INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT
ISSUE ON APPLIED MECHANICS RESEARCH
Volume 8, Issue 4, 2017 pp.291-298
Journal homepage: www.IJEE.IEEFoundation.org

Characterization of materials used in manufacturing the ankle foot ortheses

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Received 25 Apr. 2016; Received in revised form 23 July 2016; Accepted 26 July 2016; Available online 1 July 2017

Abstract
This work covered the experimental program to obtain the mechanical properties of the ankle Foot Ortheses (AFO) composite materials by using tensile, flexural and fatigue tests. They are composed of number of layers (12 layers) perlon with two lyers of carbon-fiber and (10 layers) without carbon fiber. Also, the Ground Reaction Force (GRF), Center of Pressure (COP) and pressure distribution were determined experimentally for patients (first is about (42)year old with height (173cm) and weight (82kg) and the second about (10) years old with height (130cm) and weight (23 kg)) with and without AFO. The results showed that the ultimate stress (σ_{ult}) for perlon 31 MPa, for perlon with carbon fiber of matrix (80:20) 36MPa and perlon with carbon fiber of matrix C-orthocryl 55 MPa. The Fatigue life equation for perlon is $\sigma=33.64(N_f)^{-0.30}$ and for perlon with carbon fiber $\sigma=60.98(N_f)^{-0.33}$. The fatigue limit for perlon is 16MPa and for perlon with carbon fiber 28MPa. The GRF data were measured by using force plate and the pressure distribution are obtained by using F-socket. The gait velocity without AFO equal to 0.43m/sec and with lamination AFO equal to 0.607 m/sec for patient 1 and gait velocity without AFO equal to 0.697m/sec and with lamination AFO equal to 0.837m/sec. The gait cycle time for patients without AFO equals to 42.6% but when wearing AFO equals to 97%.The interface pressure between leg and AFO is measured for AFO surface area by using F- socket sensor reaches 72 MPa and may reach more than this value at the moment of toe off due to the foot drop.
The numerical results were obtained by employing the finite element method using ANSYS 15 package using the measured pressure loading and investigating many models to calculate the Von Mises stress and the fatigue safety factor. The fatigue safety factor was found for composite materials AFO with carbon fiber (3.0321), without carbon fiber (1.7578).

Keywords: AFO; Tensile; Flexural; Fatigue; Composites.

1. Introduction

The AFO shown in Figure 1 are widely used in clinical applications to substitute the gait abilities of hemiplegic patients ortheses. The abnormalities of the drop foot due to insufficient push-off during the stance phase are corrected and the medio lateral stability is ensured during the stance phase. Also, an adequate toe clearance is maintained during the swing phase [1].
Drop foot is a reduced or lack of action from the muscles that lift the foot. When these muscles lack function they are unable to dorsiflex the ankle which causes the foot to be dragged on the ground. For

some people the lack of function is so severe that they are not able to walk without treatment, while others have a steppage gait. The recommended treatment depends on the etiology of drop foot. Sometimes surgery is necessary while some patients can be treated by wearing an ankle foot orthosis, a brace that stabilizes the foot and lifts it in an upright position while the foot swings. A very large number of people suffering from drop foot but no exact numbers are to the authors knowledge available. Nevertheless, it can be estimated that 20 % of those surviving stroke suffer from drop foot [2].

Drop foot is defined as a weakness on foot dorsiflexion. The reason for this disease is due to the lower motor neuron (LMN) such as L4-L5 radiculopathy, which are caused by either an intervertebral disc prolapse or foramina stenosis, and personal neuropathy. Figure 2 shows a young patient with insidious onset of unilateral foot drop caused by an extensive spinal pathology [3]. The other diseases reasons of the foot drop are axonal or demyelinating damage along the peripheral nervous system such as lower spinal cord lumbar plexus, and peripheral mixed nerve. The drop foot may be caused by central nervous pathology where the nerve fibres are highly condensed along the spinal cord pyramidal tract.

In this work, fatigue test was applied for different samples of lamination from perlon and perlon with carbon fiber in order to be used in manufacturing of ankle foot orthoses with drop foot to achieve the requirement of good AFO design for acceptable mechanical properties and minimizing the cost.

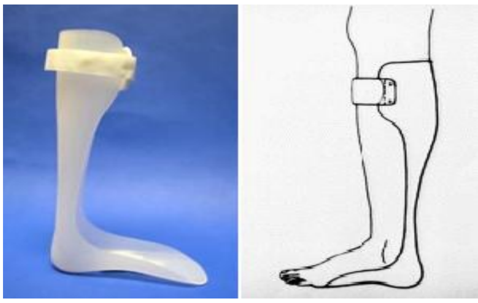

Figure 1. Solid ankle-foot orthosis [1].

Figure 2. Drop foot [3].

2. Experimental part

2.1 Materials

The materials of the AFO needed in lamination for this study are as follows [4].

- Perlon stockinet white (Otto bock health care 623T3).
- Carbon fiber (Otto bock health care 616G15).
- Lamination resin 80:20 polyurethane and C-Orthocryl lamination resin for use with carbon fiber (proter hand icap technology).
- Hardening powder (Ottobock health care 617P37).
- Polyvinyalcohol PVA bag (Ottobock health care 99B71).
- Materials for Jepson.

2.2 Equipment

The equipment used in this respect is as follows:

- Jepson positive mold rectangular cuboids in shape that manufactured with size 10*15*25 cm^3.
- Vacuum forming system including vacuum pump and different types of stands, pipes and tubes.
- Workshop equipped with different types of cutting and forming and machines.
- Universal instrument machine test (testometric) for tensile.
- Universal instrument machine test (testometric) also used for flexural bending test (three point bending load).
- Material fatigue test for flat specimen.
- Force plate devise are used to analysis the gait cycle of patient with AFO.

2.3 Preparing of samples for tensile, flexural bending and fatigue tests

The procedure may be summarized as follows:

- Mounting the positive mold at the laminating stand and completing the connection with the vacuum forming system through the pressure tubes. The inner (PVA) bag is pulled in the positive mold and the pressure valves are opened to value of approximately 30 mm Hg at room temperature.

- Arranging the perlon stockinet (10 perlon) layers and pulling the outer (PVA) keeping the smaller end positioned over and using cotton string to tie off the (PVA) bag. Then this procedure is repeated by putting perlon with carbon fiber (5 perlon+2 carbon fiber+5 perlon) layers for other samples.
- Mixing the lamination resin 80:20 polyurethane for perlon and C-Orthocryl lamination resin for use with carbon fiber with the hardener about (500-600) ml of resin mixed with(1-2) part of hardener. The resulting matrix mixture is distributed homogenously inside the (PVA) bag.
- Maintaining constant vacuum until the composite materials becomes cold and then left the resulting lamination.
- Cutting the composite materials after cold to manufacturing samples for tensile, flexural bending and fatigue testing.
- For tensile test three samples were prepared for each lamination according to ASTM D638 type I [5] while thickness varies according to the type of lay up. Figure 3 shows the shape and dimensions of tensile sample.
- All tensile test samples tested using the universal testing instrument (testometric).
- For flexural bending test three samples for each lamination were machined according to ASTM D790 [6] while thickness various with the type of layup.
- For fatigue test,10 samples for each lamination were machined. The dimensions of samples are length 100mm and width 10mm according to the fatigue device test while thickness various with the type of layup. Figure 4 shows the shape and dimensions of fatigue samples.

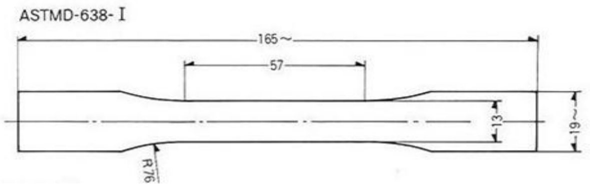

Figure 3. The shape and dimensions of tensile specimen.

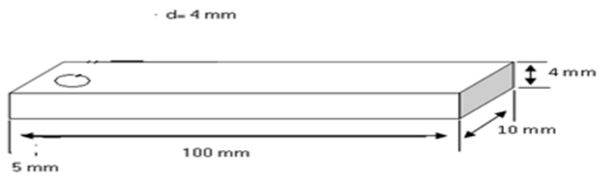

Figure 4. The shape and dimensions of fatigue specimen.

2.4 Manufacturing the ankle foot orthosis (AFO)

The procedure is summarized as follows:

- Mounting the positive mold at the laminating stand according to the item (i) above.
- Putting the perlon stockinet(5 perlon)layers and put 2 layers of carbon fiber with width 2 cm at each end of ankle foot orthosis and put (5 perlon) layers and pull the outer (PVA) keeping the smaller end positioned over the value area using cotton string to tie off the (PVA) bag.
- Mixing the C-Orthocryl lamination resin for use with carbon fiber with the hardener about (800-900) ml of resin mixed with (2-3) part of hardener. The resulting matrix mixture is distributed homogenously inside the outside PVA bag.
- Maintaining constant vacuum until the composite materials becomes cold and then left the resulting lamination and cut it in the shape of ankle foot orthosis with required dimensions as shown in Figure 5.

Figure 5. The suggested ankle foot orthosis (AFO).

3. Results and discussions

3.1 Tensile properties results

The average thickness for the Samples set were measured using digital Vernier are:

- Sample of perlon (10 layers).
- Sample of perlon with carbon fiber (12 layers).

The prepared laminations are shown in Table 1.

Table 1. The manufactured laminations with different layup method.

Lamination NO.	Thickness (mm)	Layup Symbol	Total No of layers	Lamination lay up procedures
Lamination 1	3	505	10	(5Perlon +zerocarbonfiber +5perlon)layers
Lamination 2	4.3	525	12	(5Perlon +2carbon fiber +5perlon)layers

The mechanical properties for all laminations can be found as shown in Table 2. Three specimens for each lamination were tested to obtain the load extension curve. Figure 6 shows stress-strain curve for one of the samples of the lamination 1 and Figure 7 shows stress-strain curve for one of the samples of the lamination 2 from these curves the mechanical properties of each sample determined and recorded in Table 2. The results explain the effects of increasing carbon fiber layers with constant value of perlon layers on mechanical properties were that lead to increase σy, σult.

This leads to increase the mechanical properties (σ_y, σ_{ult}) but elongation at break is decreased because of increasing the absorbing ability that results by increasing the lamination thickness of samples and the different in plastic behavior for both materials.

Table 2. Mechanical properties that determined from stress-strain curves.

Lamination NO.	Thickness (mm)	Layup	σ_y MPa	σ_{ult} MPa	E GPa	Elong. at Breakm (mm)
Group A	3	505	24.133	31	0.696	18.633
Group B	4.3	525	44.666	49.333	1.15	5

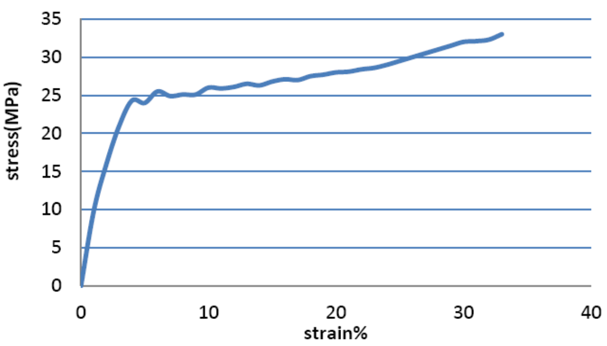

Figure 6. Stress-strain curve for one sample of lamination 1.

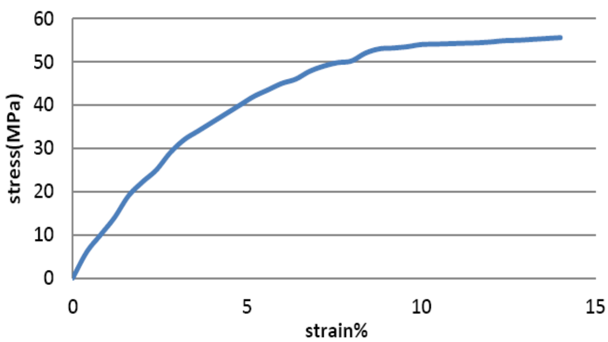

Figure 7. Stress-strain curve for one sample of lamination 2.

3.2 Flexural properties results

The flexural properties can be calculated from the bending curves of three samples for each lamination and by averaging the results, the mechanical bending properties of the all lamination layup are listed in Table 3. Figure 8 shows stress-strain curve for one of the samples of the lamination 1 and Figure 9 shows the stress-strain curve for one of the samples of the lamination 2. From these curves the mechanical properties of each sample determined and record in Table 3.

3.3 Fatigue properties results

The results of fatigue test are shown in Figures 10 and 11 show S-N curve for samples of all laminations, the failure stresses are decreasing and the number of cycles to reach to the failure are increasing at constant temperature.

Table 3. Mechanical properties that determined from stress-deflection curves.

No. of Lam.	Layup	σ_b max MPa	$E_{flexural}$ GPa
Lamination 1	505	65.8	3.15
Lamination 1	505	78	3.6
Lamination 1	505	59.2	2.5
Lamination 2	525	55.8	1.8
Lamination 2	525	79.4	3.7
Lamination 2	525	61.5	3.2

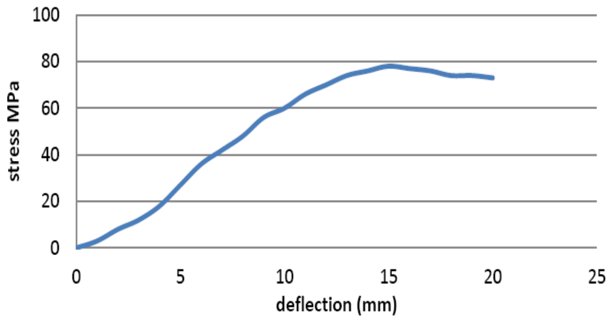

Figure 8. Stress-deflection curve for one sample of lamination 1.

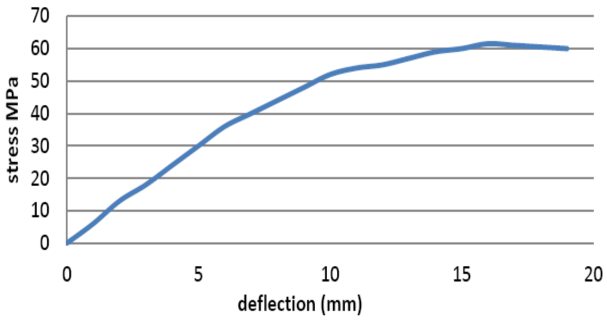

Figure 9. Stress-deflection curve for one sample of lamination 2.

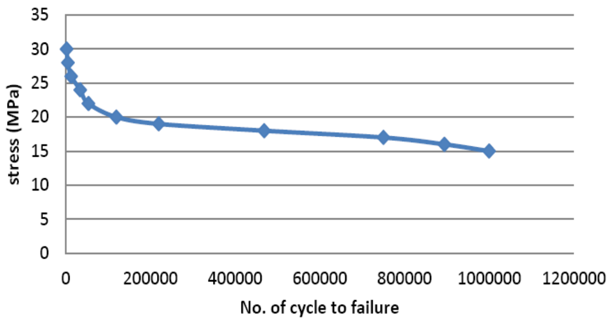

Figure 10. S-N curve for perlon.

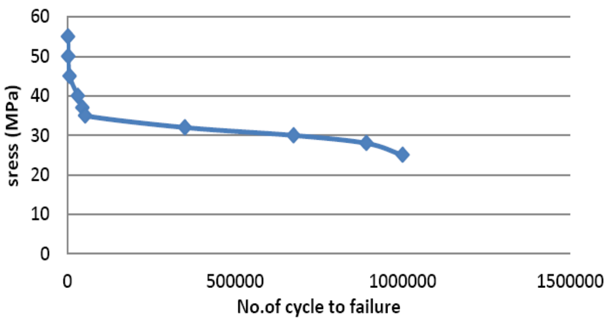

Figure 11. S-N curve for perlon and carbon fiber.

3.4 Force plate and F-socket with AFO results

The obtained data from the gait cycle test were compared for the patient with and without AFO for two case studies, to recognize the major differences for the parameters of the right and the left leg. Gait table and gate cycle table for patient one without AFO results were shown in Tables 4 and 5 respectively.

Gait table and gait Cycle Table for patient one with AFO results were shown in Tables 6 and 7 respectively. Gait table and gait Cycle Table for patient two without AFO results were shown in Tables 8 and 9. Gait table and gait Cycle Table for patient two with AFO results were shown in Tables 10 and 11 respectively.

The analysis of AFO's models for patient I was established by FEM software to compute the equivalent (Von-Mises) stress and safety factor of fatigue. According to the Von-Mises theory that considers the yield stress as criteria; ($\sigma_e<\sigma_y$, safe), ($\sigma_e = \sigma_y$, critical) and ($\sigma_e>\sigma_y$, failed). Where, (σ_e) is the equivalent stress, and (σ_y) is the yield stress.It is seen that the fatigue safety factor is safe in design applications if the safety factor is about or more than (1.25) [7, 8].

Table 4. Gait table for patient I.

Gait Table	Patient I
Number of Strikes	27
Cadence (steps/min)	56.8
Gait Time (sec)	19.02
Gait Distance (m)	8.187
Gait Velocity (m/sec)	0.430

Table 5. Gait cycle for patient I.

Gait Cycle Table (sec)	Patient I		
	Left	Right	Difference
Gait Cycle Time	3.82	1.63	-2.18
Stance Time	1.03	0.93	-0.10
Swing Time	2.79	0.70	-2.08
Single Support Time	0.67	0.64	-0.03
Initial Double Support Time	0.15	0.17	0.02
Terminal Double Support Time	0.17	0.15	-0.02
Total Double Support Time	0.33	0.33	0.00
Heel Contact Time	0.73	0.35	-0.37
Foot Flat Time	0.64	0.03	-0.61

Table 6. Gait table for patient I.

Gait Table	Patient I
Number of Strikes	32
Cadence (steps/min)	82.7
Gait Time (sec)	14.5
Gait Distance (m)	8.809
Gait Velocity (m/sec)	0.607

Table 7. Gait cycle for patient II.

Gait Cycle Table (sec)	Patient1		
	Left	Right	Difference
Gait Cycle Time	1.48	1.44	-0.04
Stance Time	0.95	0.95	0.00
Swing Time	0.54	0.49	-0.04
Single Support Time	0.45	0.47	0.02
Initial Double Support Time	0.22	0.24	0.02
Terminal Double Support Time	0.24	0.22	-0.02
Total Double Support Time	0.47	0.47	0.00
Heel Contact Time	0.74	0.68	-0.05
Foot Flat Time	0.59	0.46	-0. 13

Table 8. Gait data for patient II.

Gait Table	Patient II
Number of Strikes	18
Cadence (steps/min)	85.4
Gait Time (sec)	7.73
Gait Distance (m)	5.387
Gait Velocity (m/sec)	0.697

Table 9. Gait cycle table (sec) for patient II.

Gait Cycle Table (sec)	Patient II		
	Left	Right	Difference
Gait Cycle Time	1.38	1.27	-0.10
Stance Time	0.85	0.66	-0.18
Swing Time	0.53	0.61	0.08
Single Support Time	0.66	0.43	-0.23
Initial Double Support Time	0.08	0.12	0.04
Terminal Double Support Time	0.12	0.08	-0.04
Total Double Support Time	0.21	0.21	0.00
Heel Contact Time	0.42	0.16	-0.26
Foot Flat Time	0.17	0.00	-0.17
Mid stance Time	0.30	0.00	-0.30

Table 10. Gait data for patient II.

Gait Table	Patient II
Number of Strikes	33
Cadence (steps/min)	107.6
Gait Time (sec)	12.36
Gait Distance (m)	10.263
Gait Velocity (m/sec)	0.837

Table 11. Gait Cycle for patient II.

Gait Cycle Table (sec)	Patient II		
	Left	Right	Difference
Gait Cycle Time	1.14	1.10	-0.03
Stance Time	0.71	0.66	-0.04
Swing Time	0.43	0.44	0.01
Single Support Time	0.44	0.41	-0.04
Initial Double Support Time	0.11	0.13	0.01
Terminal Double Support Time	0.13	0.11	-0.01
Total Double Support Time	0.24	0.24	0.00
Heel Contact Time	0.39	0.24	-0.14
Foot Flat Time	0.21	0.16	-0.05

The results of Von-Mises stress for composite material AFO model are presented in Figures 12 and 13 respectively, the changes of the properties of materials are affecting on the results of Von-Mises stress. The safety factors for composite material AFO model are acceptable in design applications as shown in Figures 14 and 15 respectively. The model of composite material AFO showed that the fatigue safety factor for (5 perlon+2 carbon fiber+5 perlon) layers is about (3.0321) and for (10 perlon) layers about (1.7578) which are safe in design.

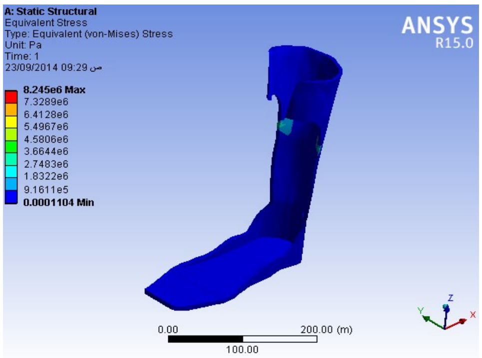

Figure 12. Equivalent stress (Von-Mises) (carbon & perlon).

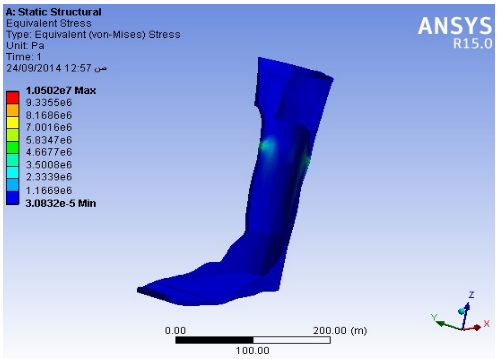

Figure 13. Equivalent stress (Von-Mises) (perlon).

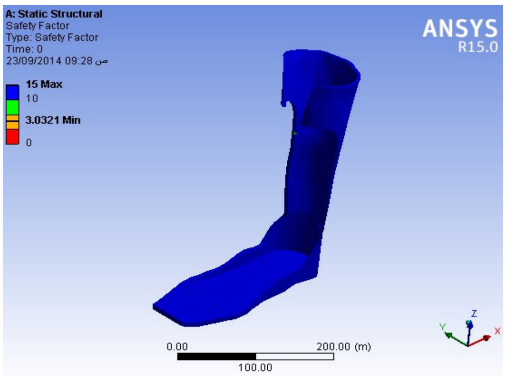

Figure 14. The safety factor for fatigue (carbon & perlon).

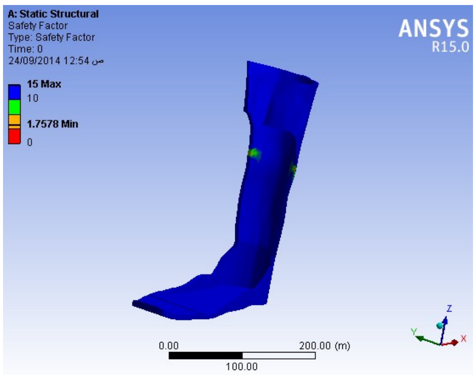

Figure 15. The safety factor for fatigue (perlon).

4. Conclusions

This study gives a good database for manufacturing suitable lamination of an ankle foot ortheses suitable for patients with drop foot. The conclusions of this work are as follows:

1. The suggested lamination of AFO gave acceptable results for Von Mises stresses and the fatigue safety factor which ensure a long life of AFO.
2. Manufacturing of the new lamination of flexible AFO made from (perlon – carbon fiber – C-Orthocryl lamination resin), gave a good control to patient's leg during gait cycle and ease in packing. AFO correct the gait cycle of patient.
3. Higher reduction in friction between patient's skin and (perlon – carbon fiber – perlon) calf has been obtained as compared with that developed with PP calf. Therefore fewer high stress regions are observed after ortheses has been worn-off, hence there is no need to use bulky cushion pad.
4. For lamination 2(5perlon+2carbon fiber+5perlon) layers, the mechanical properties are acceptable to give the Strength and durability for AFO.
5. The patient of weight 82 Kg has a gait velocity without AFO equals to 0.43m/sec when wearing plastic AFO this velocity becomes equal to 0.64 m/sec and for lamination AFO equals to 0.607m/sec and patient of weight 23 Kg has a gait velocity without AFO equals to 0.697m/sec when wearing plastic AFO equals to 0.756m/sec and for lamination AFO
6. The gait cycle time for patients without AFO is equal to 42.6% but when wearing AFO equals to 97%.
7. The model of composite material AFO showed that the fatigue safety factor for (5 perlon+2 carbon fiber+5 perlon) layers is equal to (3.0321), for (10 perlon) layers is equal to (1.7578) which are safe in design.

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