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Fatigue characteristics of patellar tendon bearing orthosis reinforcement materials

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Abstract
In this work, two types of composite materials were used to enhancement Patellar tendon Bearing Ortheses where they are fabricated from resin 80-20 as a matrix material, Perlon, Fibers of glass and carbon as a reinforced materials. The mixing of the fibers of class and carbon together in texture way to made with resin to form a hybrid material, A vacuum molding technique was used to made two type of composite materials, the first one is made from (10 Hybrid layer) and the second is made from (3 Perlon + 2 Hybrid + 3 Perlon) layers, tensile and fatigue properties were studied experimentally, theoretically and by using Ansys ver.15 package. It was found that the composite has the highest safety factor failure index and lower deformation level compare to the polypropylene results in a best candidate to give better fatigue characteristics of Patellar Tendon Bearing Ortheses.

Keywords: Orthese; Patellar tendon; Fatigue; FEM; Hybrid composites.

1. Introduction

Ortheses are external appliances used to intercept or facilitate movement by supporting, aligning and Keep body parts. Orthotics can enhance the duty of dynamic body parts and prevent or correct deformation [1]. Lower-limb tissues loss may lead to immobility especially if weighted bearing surface of foot have some effects. Patients suffer from Diabetic in some cases are prone to the above problems because of the ischemia and peripheral neuro pathology. Peripheral neuropathy is present in approximately 50% of cases. The PTBO was basically designed to support or off-load body weight for the below-knee part which is structurally inappropriate or causes pain [2]. H. Tanaka [3] estimated the unloading case effects of the patellar tendon-bearing (PTB) model for five healthy peoples using a dynamic plantar pressure system analysis. A method to enhance the unloading effect of the PTB, and tested this by using the same system. He concluded that the conventional PTB offers unloading of 30% of the body-weight while the part of the cast on the leg offered the most importance role in the unloading. It was also shown that when the depth of the space under the foot inside the PTB cast 1, 2 and 3 cm, the unloading effects were 60%, 80% and 98%, respectively. Muhsin J. Jweeg et al [4] achieved research of analysis for enhance the fatigue behavior (safety factor) of non-articular prosthetic foot (SACH) in the part (Bolt Adapter).The laser peening was supplied to the fatigue specimens to enhance the fatigue properties of bolt's material. The tests of mechanical properties to the program of engineering analysis (Ansys) to estimate the safety factor of fatigue. The results appeared that the safety factor after hardening by laser is increased by 42.8%. Muhsin J. Jweeg et al [5] initiated a database for the properties of materials used in manufacturing of sockets of prosthetic limbs as lamination materials and they put them in 14 group of different system of stacking materials layers are made by using perlon, fiber glass and acrylic resin. The investigation of decrease or increase the fiber glass layers and the perlon on mechanical and physical properties are examined subjected the 82 manufactured samples of the different 14 group of laminations to tensile and flexural test. Muhsin J. Jweeg et al [6] worked on an experimental part to calculate the Ground Reaction Force (GRF), and pressure distribution for old and new prostheses. The F-Socket sensor was used to calculate interface pressure (IP) between leg and socket. The impact hammer test was used to calculate natural frequency. In this work, the fatigue strength of the reinforcement materials used in patellar tendon bearing ortheses investigated experimentally.

2. Theory

Fatigue limits criterions are as follows:

a) Goodman criteria: In this respect the suggested empirical relation relates the fatigue limit and mean stress as follows [7]:

$$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_{ts}} = 1 \tag{1}$$

where: σa = amplitude stress, σe = endurance limit, σts =the ultimate strength.

b) The equivalent Von Mises Stress: In this approach, the stress system is converted to a single equivalent value (Von Mises Stress) as follows [7, 8]:

$$\sigma_{eq} = [\tfrac{1}{2}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)\right]]^{1/2} \tag{2}$$

where: σeq = equivalent stress, σx = direct stress in x-direction, σy = direct stress in y-direction, σz = direct stress in z-direction, τxy = shearing stress in xy-plane, τyz = shearing stress in yz-plane, τzx = shearing stress in zx-plane.

c) Soderberg theory: The relationship for fatigue safety factor are:

$$S_a = S\left[1 - \left(\frac{S_m}{S_y}\right)\right] \quad \text{Soderberg's law} \tag{3}$$

where: S_y; static yield strength, S_m; the mean stress, S_a; is the alternating stress, S; is the alternating fatigue strength.

3. Experimental part

The materials of the Orthotics chosen and manufactured by vacuum cleaning method. Table 1 includes the contents of 2 lamination used in this work. The experimental tests used for the characterization of materials are as follows:

The Tensile tests: All samples tested using the universal testing instrument (testometric). For the laminate piece and composite the standard specimens are cut according to ASTM D638 [9]. The crosshead speed was 4mm/min. The tensile strength and Young's modulus of the composite used in this work are determined from stress-strain curve Figures 1and 2. Table 2 contains the mechanical properties of the two composites used this work.

The flexural bending test: All samples tested using a three point bending test. The standard specimens are cut according to ASTM D638 [9]. Mechanical properties (Maximum bending strength and flexural Young's modulus) of the composite used in this work are determined from stress-deflection curve Figures 3 and 4. Table 3 contains mechanical properties of the two composites of this work.

Also, the Fatigue tests were achieved of type alternating bending with constant amplitude. The specimens deflections are perpendicular to the axis of one side of the specimens, and the bending stresses is on the other side.

Table 1. Laminated composites used in this work.

No. of Lamination	Composite layers
Lamination 1	(10 Hybrid (Carbon Fiber & Fiber Glass)
Lamination 2	(3perlon+2 Hybrid (Carbon Fiber & Fiber Glass)+3 perlon)

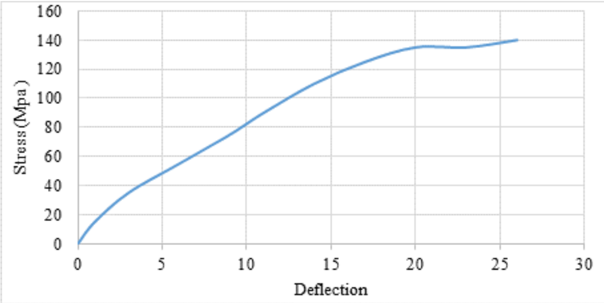


Figure 1. Stress-Deflection curve for one sample of lamination 1.

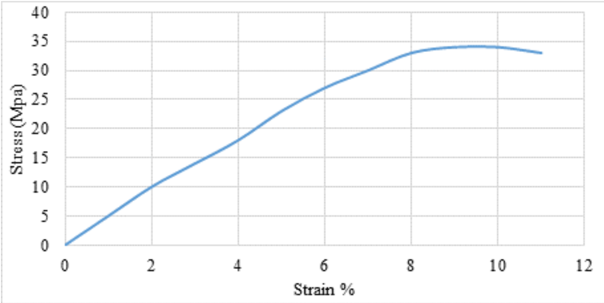


Figure 2. Stress-Strain curve for one sample of lamination 2.

Table 2. Mech properties of tested composites.

No. of Lam.	Lay up	Thickness (mm)	σ_y MPa	σ_{ult} Mpa	E GPa	Elong. At break (mm)
Lamination 1	10	4	56	128	1.89	14
Lamination 2	323	3.5	21	35	1	4

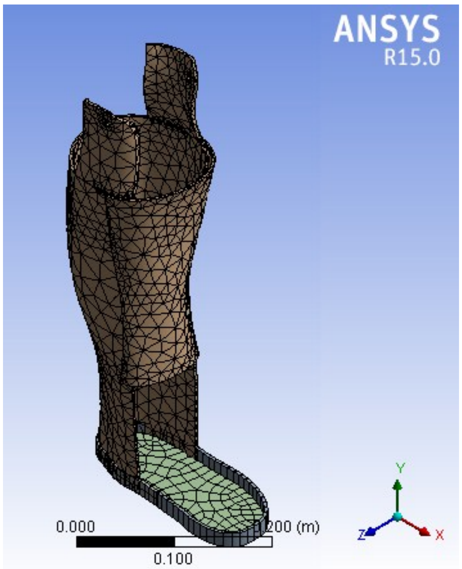


Figure 3. The meshed of geometry.

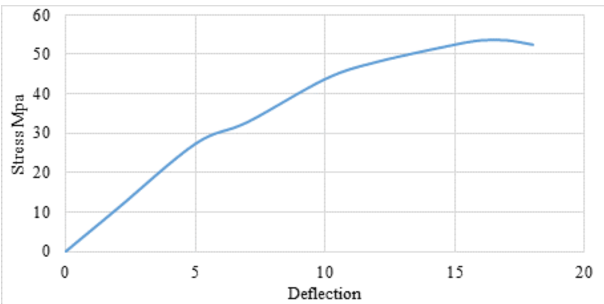


Figure 4. Stress-Deflection curve for one sample of lamination 2.

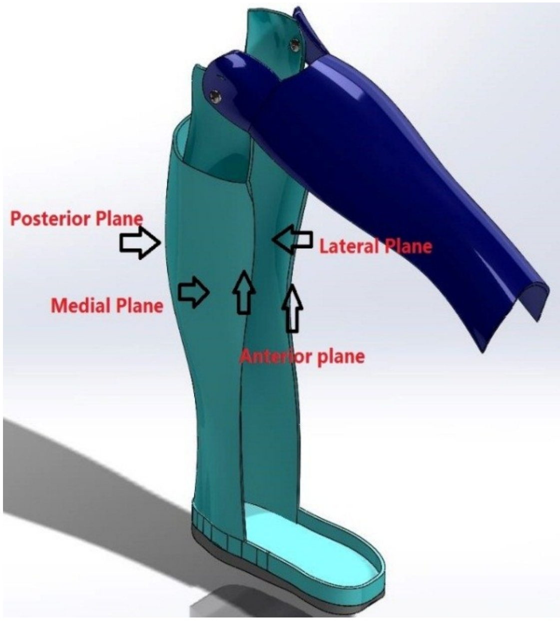
Table 3. Mechanical properties (flexural properties).

No. of Lam.	Lay up	σ_b max (MPa)	$E_{flexural}$ (Gpa)
Lamination 1	8	135	7
Lamination 2	323	52.47	3

4. Finite element method (FEM)

The FEM was used to evaluate the fatigue life and the factor of safety. The equivalent alternating stress and the total deformation were calculated for patellar tendon bearing ortheses of a patient of mass 85 Kg. The model of orthotic was designed in Solidwork program and finally exporting the design geometry to Ansys-15 work bench. As shown in Figure 5 (a, b). The orthotic is analyzed at the maximum load conditions, which in single point standing in. Pressures values measured during gait cycle are listed in Table 4 and applied on orthotic plane as shown in Figure 5b. The Ansys 15 package was employed using the three-dimensional element is SOLID 185 as shown in Figure 6. The element has three degrees of freedom at each node i.e translations in the nodal x, y, and z directions only.

(a)



(b)

Figure 5. (a) PTBO (b) PTBO geometry in solid work program.

Table 4. Average pressure values and locations in the socket at heel strike position.

Location	Anterior	posterior	medial	lateral
Average Pressure value (KPa)	100	250	150	150

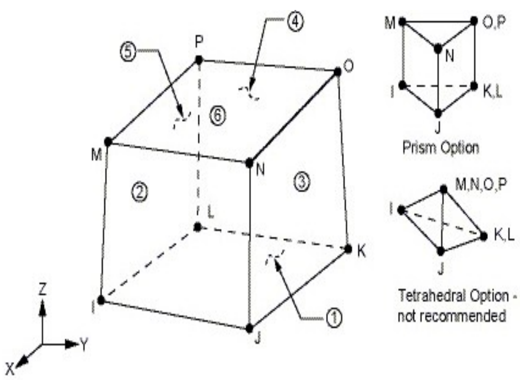


Figure 6. Three dimensional elements solid 185.

5. Results and discussion

5.1 Experimental results

i. Results of tension test:

The tensile test results are listed in Tables 2 and 3. For the flexural test, the mechanical properties are obtained, modulus of elasticity (E), elongation, and the ultimate tensile strength. The flexural test results in Table 3 give the maximum bending stress and flexural Young's modulus In general, it is noted that the Young's modulus of elasticity (E), ultimate tensile strength, maximum bending stress and flexural Young's modulus of lamination 1 (10 Hybrid (Carbon + Glass)) reinforced composite is more than lamination 2 and it is noted that the Elongation of the (10 Hybrid (Carbon + Glass) reinforced composite was higher than other lamination composite materials, which indicates that addition of this reinforcement to composite increases its elasticity.

ii. The S-N curve

Fatigue test results for 8 samples of each lamination were shown in Figure 7. The S-N curves for samples of the lamination 1 (10 layers of Hybrid) and lamination 2 (3 perlon +2 carbon fiber Fiber glass +3 perlon). From Figure 8, it is evident that the using of reinforcement in the two laminates, gave a clear effect on the values of the fatigue strength. When comparing the composites behavior, the fatigue limit was significantly higher in (10 Hybrid (Carbon + Glass)) reinforced composite, whereas, a severe reduction in fatigue limit is noted in lamination 2 with perlon reinforced with 2 layer of hybrid composite. The fatigue strength was defined at number of cycles 106 [10]. Fatigue limit of (10 Hybrid (Carbon + Glass)) reinforced composite increases as much as 3.6 orders of magnitude as compared to perlon reinforced with 2 layer of hybrid composite as shown in Figure 9. It can be concluded that the fatigue strength of materials is directly proportional to its tensile strength [11]; hence in choosing the materials it should be taken into consideration that the grater ultimate tensile strength material has a greater fatigue limit.

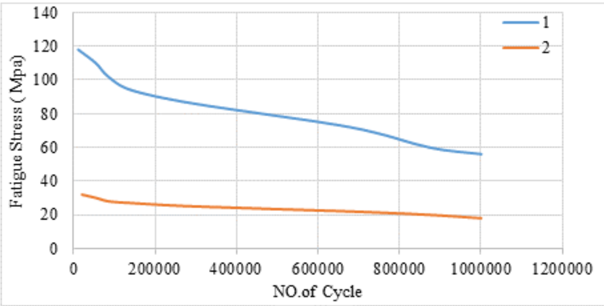


Figure 7. 1- Hybrid (10 layer) SN-Curve
2- 3Perlon-Hybrid (2 layer) - 3Perlon SN –curve.

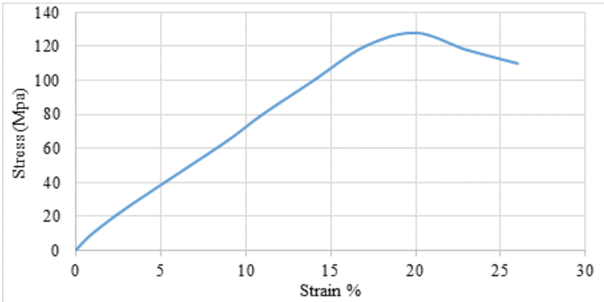


Figure 8. Stress-Strain curve for one sample of lamination 1.

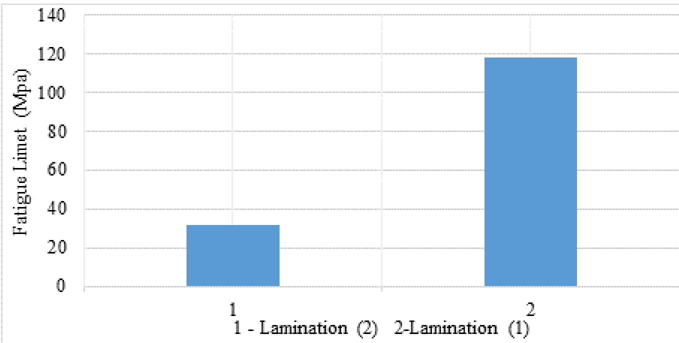


Figure 9. The fatigue limit of two composites.

5.2 Numerical results

i. Fatigue life estimation:

Figure 10 shows the obtained fatigue life from numerical results which display the overall life distribution throughout the orthotic for each type of used laminates. In the analysis of stress life with constant amplitude, the life to be used can be defined by S-N curve if the equivalent alternating stress is lower than the lowest alternating stress [7].

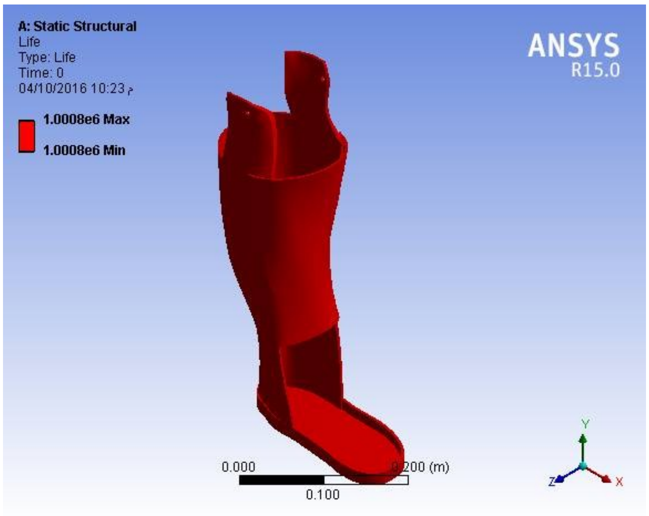


Figure 10. Contours of fatigue life distribution.

ii. Fatigue factor of safety:
The factor of safety at a given design life with respect to fatigue failure. In Ansys- 15, the maximum safety factor is 15, failure before the design life was reached when values less than one [7]. Figure 11 presents the distribution of safe and unsafe regions of two composite materials used. The lowest safety factor recorded of two composites is shown in Figure 11 where (10 Hybrid (Carbon + Glass)) reinforced composite were used with the highest safety factor of (7.718) and perlon reinforced with 2 layer of hybrid composite reinforced laminates composites with the lowest safety can be used safely.

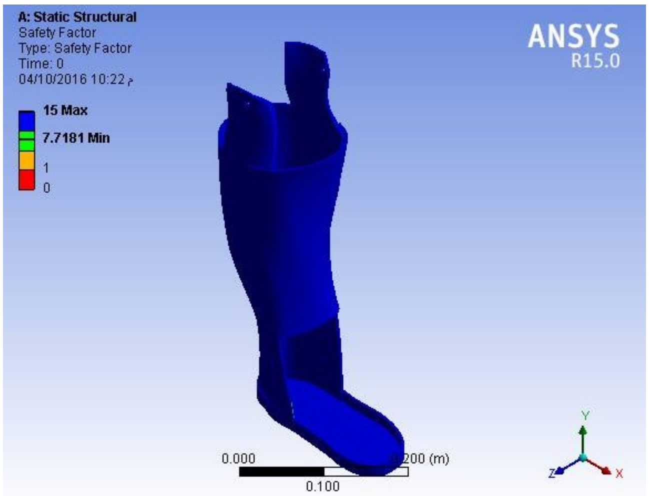


Figure 11. Sample of contours of fatigue safety factor distribution.

iii. The Von Mises stress:
This stress is used to explain the fatigue S-N curve of the fatigue test taking into account the type of fatigue loading. Figure 12 shows the overall distribution of the Von Mises stresses throughout the design and the approximate value and its location of the maximum Von Mises stress may be defined throughout the region of interest.

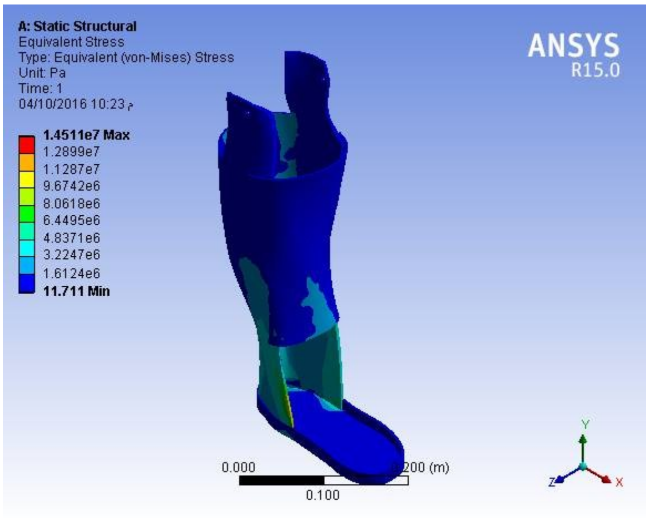


Figure 12. Contours of Von Mises stress distribution.

iv. Maximum total deformation:
Figure 13 shows the maximum deformation for the each type of lamintion composites. For the reinforced composites (10 Hybrid (Carbon + Glass)) the smallest amount of deformation is 6.4 mm) while for perlon reinforced with 2 layer of hybrid composite,the highest amount of deformation is (12 mm).

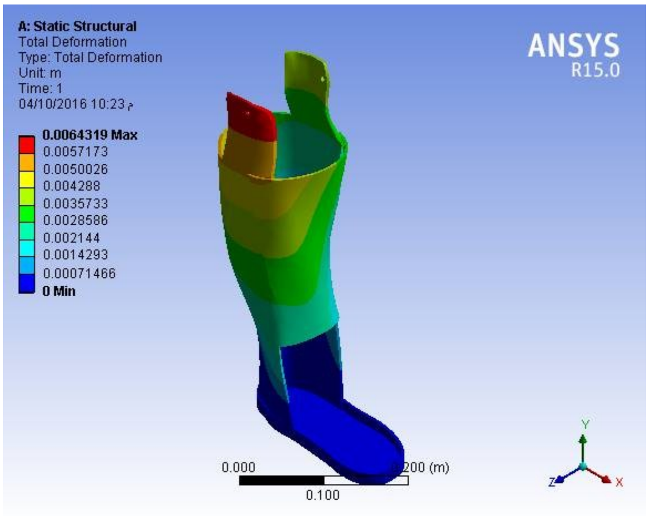


Figure 13. Sample of total deformation.

6. Conclusions
The results of tensile, flexure and fatigue tests of the PTBO indicate the following conclusions:
1. The results of the ultimate tensile stress (σ_{ult}) show that for the 10 Hybrid (CF+FG) with risen 80:20 is 128 MPa and for 8 layer (3P+2Hy+3P) with risen 80:20 is 35 MPa.
2. The fatigue limits for10 Hybrid (CF+FG) is (56 MPa) and for 8 layer (3P+2Hy+3P) is (18).
3. The obtained results of safety factor of fatigue, for composite materials PTBO with10 Hybrid (CF+FG) is (7.718), and for 8 layers (3P+2Hy+3P) is (3.721).

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