Simulating the Effects of Static Loads on a Transtibial Prosthetic's Major Components Made of Composite Materials Modeled on SolidWorks

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Abstract- *The purpose of this design project was to investigate the effects of weight and durability of a transtibial prothesis modeled on composite materials subjected to loads. The work focused on solid mechanics and modules of failure such as stress, strain, and fatigue. The work was achieved through simulation and tests on the SolidWorks software. Three models were designed and tested, involving some common and composite alternatives that were designated based on the geometry and usage of the part. Some of the materials considered were aluminum, titanium, and carbon fiber, among others. The results obtained were as expected, because the composite alternatives exceeded on the tests, translating into lighter and more durable parts that complied with the purpose. The outcome of the project is relevant to better understanding the applications and improvements that the composite materials can contribute to daily life activities.*

Key terms: *composite materials, fatigue, solid mechanics, SolidWorks*

INTRODUCTION

All materials possess physical and mechanical properties that allow them the capacity to endure stresses without suffering significant deformation [1]. Some of these properties are density, linear elastic deformations, stresses, and strain. Sometimes, materials or material alloys, such as single metals, ceramics, or simple polymers, cannot comply with the requirements of the project due to being heavier than expected. An alternative to heavy materials for many high-strength and low-weight applications is to use composite materials. Composite materials are the binding of two or more types of materials to improve the resistance of the part to support the required forces and stresses. Generally, the composite possesses a reinforced phase (fiber, flakes, or particles) and a matrix [2].

It is important to highlight that most materials possess elastic and plastic properties. The elastic region is considered linear and reversible, which means that the material can return to an undeformed state despite being loaded. Once the loads reach the yielding point, micro-deformations start to develop, which cannot be reversed because the material is in the plastic zone [1]. The material keeps deforming until the ultimate tensile stress is reached, and it heads until it fails or fractures. If the material presents a large plasticity zone, the material is considered ductile; if the material possesses a low plastic behavior and fractures more easily, it is considered brittle. Even though ductile metals can support heavy loads, sometimes they can overcome their limits. On the other hand, polymers are lighter but cannot support large stresses as well as metals. Ceramics can support large stresses, but crack easily because of their typical brittle behavior. For that reason, composite materials help achieve an acceptable level of stiffness and weight to comply with the requirements [2].

The structure that will be studied is a transtibial prothesis that includes a foot, a pylon, and a socket. A previous work [3] proposed to evaluate the effects on a single-foot structure made of 3D-printed materials subjected to loads and stresses. The focus was to prove the variations of suitable materials and how they affect the durability or endurance of the model. The materials used were PLA, ABS, and HDPE. One of the relevant tests that were performed was a fatigue test to determine its life. HDPE prevailed on the test, yielding excellent results that translate into comfort and safety for the user. It is important to analyze the effects on the socket due to it being the part that is most in contact with the patient's limb.

Another work [4] presents alternatives to design a socket, with the purpose of finding a more comfortable but also more durable option for the patient. The socket was subjected to simulation of loads such as tension and bending, to ensure the appropriate results. The sockets evaluated were made of several types of composites involving the use of carbon and perlon as matrix, and acrylic resin as the bonding agent. It is important to establish that the materials were tested at different numbers of layers and configurations. The materials were subjected to fatigue tests to establish the optimal number of cycles that they could resist.

Another work [5] studied pylon. Its focus was to establish optimal alternatives involving composite materials. The purpose of the project was to lower costs and reduce mass. The material was designed and modeled in SolidWorks, and some tests were performed. Some of the relevant tests performed on the materials were the tensile and fatigue tests. The material was also analyzed by finite element methods. The outcome was a pylon lighter than a common aluminum or titanium one. It also behaved in the tests better than common materials.

In summary, the study of mechanical properties in composite materials is a wide field of investigation that is still in development. Previous research shows that it is important to consider the material in terms of the applications to obtain optimum results on the project. The most important categories of materials are the main constituents (single alloys, single composites, or multilayered composites), their capacity to support loadings, and their weight distribution. Another major concept to consider is the type of loading to which it is subjected and how it makes the part behave in terms of deformations. Considering the previous information, the present project will be centered on studying how weight and durability are affected by using a reinforced composite on the major components of a transtibial prosthetic.

The purpose of this project was to study the effects of static loads on a transtibial prosthetic structure by analyzing the elastic properties acting on a 3D model made of composite materials. The study area focused on solid mechanics, which involved the study of elastic and plastic properties present on the material. At the same time, it is important to establish the basics of material selection, taking into consideration its composition, mass, and mechanical properties.

METHODOLOGY

To comply with the proposed objectives of the project, the following methodology was employed. The work was performed by simulation with the SolidWorks software, in which the model of a transtibial prosthetic underwent various kinds of tests. The first phase was to design the CAD models of the pieces in the modeling software. The parts that were designed were a foot, a pylon, and a socket. These elements were designed to assign common materials and composite alternatives to determine mass distributions. The next phase involved the study of the properties such as stress, strain, deformations, and displacements due to applied forces. These tests were performed on the simulator of the software. The last phase involved the study of the assembly to define the fatigue and buckling of several combinations. Lastly the results were compared to establish the alternative with the best results.

RESULTS AND DISCUSSIONS

Weight and Mass Distribution Results

Several tests and analysis were conducted to establish the optimal combination of materials to use on the models. The materials analyzed were common materials such as aluminum Al 6061T6 and titanium TI-13V-11Cr, having densities of 2700 $\frac{kg}{m^3}$ and 4820 $\frac{kg}{m^3}$ respectively; and composite materials such as carbon fiber Hexcel AS4C 3k, fiberglass type S, perlon fiber PA 6, and HDPE. The densities of the composites were 1780 $\frac{kg}{m^3}$, 2485 $\frac{kg}{m^3}$, 1120 $\frac{kg}{m^3}$, and 952 $\frac{kg}{m^3}$ respectively. Each material was assigned and tested based on its purpose and usage. The volume of each part was as follows: $2.89x10^{-4}\ m^3$ for the foot, $7.6389x10^{-5}\ m^3$ for the pylon, and $3.1789x10^{-4}\ m^3$ for the socket. In terms of mass, the following was obtained: for the foot, the aluminum option's mass was 0.78 kg (1.72 lb), the titanium option's mass was 1.39 kg (3.07 lb), the carbon fiber option's mass was 0.51 kg (1.13 lb), and the fiberglass option's mass was 0.72 kg (1.58 lb) (table 1).

Table 1
Mass distribution of materials used on foot

Materials Used on Foot			
Common Materials		Composite Materials	
Aluminum	0.78 kg/1.72 lb	Carbon Fiber	0.51 kg/1.13 lb
Titanium	1.39 kg/3.07 lb	Fiberglass	0.72 kg/1.58 lb

For the pylon, or connecting rod, the results are presented on table 2. The aluminum alternative had a mass of 0.21 kg (0.45 lb), the titanium model had a mass of 0.37 kg (0.81 lb), and the carbon fiber alternative had a mass of 0.14 kg (0.30 lb).

Table 2
Mass distribution for the materials used on the pylon

Materials Used on the Pylon			
Common Materials		Composite Materials	
Aluminum	0.21 kg/0.45 lb	Carbon Fiber	0.14 kg/0.30 lb
Titanium	0.37 kg/0.81 lb		

For the socket component, due to the complexity of the geometry, the options are the composites and common polymers shown on table 3. The mass was the following: the carbon fiber option had a mass of 0.57 kg (1.25 lb), the perlon fiber option had a mass of 0.36 kg (0.78 lb), the fiber glass option had a mass of 0.79 kg (1.74 lb), and the HDPE option had a mass of 0.30 kg (0.67 lb).

Table 3
Mass distribution of the materials used on the socket

Materials Used for the Socket			
Common Polymers		Composite Materials	
HDPE	0.30 kg/0.67 lb	Carbon Fiber	0.57 kg/1.25 lb
		Fiber Glass	0.79 kg/1.74 lb
		Perlon Fiber	0.36 kg/0.78 lb

Therefore, considering the mass distribution of the studied materials, the optimal combination for a lighter prothesis is a foot and a pylon made of carbon fiber and a socket made of HDPE (table 4).

Table 4
Mass distribution of the assembly

Assembly Components		
Foot (carbon fiber)	0.51 kg	1.13 lb
Pylon (carbon fiber)	0.14 kg	0.30 lb
Socket (HDPE)	0.30 kg	0.67 lb
Total Mass	0.95 kg	2.1 lb

Stress Results and Analysis

Moving on with the tests performed, the modules of failure were analyzed, taking into consideration the stress, strain, and displacement, fatigue, and buckling presented by each component, which was subjected to a static load of 1334N (300 lb). Figure 1 shows the results for the foot model. The aluminum option presented a yield strength of 275 MPA and the model presented localized points in which the stress overcomes the limit. The titanium alternative yield strength was 830 MPA; it also presented localized points of stress overcoming the limit, but it was not as significant as on the aluminum option. The composite materials alternatives presented better results. The carbon fiber option had a yield strength of 2.26 GPA; in this case, the damage was reversible because it did not exceed the limit. Meanwhile, the fiberglass option presented a yield strength of 4.2 GPA, and it was also inside the elastic region, which means it did not deform.

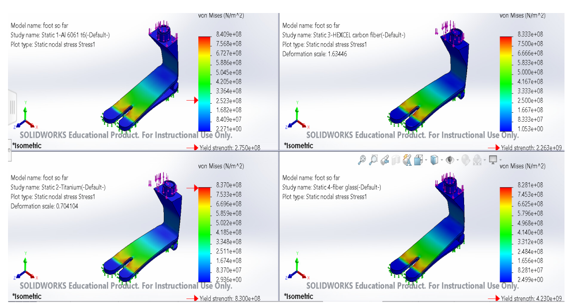

Figure 1
Stress distributions on foot element

The same analysis was performed on the pylon. Figure 2 shows the results obtained on the element modeled on the same aluminum, titanium, and composite carbon fiber as the foot element. In this case, all model stresses were below the yielding limits respectively; therefore, there was no considerable damage on the part.

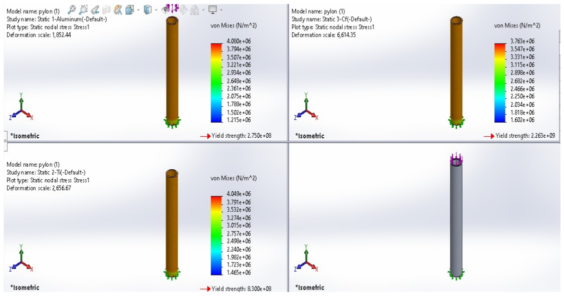

Figure 2
Stress distributions on pylon element

Figure 3 shows the results obtained on the socket. The analysis was performed on CAD models made of carbon fiber with yield strength of 2.26 GPA, perlon fiber with strength of 0.104 GPA, fiberglass with yield strength of 4.2 GPA, and HDPE with a very low yield strength of 41 MPA. Similarly to the pylon, the models were below the elastic limit, which implies that the deformation was not permanent.

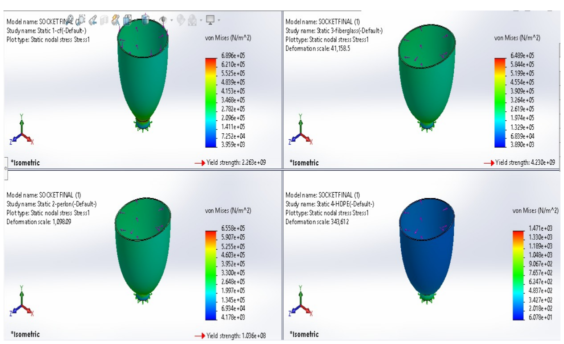

Figure 3
Stress distributions on socket element

Strain Results and Analysis

Analyzing the results obtained for the strain, the following was found (figure 4): the aluminum alternative had an average strain deformation of $3.61\text{x}10^{-3}$ and in the titanium version the strain was $4.21x10^{-3}$. Regarding the composite material alternatives, the carbon fiber model presented a strain of $5.76x10^{-2}$ and the fiberglass model had a strain of $3.80x10^{-3}$. The zone near the toe was the most deformed area; however, the deformations were not significant enough to produce failures or shape variations. Therefore, they are considered small strains due to being much lower than 1.

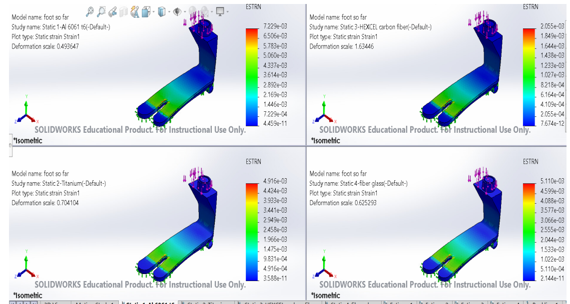

Figure 4
Strain distributions on foot element

Figure 5 shows the results of the strain for the pylon element: aluminum had a strain of $3.85x10^{-5}$, titanium had a strain of $2.69x10^{-5}$, and carbon fiber had a strain of $1.08x10^{-5}$. In this case, the strain was uniform along the element, resulting in higher deformation near the end of the shaft. However, the deformations were not significantly enough to produce changes nor failure on the studied element. Since the strain was on the order of $x10^{-5}$, it is considered small strain because it is way lower than 1 (ε<<1).

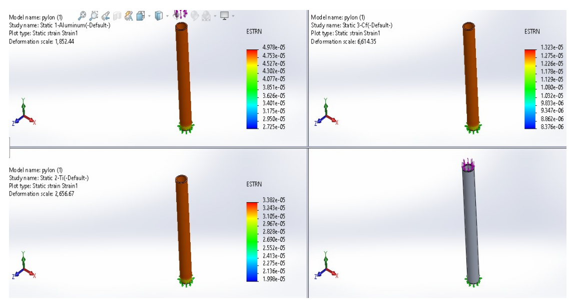

Figure 5
Strain distributions on pylon element

Regarding strain suffered by the socket component (figure 6), the following strains were established: for the model tested on carbon fiber the strain was $9.86x10^{-7}$, perlon fiber had a strain of $8.58x10^{-5}$, fiberglass had a strain of $2.33x10^{-6}$, and HDPE had a strain of $6.51x10^{-7}$. For this element, the strains ranged from 10^{-7} to 10^{-5}, resulting in lower strains than the other elements, meaning small strain and low deformations on the part. In addition, the strain was more distributed along the model on all four cases, resulting on resistance to change and deformation, and acceptable values below the limit of 1 for small strains.

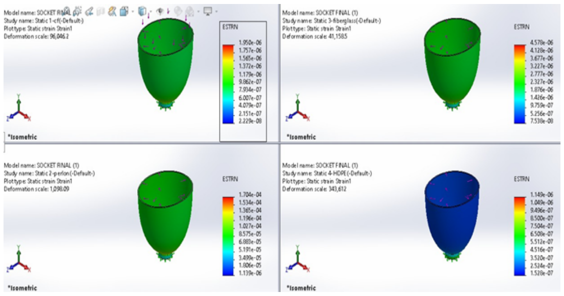

Figure 6
Strain distributions on socket element

Displacement Results and Analysis

Displacement was analyzed on the same models. Figure 7 presents the displacement results for the foot component: the aluminum alternative shows an average displacement of 3.19 mm and titanium had 2.24 mm of displacement. On the composite materials alternatives, carbon fiber presented a displacement of 0.96 mm, and fiberglass had displacement of 2.52 mm. For this component, displacement was mostly perceived on the heel of the foot, especially near the connecting end. These displacements are significantly low due to the strain deformation values which makes them acceptable. As predicted, the composite alternatives behave better than the common material options.

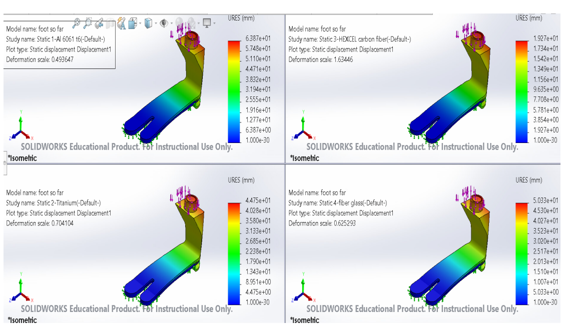

Figure 7
Displacement on foot element

Figure 8 shows results of displacement on the pylon component. The aluminum alternative had 0.0081 mm of displacement, the titanium option had a displacement of 0.0056 mm, and the carbon fiber model had a displacement of 0.0023 mm. This component presented considerably low displacement on all cases, due to the low strains presented. The more focused displacement was reported on the free end near the load. Meanwhile, the fixed end's displacement was unnoticeable. Therefore, the displacements are acceptable. The difference is not significant, but the composite alternative showed the lower displacement.

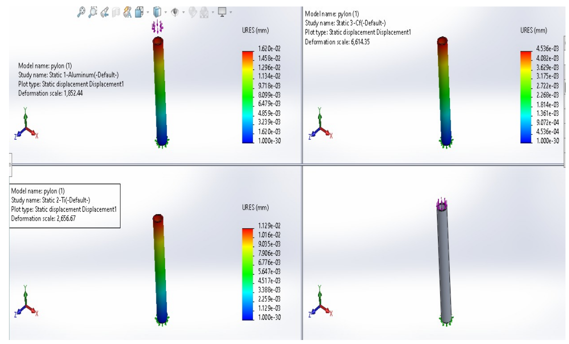

Figure 8
Displacement of pylon element

After analyzing the results on figure 9 for the displacement of the socket, it was observed that the alternative modeled on carbon fiber had a displacement of 0.00016 mm, the perlon fiber alternative had a displacement of 0.1360 mm, the fiberglass option had a displacement of 0.00037 mm, and HDPE had a displacement of 0.00004 mm. In this case, displacement varied in the same way as strain; however, the values were considerably low. The maximum displacement zone were the walls of the socket near the free end; the displacement on the base of the socket was unnoticeable and, therefore, acceptable.

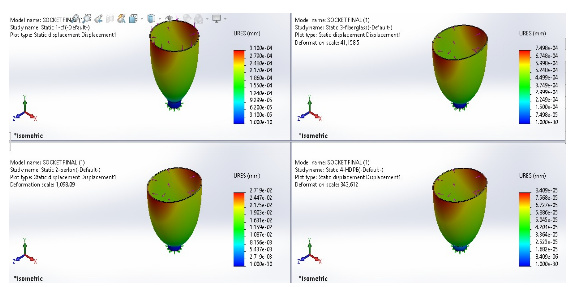

Figure 9
Displacement of socket element

Fatigue and Buckling Results and Analysis

To establish durability, a fatigue test was performed taking in consideration the following combinations with a socket made of HDPE: foot and pylon made of aluminum (figure 10), foot and pylon made of titanium (figure 11), foot and pylon made of carbon fiber (figure 12), and foot and pylon made of fiberglass (figure 13).

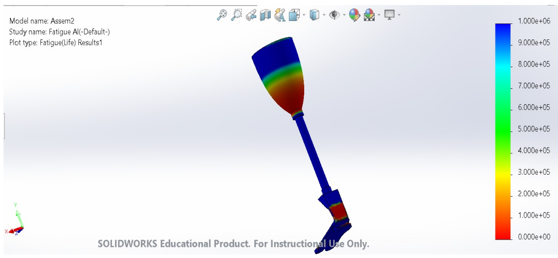

Figure 10
Fatigue test on assembly aluminum-aluminum-HDPE

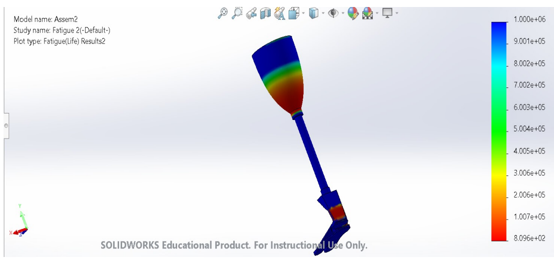

Figure 11
Fatigue test on assembly titanium-titanium-HDPE

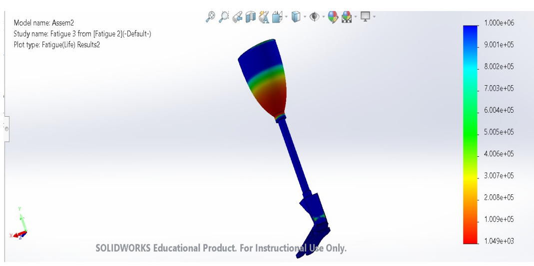

Figure 12
Fatigue test on assembly carbon fiber-carbon fiber-HDPE

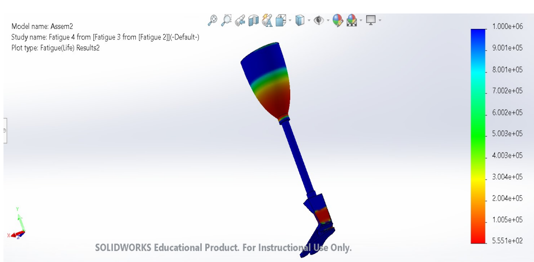

Figure 13
Fatigue test on assembly fiberglass-fiberglass-HDPE

The results obtained were that the common material models presented areas of low-cycle fatigue ranging from the order of 10^2 and an extended damage area significantly seen on the base of the foot. For the models made of composite materials, the results were mixed: the model made of fiberglass presented large damage areas, but they were reaching the borderline of low-cycle fatigue with the order of $5.551x10^2$. However, the parts modeled on carbon fiber presented high-cycle fatigue and smaller damage zones on the foot. The pylon of every model reached infinite life and the socket that was modeled on HDPE exhibited high-cycle fatigue ranging from the order of 10^5. Therefore, in terms of durability, the carbon fiber models overcame the common material models.

Also, a buckling test was performed on the previous mentioned assemblies assuming fixed-free configuration. This test is measured on ampres, which means "resultant amplitude." For the first configuration (Al) (figure 14), the maximum amplitude was 0.01738 and a load factor of 0.72421. The next configuration (Ti) (figure 15) had a maximum amplitude of 0.01737 and a load factor of 1.0302. The carbon fiber assembly (figure 16) presented a maximum amplitude of 0.01737 and a load factor of 2.3867. The fiberglass option (figure 17) presented a maximum amplitude of 0.6345 and a load factor of 1.216. Therefore, carbon fiber excelled on all the tests.

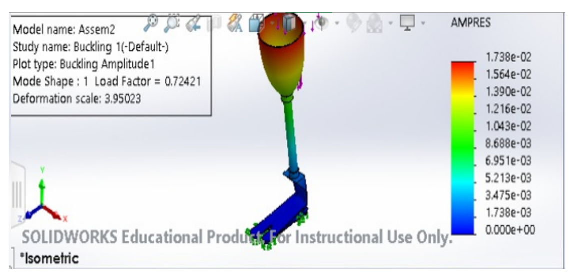

Figure 14
Buckling test on assembly aluminum-aluminum-HDPE

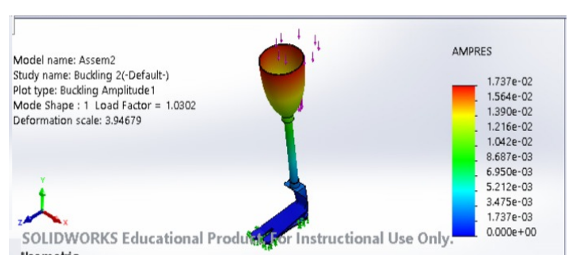

Figure 15
Buckling test on assembly titanium-titanium-HDPE

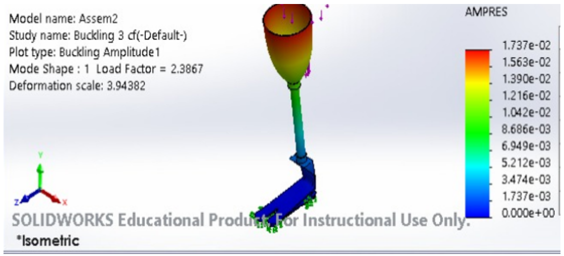

Figure 16
Buckling test on assembly carbon fiber-carbon fiber-HDPE

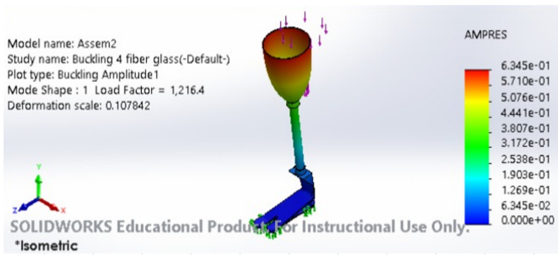

Figure 17
Buckling test on assembly Fiberglass-Fiberglass-HDPE

Conclusion

After reviewing the results, it can be concluded that the objective of the project was met, which was to test and prove that the composite materials are a better alternative for the manufacturing of medical equipment due to their capacity to withstand the loads more appropriately, while being lighter than common materials. In terms of mass, it was proven that the lighter option for the model was a foot and pylon made of carbon fiber and a socket made of HDPE. In terms of stresses, the carbon fiber alternatives endured the loads without reaching elastic limits, as well as the alternatives used on the socket element. Also, the strains and displacements present in the composite alternatives were lower than the ones in the common materials. In terms of durability, the composite models reached high-cycle fatigues and, on the pylon, infinite life was achieved. When testing for buckling, deformation was lower on the composite materials. In conclusion, the composite material alternatives did better on the tests, therefore meeting the proposed objective.

Recommendations

The field of composite materials and its properties is a wide study area that is still in development and requires more learning. Some recommendations for future projects: expanding on the types of composite materials, studying different behaviors, analyzing other compositions of the studied materials, and exploring other geometries for the developed models. Another recommendation is studying the economic impact of the different materials.

References

[1] R. C. Hibbeler, "Mechanical properties of materials," in *Mechanics of Materials*, 9th ed., Boston, Prentice Hall, 2014, pp. 82–117.

[2] K. Kaw, "Introduction to composite materials," in *Mechanics of Composite Materials*, 2nd ed., New Wark, FL, Taylor & Francis Group, 2006, pp. 1–46.

[3] L. Yousif, K. Resan, and R. Fenjan, "Temperature effect on mechanical characteristics of a new design prosthetic foot," *IJMET*, vol. 9, no. 13, pp. 1431–1447, Dec. 2018. Available: https://iaeme.com/MasterAdmin/Journal_uploads/IJMET/VOLUME_9_ISSUE_13/IJMET_09_13_143.pdf

[4] M. J. Jweeg, Z. S. Hammoudi, and B. A. Alwan, "Optimised analysis, design, and fabrication of trans-tibial prosthetic sockets," 2nd International Conference on Engineering Sciences, 2018. Available: https://iopscience.iop.org/article/10.1088/1757-899X/433/1/012058/pdf

[5] M. S. A.-D. Tahir and F. M. Kadhim, "Design and manufacturing of new low (weight and cost) 3D printed pylon prosthesis for amputee," *INTCSET*, 2020. Available: https://iopscience.iop.org/article/10.1088/1757-899X/1094/1/012144/pdf