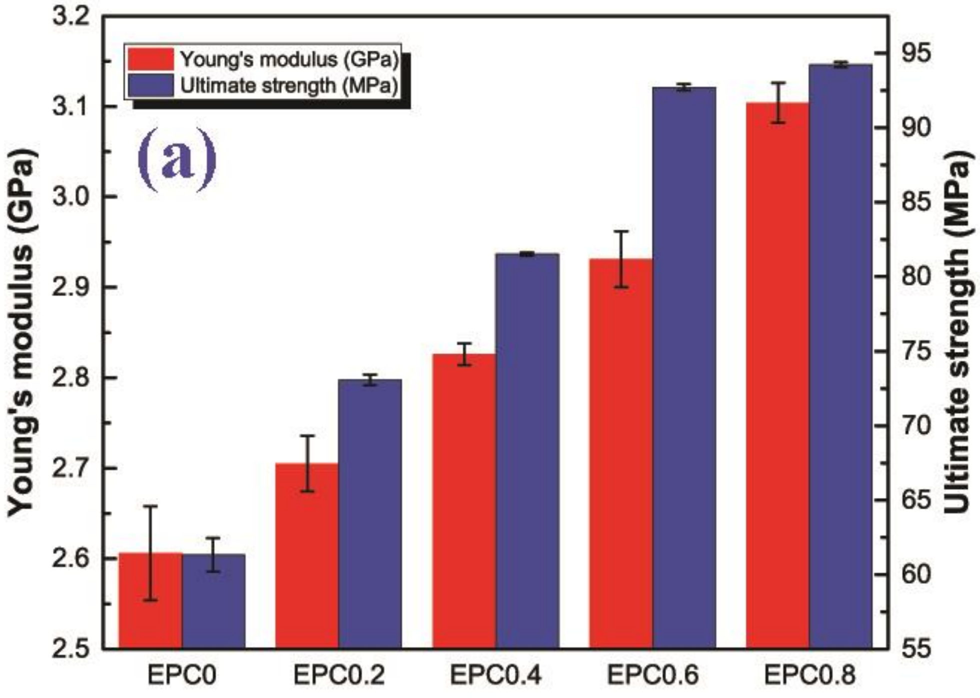
Tension tests have been performed to estimate the mechanical properties of epoxy-CNFs, epoxy-glass fibers, and epoxy-carbon fibers composites as shown in Fig. 5.

Fig. 5 Tension test of the different types of composites.

However, the existence of CNFs could enhance the strength of the epoxy composites sharply. Furthermore, Young's modulus recorded the same behavior as the ultimate strength as shown in Fig. 6(a). Using glass fibers as reinforcement phase showed higher strength than using CNFs. Besides, increasing the number of layers has a beneficial effect in the strength of epoxy composites. It is noticed that raising the numbers of layers led directly to an increase in the weight. Epoxy-carbon fibers composite recorded the highest strength, and highest modulus of elasticity among all composites, preserving the lowest weight as well. Based on the experimental results, it is concluded that epoxy-carbon fiber composite is the most suitable material to be used for achieving our goal of reducing the weight by 42.3 % if compared to the aluminum frame and enhancing the structural performance at the same time.

Stresses analysis and topology optimization of the robot frame

The topology optimization is used to decrease the weight of the robot. Finite element software package (ANSYS) is used to estimate the stresses acting on the robots. Furthermore, the topology optimization using ANSYS is performed to obtain the optimum structure of the climbing robot. The initial base of the robot is a square plate with dimensions of (280 × 280 mm) as shown in Fig. 7.



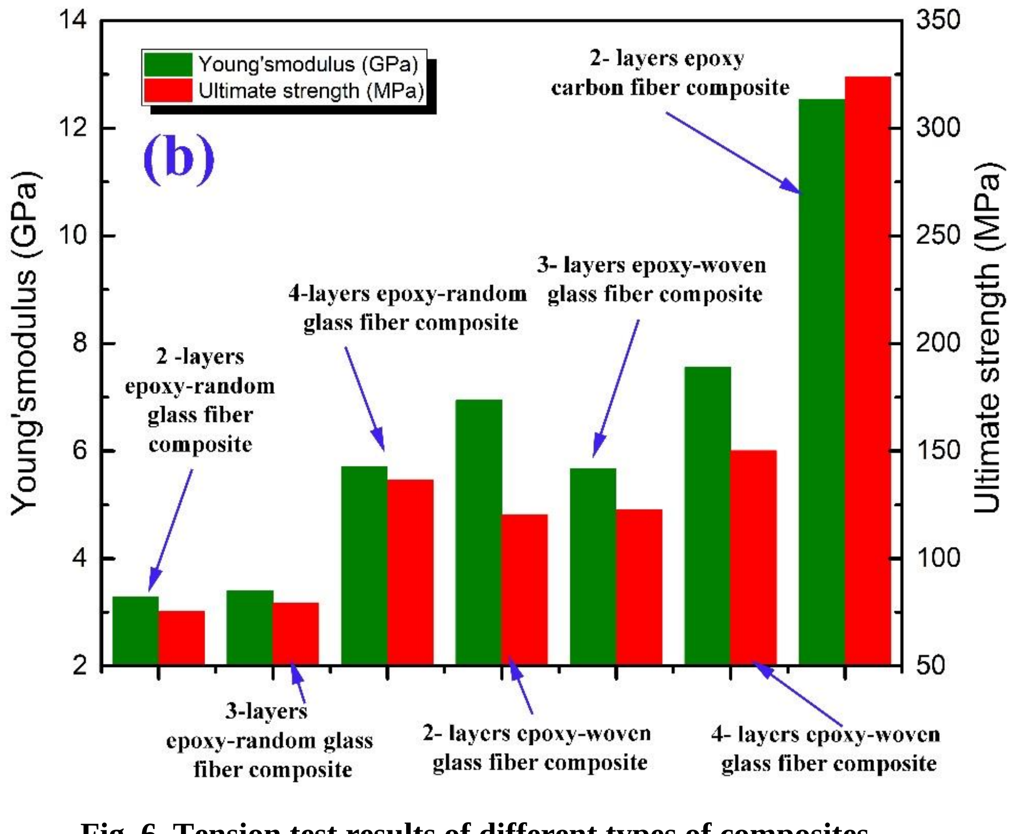


Fig. 6. Tension test results of different types of composites

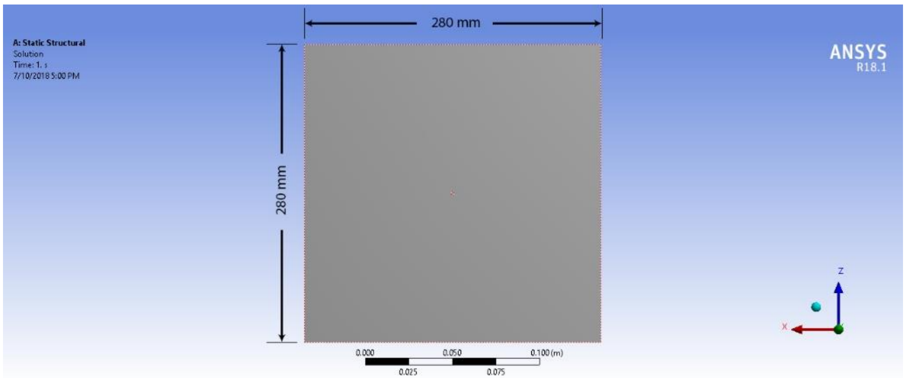


Fig. 7 Square composite material plate with dimensions of (280 × 280 mm).

The thrust force per single propeller is calculated as 900 gm. The boundary conditions are applied as shown in Fig. 8. The thrust force is acting on the middle of the plate, while, the plate is fixed from the four corners as shown in Fig. 14. After applying the boundary conditions, the plate model is meshed using tetrahedral element to ensure accurate results as shown in Fig. 8.

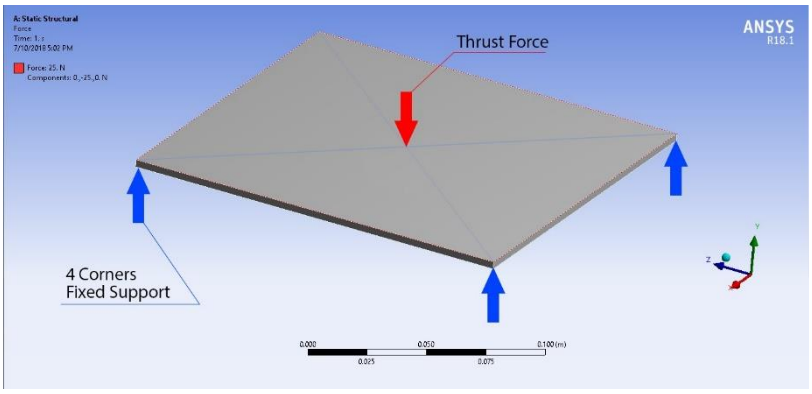


Fig. 8 The boundary conditions are applied.

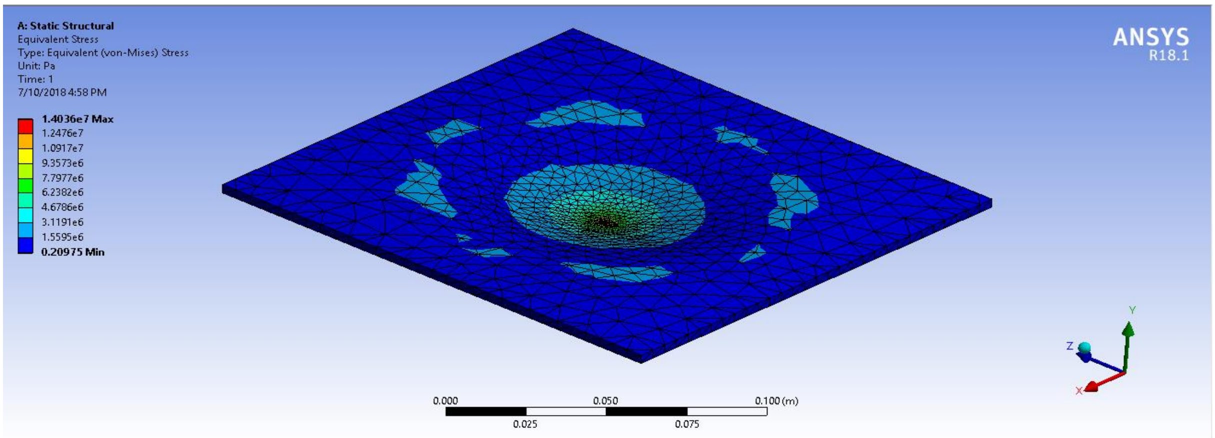


Fig. 9 The stresses distribution is obtained through the static analysis.

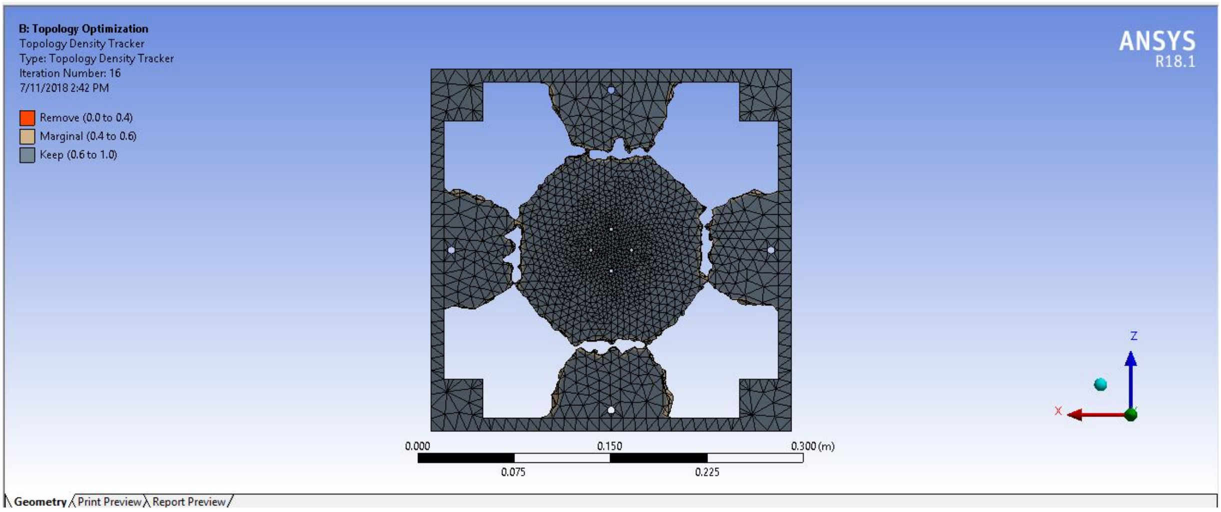


Fig. 10 Mass topology optimization process is initiated on ANSYS software.

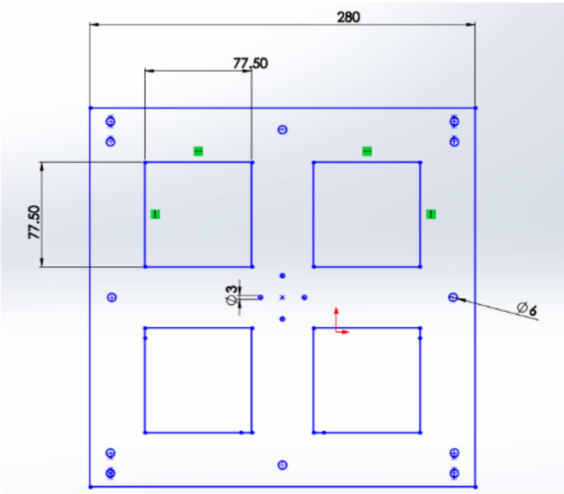


Fig. 11 The final shape of the robot frame after the topology optimization.

The stress distribution is obtained through the static analysis based on the boundary conditions that are acting on the plate. Fig. 9 shows the stresses distribution on the plate resulting from the thrust forces. It is clear that the stresses are concentrated on the center of the plate. Based on the previous results, a mass topology optimization process is initiated on ANSYS software. The results are shown in Fig. 10. According to the results of the topology optimization a new design is being developed for the robot body which is shown in Fig. 11. The final shape of the frame (epoxy-carbon fiber composite) has been tested and showed superior performance as a structural material. Furthermore, the weight has been reduced by 29.3% after the topology optimization.

CONCLUSIONS

The recent study aims to reduce the weight of the climbing robots through developing an efficient composite material and using the topology optimization to estimate the optimal geometry of the robot frame. Polymer based composite material has been suggested as a promising candidate with the limitation of the strength. Thus, it becomes necessary to

choose a proper reinforcement material to enhance the mechanical properties of epoxy composites. Epoxy - carbon nano fibers with content percentages of 0, 0.2, 0.4, 0.6, and 0.8 wt.% [EPC0, EPC0.2, EPC0.44, EPC0.6, and EPC0.8] have been fabricated and tested. Additional group of epoxy glass fibers with 2, 3, 4 layers have been fabricated as well. The results revealed that epoxy-carbon fiber composites [2-layers] showed the best structural performance and could decrease the weight of the robot frame by 42.3% when compared with the aluminum frame preserving enough strength and stiffness to withstand the acting stresses concurrently. For further saving the costs and lowering the weight, a topology optimization has been applied to the new frame that led to a total weight reduction of 71.6 % in the comparison of aluminum frames.

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