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Design and Manufacturing of New Low (Weight and Cost) 3D Printed Pylon Prosthesis for Amputee

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Abstract. The standard traditional prosthetic pylon is manufactured from stainless steel, titanium, Aluminium alloys due to their lightweights. Despite the low weight of pylon made of these alloys, the pylon is characterized by its high costs. In this study, a new prosthetic pylon is designed and manufactured from PLA carbon fiber material to produce a pylon characteristic with a lighter weight and cheaper than the standard pylon with its ability to bear the patient's weight without any mechanical failure. The mechanical properties (yield stress, ultimate stress, and endurance stress) of the PLA carbon fiber filament were measured. The finite element method analysis of the pylon was done by using the ANSYS-14.5 program. The experimental and numerical results showed that the weight of the new prosthetic pylon is less than the weights of Stainless steel, Titanium, and Aluminium pylon by 60%,42%, and 50%, respectively, and the cost of the new prosthetic pylon is cheaper than the Stainless steel, Titanium, and Aluminium pylon by 97.5%,98%, and 96%, respectively. The mechanical properties of printed pylon material are the modulus of elasticity equal to 1.38GPa, the yield stress is 33.5MPa, the ultimate stress is 49.14 MPa, and the endurance stress is 19.16 MPa.The results also showed that the pylon's buckling stress is higher than the yield stress and von mises stress is less than the yield stress; this proves the successful design of the pylon. The new design is cheaper, lighter, and can withstand higher patient weights.
Keywords. 3D Printed, Prosthesis, PLA carbon fiber.

1. Introduction

Amputation is the complete or partial surgical removal of a biological extremity or limb[1]. The prostheses are generally used to replace missed parts due to illness, injury (trauma), or missing since birth (congenital). etc [2]. The lower limb prosthetic parts are the leg section, the socket, and the foot [3]. This study deals specifically with the design and manufacturing of a pylon. Several studies are dealing with the study of pylon specifically. Muhsin J.Jweeg et al. worked on three prosthetic pylon types; the three types are designed and produced from different composite material layers (6 layers, 9 layers, and 12 layers) [4]. Jawad Kadhim Oleiwi studied PMMA tensile and buckling jute fibers reinforced for prosthetic pylon reinforced [5]. Ian Brown and Ross Stewart investigated the problem using FEM analysis, a crack growth analysis used to build a model of the pylon's expected life [6]. Prasanna developed a new socket and adjustable pylon prosthetic design that has lightweight (especially for children), easy to manufacture, and low cost (in countries with low socioeconomic status) [7]. In standardized loading conditions, Glenn K. Klute et al. studied the mechanical properties of VSAP vertical shock-absorbing pylons to evaluate the effect of VSAP on amputee gait [8]. The flexural strength of two pylons, composite pylons containing a solid titanium core with drilled holes surrounded by a porous sintered titanium shell and pylons composed of porous titanium alone, were studied by M. Pitkin. The results showed that composite pylons' flexural strength and stiffness are greater than that of pylons made of porous titanium alone [9]. While in this study, a new pylon design made of carbon fiber was manufactured using a 3D printer device. The pylon's new model is lightweight, strong, and low cost, not exceeding three dollars. The investigation and development of a prosthetic taking multi-stages, firstly development for mechanical properties of materials used to manufacture the prosthetic by using different reinforcement fiber and powder in addition to nanomaterials, and other analysis for the mechanical properties and behavior of various prosthetic part structure with different parameters, such as foot, knee, socket, finger, hand, and other parts [10-30]. Therefore, in this work, a new prosthetic pylon is designed and manufactured from PLA carbon fiber material to produce a pylon characteristic with a lighter weight and cheaper than the standard pylon with its ability to bear the weight of the patient without any mechanical failure.

2. Experimental work

2.1. Material used
The material used in manufacturing the new pylon is PLA carbon fiber filament, as shown in Figure 1. This material was chosen because it is lightweight and has suitable mechanical properties for this application. The PLA carbon fiber filament is stronger, sturdier, and more dimensionally stable. The carbon fibers printed products have excellent surface quality. PLA carbon fibers filament is perfect for printing thin, hollow models or models with rigid texture.

Figure 1. The PLA carbon fiber filament.

2.2. Design and manufacturing the pylon prosthetic
The pylon is designed as shown in Figure 2, as it differs from the traditional design by the presence of a regular polygon within the pylon's diameter, which gives the pylon sufficient durability to prevent the occurrence of mechanical failure. The pylon's outer diameter is equal to 30 mm, to be suitable with all types of adapter to connect with other parts of the prosthesis. The pylon length is 300 mm to be suitable for all leg lengths for patients, provided that the extra length is cut if the patient’s length is short. After designing and drawing the pylon with the Solidwork engineering drawing program, the pylon is printed using a 3D printer machine. This technique was used for several reasons, including obtaining an accurate dimensional product despite its complex internal shape, high quality, low manufacturing cost, and a more straightforward manufacturing method than other followed techniques in manufacturing the pylons. The final model of the pylon can be seen in Figure 3.

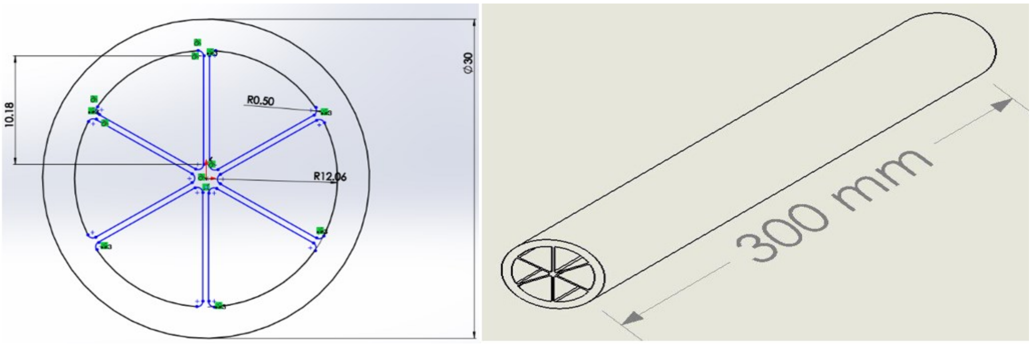

Figure 2. The model designed for the pylon.

Figure 3. The model of the pylon after manufacturing.

2.3. Tensile test

The tensile samples of PLA carbon fiber are drawn according to ASTM-D638-V dimensions [31] with a 3 mm thickness, as shown in Figure 4. Three samples of the PLA carbon fiber printed by the 3D printer devise for testing using the Testometric [32-37].

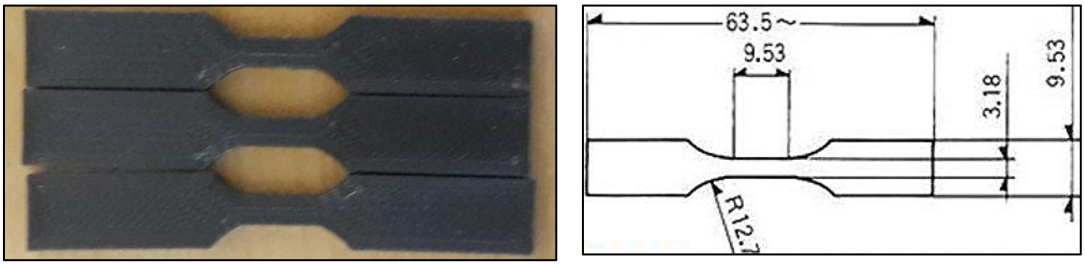

Figure 4. The dimension of the printed three carbon-fiber samples.

2.4. Fatigue test

The sample was drawn by Solidwork according to the fatigue device test dimension and printed by the 3D printer devise to six samples for testing by the fatigue machine (HI-TEICH), as shown in Figure 5 [38]. The fatigue specimen's length is 100mm, and its width is 10 mm, as shown in Figure 6.

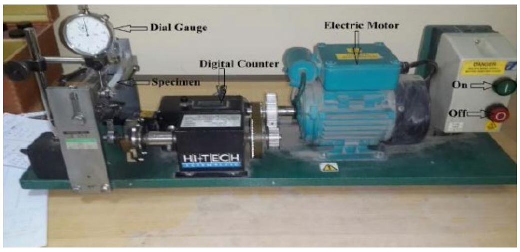

Figure 5. Fatigue tester devise (HI-TEICH).

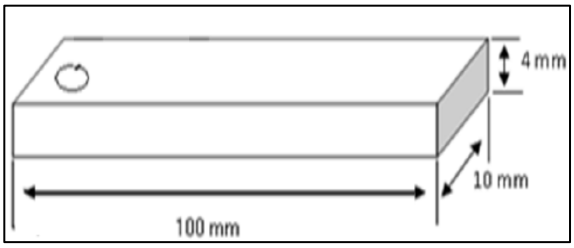

Figure 6. The dimensions of the printed samples of carbon fiber for fatigue testing.

2.5. Finite element analysis and boundary condition

For analysis, the geometry of the pylon model must be built first, then applying the boundary conditions load and obtaining the solution, finally reviewing the results [39-45]. The boundary condition must be applied to the pylon model to analyze it and evaluate buckling stress, buckling mode shape, critical load, Von Miss Stress, deformation, and fatigue safety factor [46-50]. The boundary condition includes (fix the upper region of the pylon with applying the patient's weight at the same end and fixing support at the lower end of the pylon, as shown in Figure 7. The mechanical properties of PLA carbon fiber filament parameters are used in the ANSYS data for completing the total results of this model.

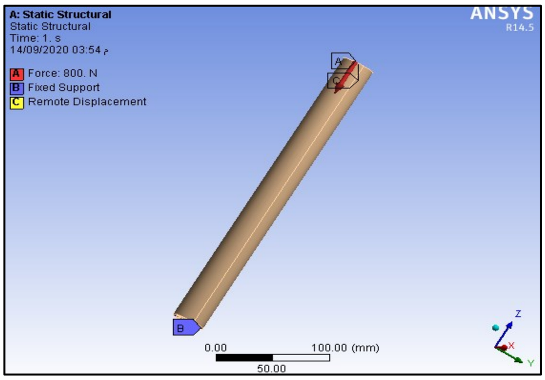

Figure 7. The applied boundary condition to the pylon model.

2.6. Result and discussions

The tensile test results of the three-carbon fiber filament samples showed that the mechanical properties are σ_{yeild}= 33.5MPa , σ_{Ultim}= 49.14MPa , E= 1.38GPa, and the stress-strain curve can be seen in Figure (8). The fatigue test result shows the relationship between the stress and the number of the carbon fiber filament cycle, as shown in Figure 9. The stress endurance for the carbon fiber equal to 19.16 MPa.

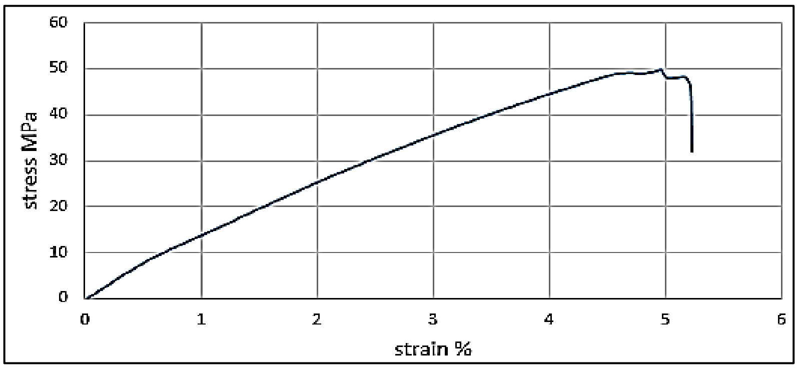

Figure 8. The stress-strain curve of the PLA carbon fiber filament.

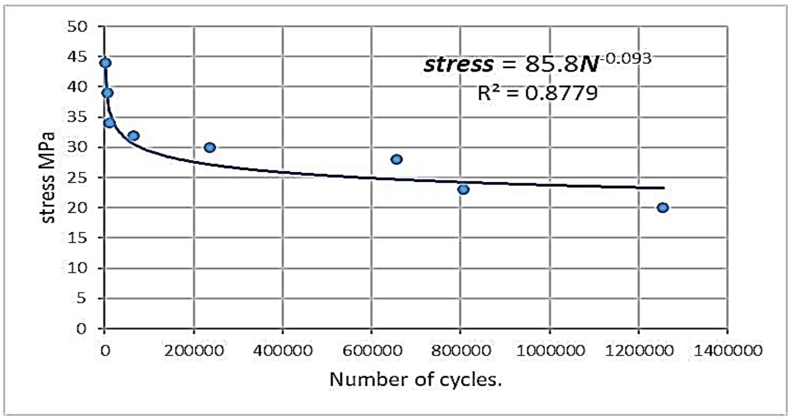

Figure 9. The S-N curve for PLA carbon fiber filament.

The numerical result of the pylon, based on the considered boundary condition, the critical load of buckling is calculated mathematically and numerically by ANSYS-14.5. The critical load (P_{cr}) is [51].

$$P_{cr} = \frac{\pi^2 EI}{(0.5\,L)^2} \tag{1}$$

L= length of the pylon, E=Modulus of Elasticity, I= Polar moment of inertia
Where, E= 1.38GPa, I=24137.07mm^4, L=300 mm

$$P_{cr} = \frac{\pi^2 * 1.38*10^9 * 24137.07*10^{-12}}{(0.5 * 300*10^{-3})^2} = 14596 \text{ N}$$

While the critical load of buckling by numerical analysis equal to 14388 N and the mode shape of the buckling can be shown in Figure 10.

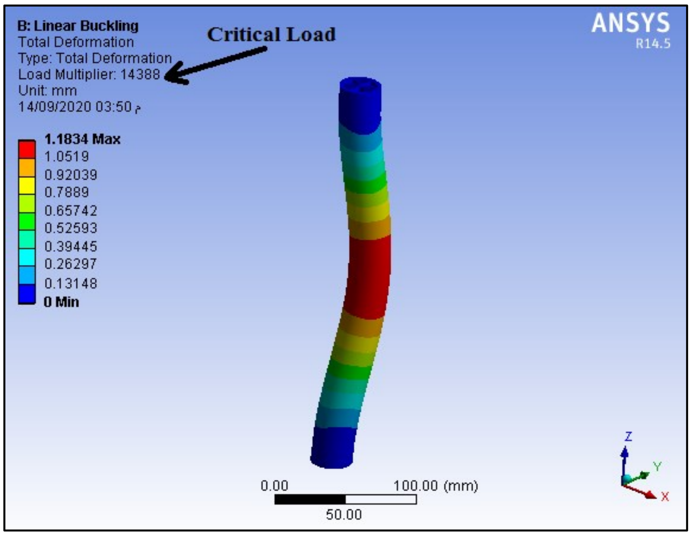

Figure 10. The buckling mode shape for PLA carbon fiber filament at 14388 N critical load.

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{14596}{289.74^{-6}} = 50.498 \text{ Mpa} \tag{2}$$

Since $\sigma_{yeild} < \sigma_{cr} < \sigma_{Ultimate}$ the modulus of elasticity can be taken as the tangent modulus $\mathbf{E_t}$, inelastic buckling occurs from the second line segment of the σ- ε diagram [52], as shown in Figure 11.

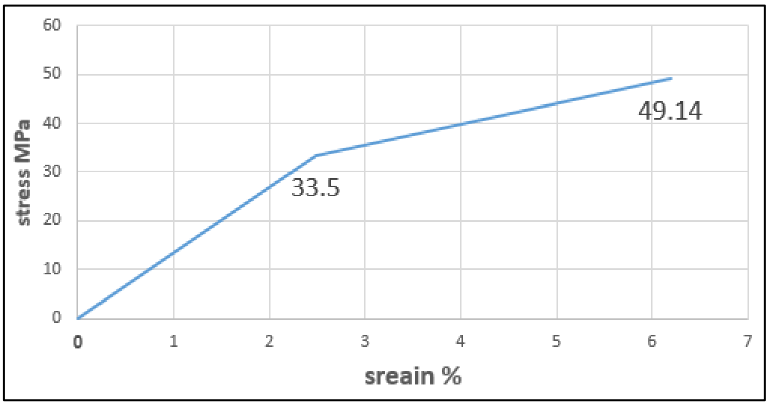

Figure 11. The inelastic buckling from the second line segment of the σ- ε diagram.

$$E_t = \frac{49.14-33.5}{6.188-2.48}\ 0.795\text{GPa}$$

$$P_{cr} = \frac{\pi^2 * 0.795 * 10^9 * 24137.07 * 10^{-12}}{(0.5 * 300 * 10^{-3})^2} = 8408\ \text{N}$$

$$\sigma_{cr} = \frac{8408}{289.74^{-6}} = 29.05\ \text{GPa}$$

Since this value falls within the limit of 33.5 MPa and 49.4 MPa, it is indeed the critical stress. The critical load on the pylon is therefore P_{cr}= 8408. The results above show the patient's allowable weight for applying on the pylon without buckling should be equal to less than the critical buckling load. When the patient wears the prosthesis and walks, the patient's weight will be applied to the pylon, and thus stresses and deformations will be generated in the pylon. These stresses must be calculated to know whether the design is safe or not. The results showed that the maximum value of stress generated in the pylon is equal to 3. 22 Mpa, as shown in Figure 12. Note the big gap between the maximum stress (3.22 Mpa) generated in the pylon and the yield stress (33.5 Mpa). Also, it was found that the maximum value of longitudinal deformation in the pylon is equal to 0.5932 mm, as shown in Figure 13. This deformation value is good and suitable for pylon prosthetic.

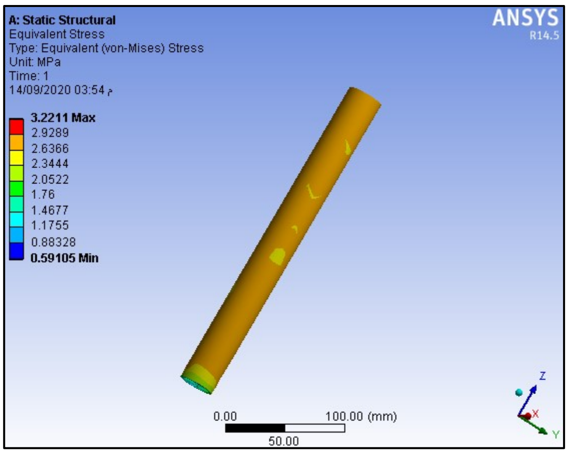

Figure 12. The Von Misses stress of the pylon model.

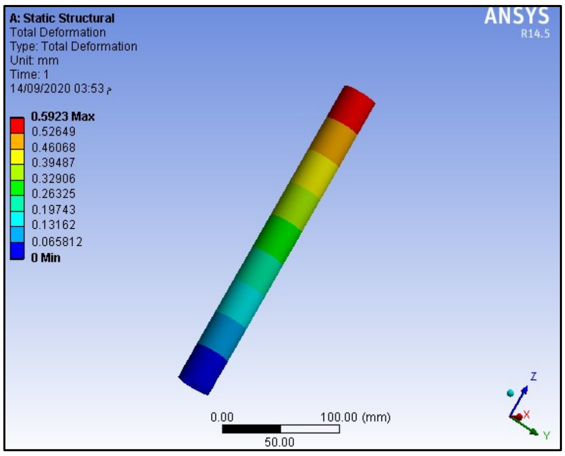

Figure 13. Deformation analysis of the pylon model.

The fatigue safety factor for the carbon fiber filament of the pylon model is passed in design. Each color indicates a specific gradient of values for the safety factor. The safety factor's value is more than (1.25), as shown in Figures 14. The fatigue safety factor will be safe in design if the safety factor is equal to or higher than 1.25 [53-57].

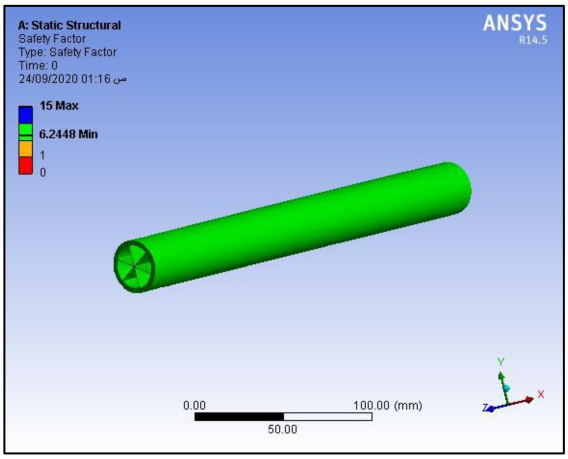

Figure 14. The safety factor of the pylon model.

Comparing the PLA carbon fiber pylon with the other types of the standard pylon for the length 300 mm, as shown in Table (1), it can be noticed that the PLA carbon fiber pylon is lighter and cheaper than the standard pylon.

Table 1. Comparing the PLA carbon fiber pylon with the other types

Pylon Type	Weight(kg)	Cost ($)
Stainless steel [58]	0.25	120
Titanium [58]	0.173	166
Aluminium [58]	0.2	95
PLA Carbon Fiber	0.1	3

3. Conclusions

1- The new prosthetic pylon is lightweight and lighter than the standard pylons, as its weight is 0.1 kg.
2- The new prosthetic pylon has a low cost and is cheaper than the standard pylon, with a vast difference, as the cost of the new pylon is 3$.
3- The new prosthetic pylon's weight is less than the weights of Stainless steel, Titanium, and Aluminium pylons by 60%, 42%, and 50%, respectively.
4- The new prosthetic pylon cost is cheaper than the cost of Stainless steel, Titanium, and Aluminium pylons by 97.5%,98%, and 96%, respectively.
5- The printed pylon has the excellent surface quality and accurate dimensions
6- The pylon is successful in design and does not suffer any mechanical failure when applying the patient's weight.
7- The Von-Mises stress of the pylon prosthesis is 3.22 MPa, and the yield stress of the fiber carbon filament is equal to 33.2 MPa, which refers to a big gap between these stresses failure.
8- The critical buckling load equal to 8408N and the buckling stress equal to 29.05 MPa.
9- The fatigue safety factor for the carbon fiber filament of the pylon model is passed in design, where the value of the safety factor is more than 1.25.

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