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Fatigue and Tensile Characteristics for Composite Materials Used in Prosthetic Socket

Zuhair Salim Khamees[1a*] **and Asmaa Shawqy Khalil**[1b]
[1]*Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq*
[b]E-mail: asmaa.khalee@sc.uobaghdad.edu.iq
[a*]Corresponding author: zouher.salem1104a@sc.uobaghdad.edu.iq

Abstract

In this research, the use of natural materials like wool and cannabis as intermediate reinforcement for prosthetic limbs due to their comfort, affordability, and local availability was discussed. As part of this study on below-the-knee (BK) prosthetic sockets, two sets of samples were made using a vacuum method. These sets were made of natural fiber-reinforced polymer composites with lamination 80:20: group (Y) had 4 perlon, 1 wool 4 perlon, and group (G) had 4 perlon, 1 cannabis 4 perlon. The two groups were compared with a socket made of polypropylene. Tensile testing was used to determine the mechanical characteristics of the socket materials. The Y group has a yield stress of 17 MPs, an ultimate strength of 18.75 MPa, and an elastic modulus of 4.021 GPa, while for the G group, these values are 12.75 MPa, 18.84 MPa, and 4.076 GPa, respectively. The fatigue test was used to evaluate the failure characteristics of the socket. An F-socket was utilized to test the interface compression between both the limb and the socket. For the Tekscan sensor, the calculated pressure in the medial region is 350 K Pa, while it is 330 KPa in the posterior region. Solid Works software was used to draw a prosthetic socket for the numerical study. The failure safety agent for the composite material for group Y was 1.26. The finite element method (ANSYS Workbench 14.5) was used to look at the fatigue characteristics to detect the maximum stress, safety factor, and total deformation.

Article Info.

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Composite Materials, Mechanical Properties, Wool, Cannabi, Prosthetic Socket.

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1. Introduction

In Iraq, 55% of amputations occur as a result of diseases or poor medical care given to patients [1, 2]. Ordinarily, lower limb amputations below the knee (BK) account for 80% of all amputations [3, 4]. Artificial lower limbs, or so-called prostheses, are used to replace the function or appearance of missing parts as much as possible [5, 6]. Knowing and studying the tensile and fatigue properties of the materials used helps to choose the appropriate design for the patient's prosthesis relative to his age, weight, health, nature of the activity, and psychological condition [7, 8]. Fiberglass is the most common and economical reinforcement in orthopedics due to its durability and flexibility. Carbon fibers offer rigidity and shape retention under stress [9, 10]. However, these materials are produced from unsustainable sources and generate harmful radiation [11-13]. Alternative materials such as biomaterials, retention resins, fibers, and plant derivatives can be used when materials are affordable and demand is high, such as in earthquake or combat zones [14, 15]. In this research, the use of wool and hemp as natural fibers instead of carbon fibers, which are artificial materials that may cause side effects, Polymer composites are ideal due to their excellent mechanical properties and ease of production [16, 17]. Hybrid materials, which consist of a matrix and fillers with unique properties, are being researched for use in prosthetic limb reinforcement, replacing artificial fibers with natural fibers. Fillers like carbon fibers, glass beads, sand, and ceramics are used in this field [18, 19]. Technological advancements have expanded the range of modern orthopedic and prosthetic devices, with fiber-reinforced composites being the most commonly used due to their superior strength and biocompatibility [20, 21]. Wichita et al. looked into how methyl methacrylate polyester resin and water hyacinth fiber composite sockets could be used instead of traditional materials. They tested how well they worked mechanically and whether they were good for socket prostheses [22]. Ayad M. Takhakh conducted an experimental study on three laminated composite materials to examine the mechanical properties of a partial foot prosthetic socket fabricated using a vacuum pressure system [23]. Group researchers presented material properties and stress analysis of sockets with knee prostheses by increasing the layers of composite material to strengthen the socket properties [24]. In other studies, the mechanical characteristics of laminated kenaf woven fabric composites were studied for the application of sockets under the knee [25]. In a study by Majdi Ahmed et al., the mechanical properties of Teflon and polyvinyl chloride materials used for prosthetic sockets for lower limbs were compared to those of standard (PP) materials [26]. Hawraa Ahmed Hamzah suggested using date palm nuts powder as a reinforcing material in lower prostheses socket production, in addition to lamination resin [27]. Researchers led by A.S. Harmaen created composite materials by mixing kenaf core with polypropylene and silica aerogel. These materials improved tensile modulus, tensile strength, and impact strength by testing them in impact tests [28]. Muhsin J. Jweeg et al. studied the mechanical properties of composite materials for socket prostheses below the knee. In which they determined maximum stress, elastic modulus, and GRF and used ANSYS 16.0 software for deformation and dynamic stress calculations. The composite material outperformed traditional polypropylene and performed better in FEL modeling [29]. Saif Mohammed Abbas and Mohammed Hassan Abbas used a new approach to increase the suspension of above-knee prostheses made from carbon fiber using a revo-fit solution [30]. Yassr Y. Kahtan worked on the modal analysis of below knee sockets using finite element software (ANSYS Workbench 15) [31]. Saif M. Abbas studied the fatigue characteristics with analysis modeling for a new resin with carbon fiber and nile glass of the above knee prosthetic socket [32, 33].The research aims to study the properties of materials used to reinforce prosthetic limbs by replacing artificial fibers with natural fibers.

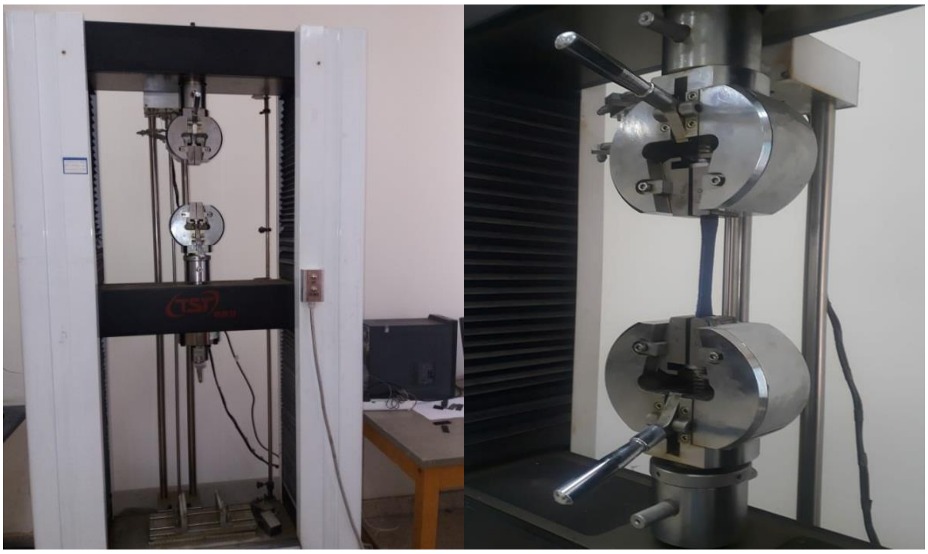
2. Experimental Work

2.1. Materials

This study's focus is on a prosthetic socket that was made from matrix lamination resin 80:20 (polyurethane) and reinforced with wool, cannabis, and perlon. It was hardened with powder. The test samples were prepared using a vacuum apparatus and polyvinyl alcohol (PVA).

2.2. Instruments

The tensile test was performed on the samples to determine their mechanical properties using the WDW-100 test machine, as shown in Fig. 1. The modulus of elasticity, yield strain, and ultimate stress of the materials utilized to manufacture prosthetic limb sockets were calculated using a computer-numerical control machine (CNC) to cut for each sample according to the American Society of Testing Materials ASTM D638(I) dimensions [34, 35]. The samples were tooled as shown in Fig. 2. A tensile test was carried out on the samples at room temperature with a speed of 1 mm/min by means of a tensioning machine with a load capacity of 5 N [36].



(a) Testing machine. **(b) During test.**

Figure 1: Mechanical testing machine.

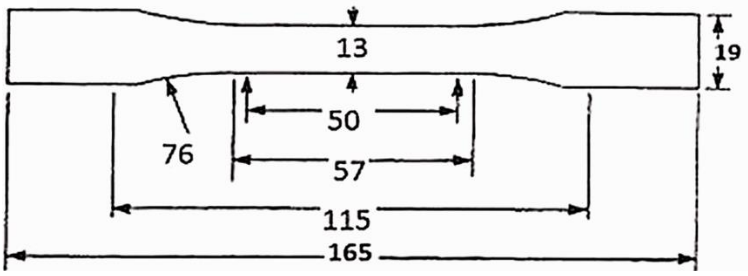


Figure 2: Specimen for tensile test [35].

The fatigue test was performed on five samples for each laminate. These samples have lengths of 100 mm and widths of 10 mm, with thicknesses varying according to the layup. The fatigue sample is depicted in Fig. 3.

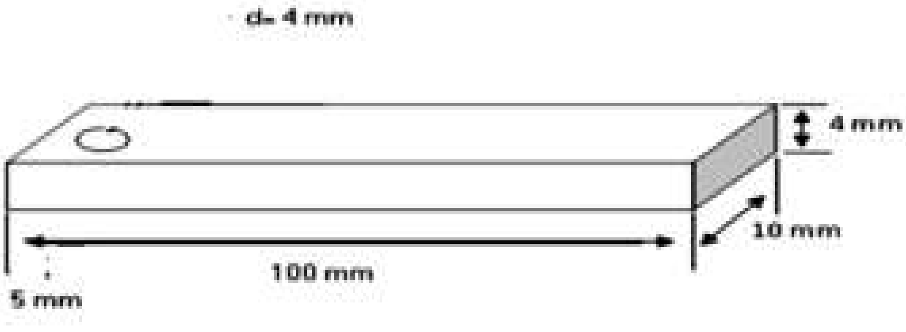


Figure 3: Dimensions of the fatigue test specimen [37].

Fig. 4 shows a fatigue testing machine as an application of alternating bending stress with constant amplitude. The specimens are subject to deflection columnar to the axis of the specimens on one side, and the other side is clamped, resulting in bending stresses [38].

Figure 4: Fatigue Machine.

2.3. Preparation Samples

To find out the mechanical properties of the composite materials being studied, samples were made in a way that is similar to how prosthetic sockets are made, with flaws and holes being avoided by using a vacuum process. Gypsum templates with dimensions of 20, 10, and 10 cm were made in the first stage. Following that, a vacuum pulled a thin layer of polyvinyl alcohol (PVA) up against the mold and covered it. Next, many layers of reinforcing material were added. The mold, which has an upper intake for liquid plastic, receives a second PVA coating. The addition of 80:20 polyurethane lamination resins with hardener was followed. The cubic composite materials were created during resin curing, and then they will be cut to the required dimensions of the samples.

3. Results and Discussion

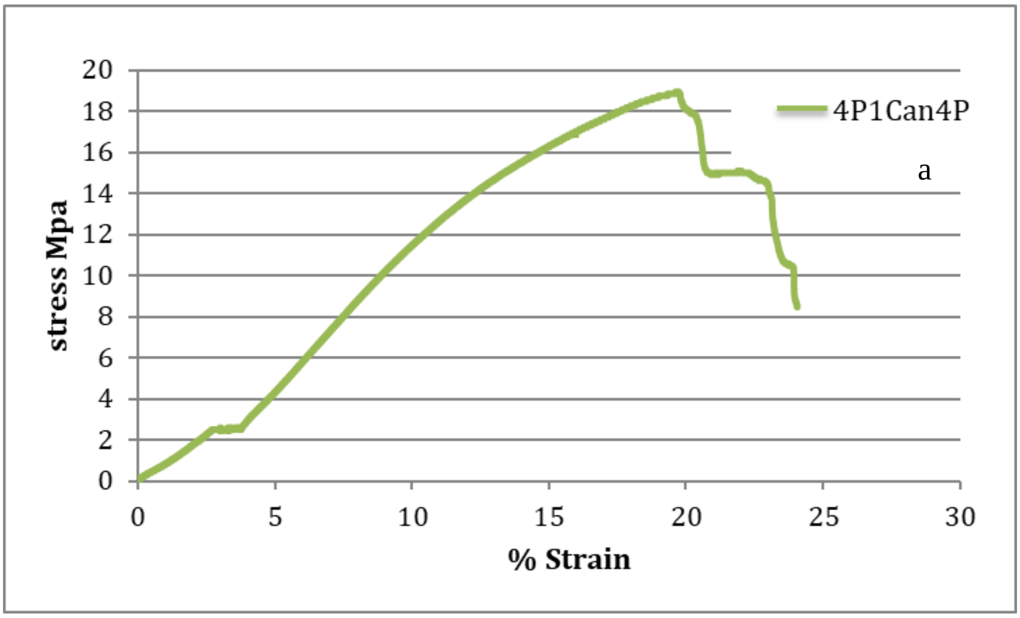
3.1. Tensile Characteristics

Table 1 provides the predefined mechanical characteristics of the used laminations. Fig. 5(a and b) shows the stress-strain graph for all the laminations. It was found that group Y's traits decreased yield strength by 37.5%, increased ultimate tensile strength by about 49.7%, and decreased E by 224% compared to the control group (Group pp). Group (Y) employs one layer of wool in the center with four layers of perlon on either side. However, combining four layers of perlon on either side of the group (G) with one layer of cannabis reduced yield strength by 53%, increased ultimate tensile strength by 49.5%, and increased E by 228.7%. The variations in the mechanical properties of the two groups of composite materials are due to the varying mechanical properties of the layers consisting of each composite material.

Table 1: The mechanical characteristics of the used laminations.

Groups Name	**Reinforcement**	**Yield Stress (**Mpa)	**Ultimate Strength (**Mpa)	**Young Modulus (Gpa)**	**Thickness (mm)**
Y	4p 1Wo 4p	17	18.75	4.021	4
G	4p 1Can 4p	12.75	18.84	4.076	4
Polypropylene [39] **(**pp**)**	Sheet	27.2	37.3	1.24	6

where Can refers to Cannabis, P refers to Perlon and Wo refers to Wool.



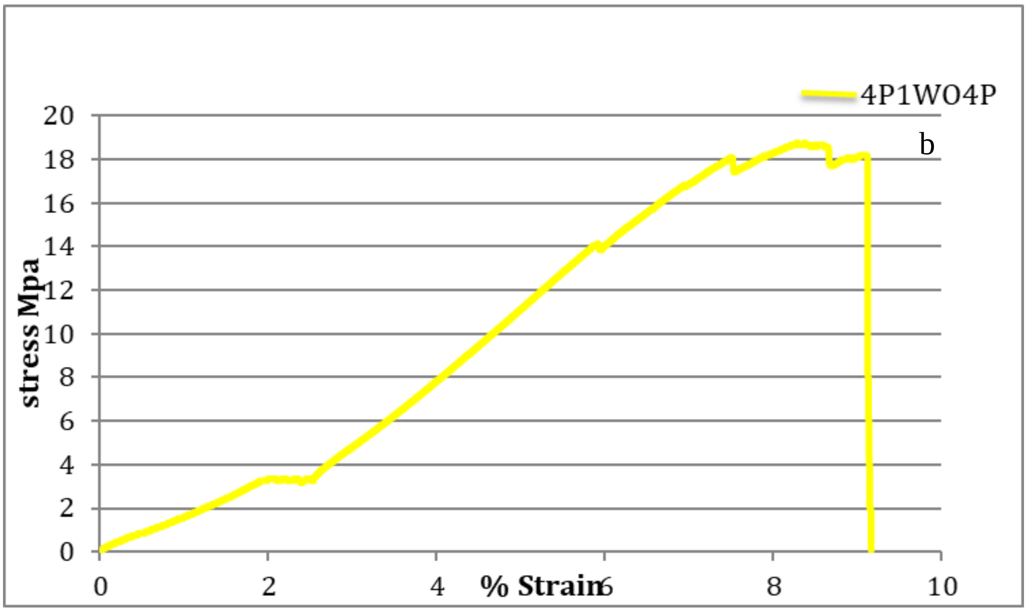


Figure 5: Stress-strain curve for the (a) group G, (b) group Y.

3.2. Fatigue Properties

Fatigue is a significant phenomenon that must be considered when analyzing the behavior of mechanical components subjected to constant and changing amplitude loads [40, 41]. Flat-sample stress failure can occur when the sample is smashed under cyclic stress. The results of the fatigue tester revealed the number of periods required to break the samples. The fatigue S-N curve is drawn by plotting a curve that reflects the experimental data of fatigue tests [42, 43]. Figs. 6 (a and b) show the S-N graphs for five specimens from each lamination. The fatigue test sample is illustrated in Figs.7 (a and b).

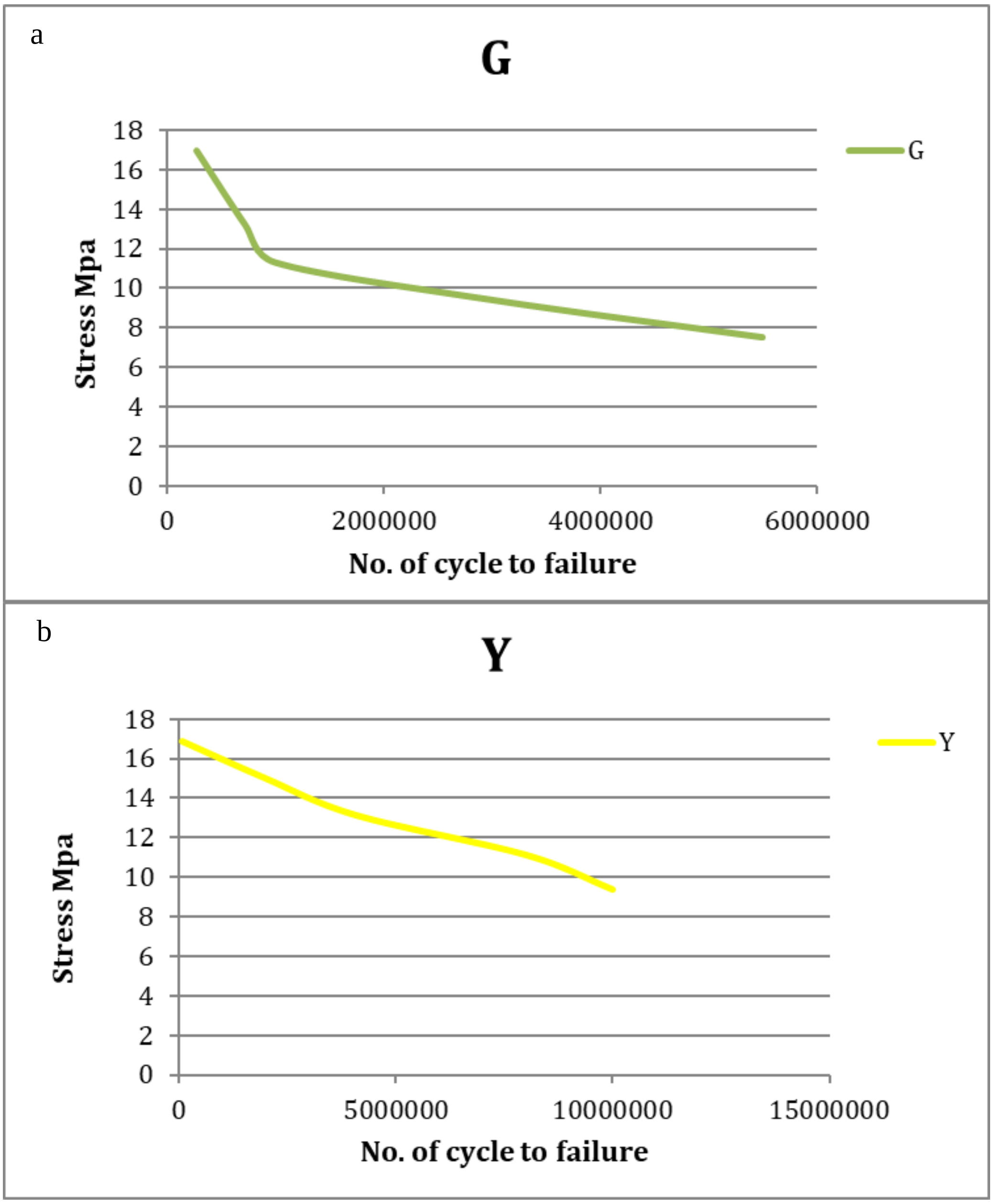


Figure 6: S-N curves for (a) group G. (b) group Y.

In the figures above, reducing failure stresses increases the number of failure cycles at the same temperature.

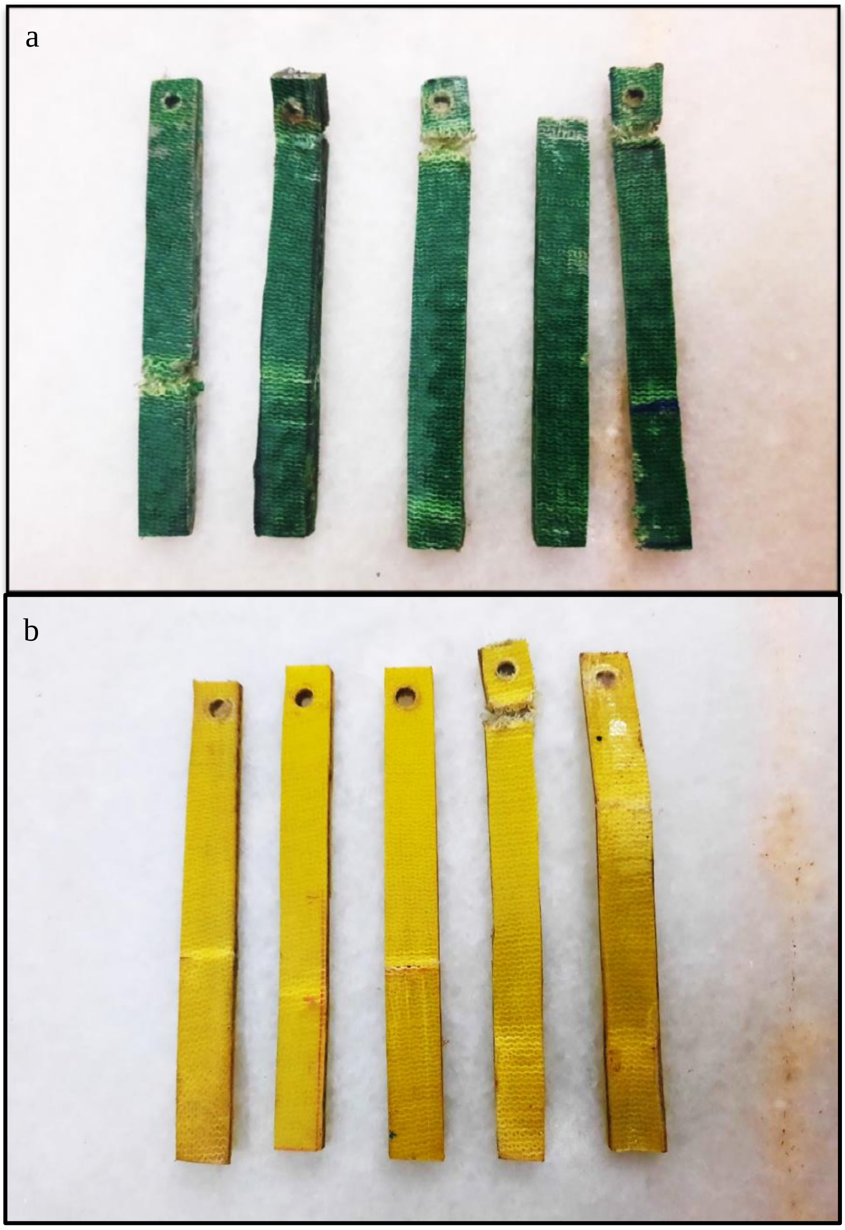


Figure 7: Samples after the fatigue test for (a) group G. (b) group Y.

3.3. Numerical Results

The finite element method (FEM), which is now widely used in a variety of fields in engineering and science, has three distinct steps [44, 45]. The first step is to create the geometric model using SOLID WORK software to draw the geometry using the dimensions of the artificial cavity, as seen in Fig.8 (A). The stresses are then divided into 15 stress zones and applied to the geometric model of the actual shape of the knee cap in Fig.8 (B). The ANSYS (workbench) preparation of the model for the lattice process entails selecting the size of the element, followed by selecting the shape of the element as a tetrahedral (automatic lattice) [46, 47], as seen in Fig.8 (C). To achieve a reasonable level of accuracy, the structure must be divided into a sufficient number of elements (this mesh has 3591 nodes and 1737 elements) to function as an artificial cavity. The second phase identifies materials with physical and mechanical properties, applicable boundary conditions, and load, which will act as a firm support in the socket adapter. As seen in Fig. 8 (D), the third step is reviewing the results [48, 49]. The interface stresses generated by the test was distributed over the F-socket according to certain positions in the front, back, middle, and side areas. The mechanical properties of each group of composite material parameters were added to the ANSYS data, which was used to compute the maximum pressure, safety factor, and cavity deformation. A finite element program (ANSYS 14.5) was used to find the equivalent (Von Mises) stress, total deformation, and fatigue safety factor for a patient's below-the-knee fixed prosthetic socket model. When the fatigue safety factor is equal to or greater than 1.25, it is considered safe in design applications [50].

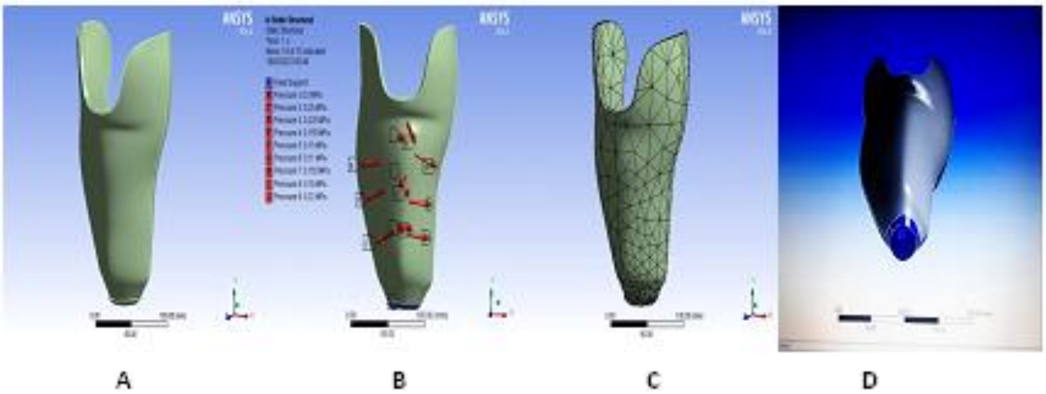


Figure 8: (A) Socket in Solid Work program (B) Socket divided into 15 parts (C) Meshing process of the socket and (D) Fixed support at the adapter of socket.

3.3.1. Safety Factor

The analysis of the socket models achieved by FEM software was used to compute the safety factor of fatigue. The safety factor for the suggested composite material groups of the socket model is passed into the design. The value of the safety factor varies from region to region depending on the distribution of stresses generated and the endurance stress for each group of composite materials. Each color indicates a certain gradient of values for the safety factor. The values of the safety factor are greater than 1.25, as shown in Figs. 9 (a, b), in group Y, and less in group G, of the composite material. The fatigue safety factor will be safe in design if the safety factor is equal to or higher than 1.25 [50].

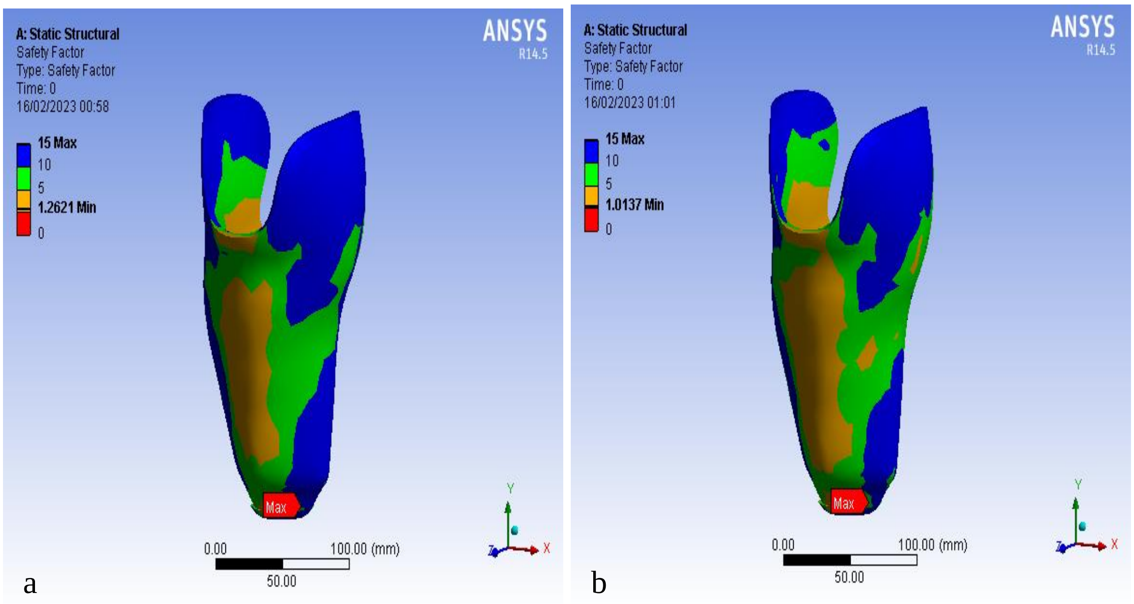


Figure 9: The safety factor for fatigue (a) Group Y, and (b) Group G.

3.3.2. Von Mises Analysis Stress

The numerical analysis is performed to obtain the values of stresses that are generated in the parts of the socket due to the generation of the interface pressure between the socket, the muscles, and the body weight during walking. The results of the analysis showed that the maximum value of stress generated in the socket is equal to 7.428 Mpa, as shown in Figs. 11 (a and b). The difference between the highest stress of 7.428 Mpa that was created in the socket and the yield stresses of 17 Mpa for group (Y) and 12.75 Mpa for group (G) shows that the suggested materials can handle the patient's weight and can be used instead of the materials that are currently used to make the socket, especially for group Y.

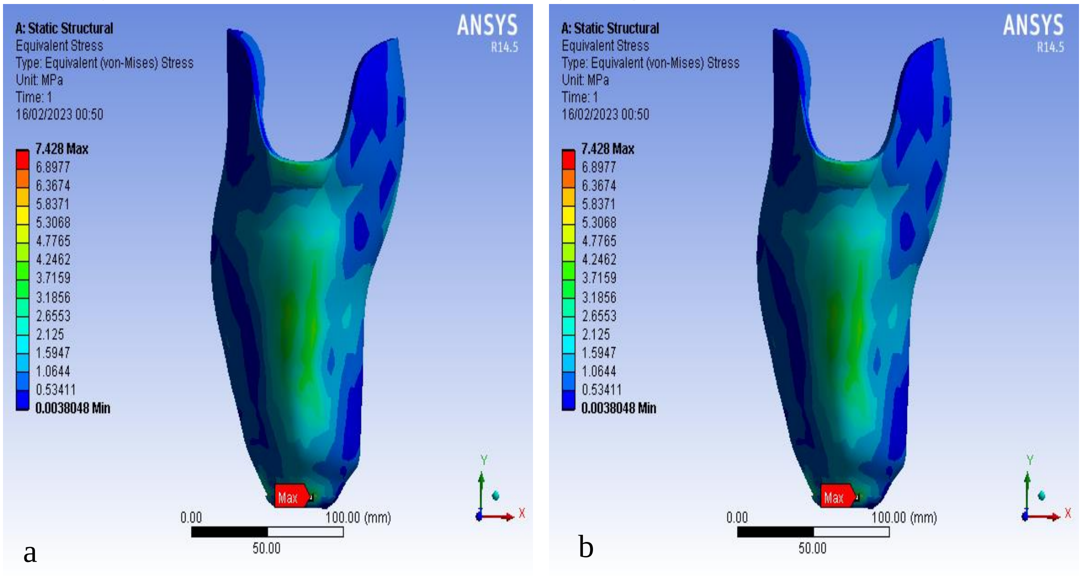


Figure 11: Von-Mises stress for (a) Group Y and (b) Group G.

3.3.3. The Numerical Analysis of Deformation

The deformation analysis provides knowledge of the values and location of the total deformation of the socket. The maximum deformation value of the socket is 0.66 mm for the model manufactured for group Y of the composite material as shown in Fig. 12 (a) while the maximum deformation recorded is 0.67 mm for the model using group G of the suggested composite material as shown in Fig. 12 (b). The deformation values for the socket were convergent for the two groups.

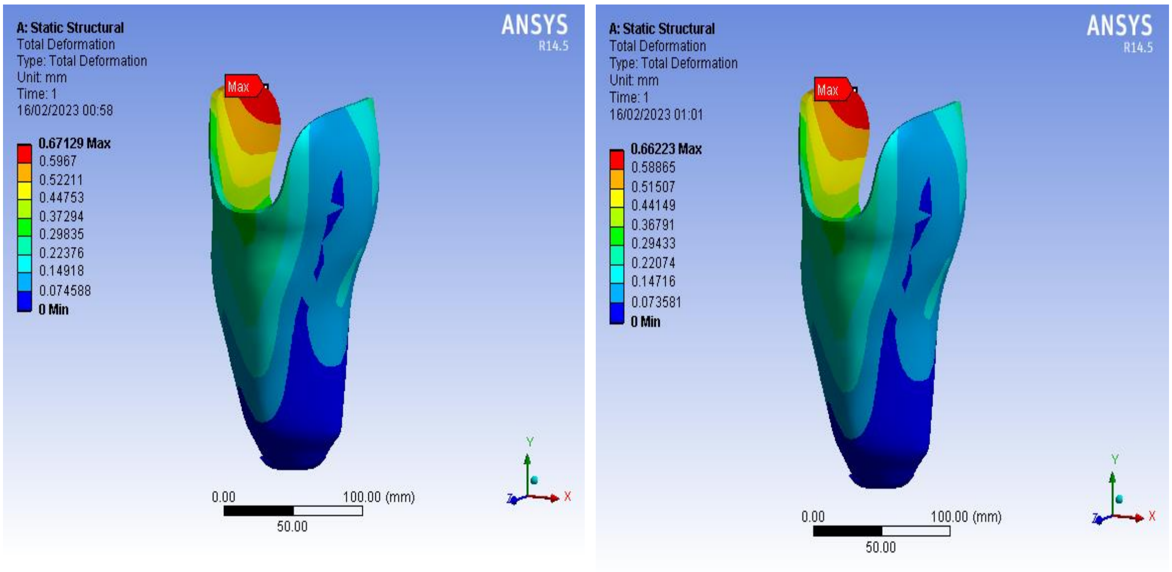


Figure 12: Total deformation (a) Group Y and Group G.

4. Conclusions

Group Y materials were more successful than Group G in the mechanical and safety factor tests. When group (Y) used four layers of perlon (p) on both sides and one layer of wool (wo), the stress and ultimate tensile strength went down by about 37.5% and 49.7%, respectively, while the elastic modulus values went up by about 224% compared to group (pp). However, group G achieved improvements of 228.7% E, and the resulting stress and final tensile strength decreased by about 53% and 49.5%, respectively. The reason for the decrease in tensile values is attributed to the different properties of wool and hemp compared to synthetic fibers. However, the use of natural fibers is a successful alternative. At a certain limit of patients' weight, while using one layer of hemp in the middle with four layers of perlon on both sides of group Y, the composite material socket type below the knee has a fatigue safety factor of 1.26, which is a safe by design.

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Conflict of Interest

Authors declare that they have no conflict of interest.

References

1. A. Takhakh, Int. J. Mech. Mechatron. Eng. **18**, 62 (2018).
2. M. Ahmed, M. Abd-Alrahman, M. Abdallah, and M. Zarog, Int. J. Mech. Ind. Tech. **6**, 18 (2018).
3. J. S. Chiad and M. S. a.-D. Tahir, Al-Nahrain J. Eng. Sci. **20**, 832 (2017).
4. A. M. Takhakh, S. M. Abbas, and A. K. Ahmed, in IOP Conference Series: Materials Science and Engineering (IOP Publishing, 2018). p. 012045.
5. J. C. H. Goh, P. V. S. Lee, and S. Y. Chong, J. Rehab. Res. Develop. **41**, 491 (2004).
6. M. J. Jweeg, A. Alhumandy, and H. Hamzah, Int. J. Mech. Mechatron. Eng. **17**, 100 (2017).
7. A. N. Kareem and M. H. Faidh-Allah, J. Mech. Eng. Res. Develop. **44**, 329 (2021).
8. A. S. Abbas and S. D. Dawood, ARPN J. Eng. Appl. Sci. **13**, 5633 (2018).
9. H. Wang, H. Memon, E. Am Hassan, M. S. Miah, and M. A. Ali, Materials **12**, 1226 (2019).
10. A. Caggiano, Materials **11**, 442 (2018).
11. M. Bazli, H. Ashrafi, A. Jafari, X.-L. Zhao, H. Gholipour, and A. V. Oskouei, Comp. Part B: Eng. **157**, 76 (2019).
12. Y.-J. Hu, C. Jiang, W. Liu, Q.-Q. Yu, and Y.-L. Zhou, Sensors **18**, 3361 (2018).
13. G. Li, J. Zhao, and Z. Wang, Materials **11**, 1028 (2018).
14. N. K. Faheed, J. K. Oleiwi, and Q. A. Hamad, Eng. Tech. J. **39**, 1715 (2021).
15. A. I. Campbell, S. Sexton, C. J. Schaschke, H. Kinsman, B. Mclaughlin, and M. Boyle, Prosthet. Orthot. Int. **36**, 181 (2012).
16. B. K. Ibrahim and F. H. Antar, Iraqi J. Sci. **59**, 1587 (2018).
17. A. S. Khaleel, Iraqi J. Sci. **63**, 1971 (2022).
18. S. I. Hussein, N. A. Ali, G. M. Saleh, and H. I. Jaffar, Iraqi J. Sci. **60**, 1 (2019).
19. H. Jaffer, Iraqi J. Phys. **10**, 98 (2012).
20. M. Nurhanisah, N. Saba, M. Jawaid, and M. Paridah, *Green Biocomposites Design and Applications* (Serdang, Selangor, Malaysia, Springer, 2017), p.127.
21. S. M. Abbas, K. K. Resan, A. K. Muhammad, and M. Al-Waily, Int. J. Mech. Eng. Tech. **9**, 383 (2018).

22. D. Widhata and R. Ismail, in IOP conference series: materials science and engineering (IOP Publishing, 2019). p. 012127.
23. A. M. Takhakh, Int. J. Mech. Mechatron. Eng. **18**, 62 (2018).
24. M. A. Al-Shammari, E. Q. Hussein, and A. A. Oleiwi, Int. J. Mech. Mechatron. Eng. **17**, 57 (2017).
25. M. Nurhanisah, F. Hashemi, M. Paridah, M. Jawaid, and J. Naveen, in IOP Conference Series: Materials Science and Engineering (IOP Publishing, 2018). p. 012050.
26. M. Ahmed, M. Abd-Alrahman, M. Abdallah, and M. Zarog, Int. J. Mech. Indus. Tech. **6**, 18 (2018).
27. H. A. Hamzah, MSc Thesis, University of Kerbala, 2018.
28. A. Harmaen, M. Paridah, M. Jawaid, A. Fariz, and B. Asmawi, *Kenaf Fibers and Composites* (Boka, Raton, CRC Press, 2018).
29. M. J. Jweeg, A. A. Ahumdany, and A. F. M. Jawad, Int. J. Mech. Mechatron. Eng. **19**, 108 (2019).
30. S. M. Abbas and M. H. Abbas, *Analysis and manufacturing of above knee prosthesis socket by using revo fit solution*, *IOP Conference Series: Materials Science and Engineering*. 2018, IOP Publishing. pp. 012025.
31. Y. Y. Kahtan, Int. J. Mech. Eng. Tech. **10**, 2127 (2019).
32. S. M. Abbas, in Defect and Diffusion Forum (Trans Tech Publ, 2020). p. 76.
33. M. R. Ismail, Y. Y. Kahtan, and S. M. Abbas, in IOP Conference Series: Materials Science and Engineering (IOP Publishing, 2020). p. 012061.
34. H. Z. Abdalikhwa, M. A. Al-Shammari, and E. Q. Hussein, in IOP Conference Series: Materials Science and Engineering (IOP Publishing, 2021). p. 012170.
35. Z. S. Khamees and A. S. Khaleel, Bio. Gecko. **12**, 1730 (2023).
36. M. Mohamed, N. Fahad, M. Al-Waily, and K. Resan, Int. J. Mech. Eng. Tech. **09**, 729 (2018).
37. M. Al-Waily, A. Kadhim, Z. Alhilo, M. Jweeg, and K. Resan, Int. J. Mech. Mechatron. Eng. **18**, 77 (2018).
38. K. Resan, I. Al-Razaq, and Y. Ibrahim, J. Eng. Develop. **20**, 147 (2016).
39. S. S. Hassan, K. K. Resan, and A. Z. Mahdi, Eng. Tech. J. **31**, 1521 (2013).
40. A. S. Hammood, M. Al-Waily, and A. Abd. Kamaz, Iraqi J. Mech. Mat. Eng. **11**, 344 (2011).
41. D. Al-Zubaidi and M. Al-Shammari, Mat. Sci. Forum **7**, 4667 (2022).
42. M. J. J. Muhsin, Iraqi J. Mech. Mat. Eng. **13**, 689 (2013).
43. Z. A. Ali, A. A. Kadhim, R. H. Al-Khayat, and M. Al-Waily, J. Mech. Eng. Res. Develop. **44**, 392 (2021).
44. M. Al-Waily and A. S. Humod, Iraqi J. Mech. Mat. Eng. **10**, 58 (2010).
45. A. A. Kadhim, E. A. Abbod, A. K. Muhammad, K. K. Resan, and M. Al-Waily, J. Mech. Eng. Res. Develop. **44**, 383 (2021).
46. M. L. Al-Waily, MSc Thesis, Kufa University, (2004).
47. E. K. Njim, S. H. Bakhy, and M. Al-Waily, J. Appl. Sci. Eng. **25**, 339 (2021).
48. F. Mohanad, A. Takhakh, and A. Abdullah, J. Mech. Eng. Res. Develop. **42**, 118 (2019).
49. F. M. Kadhim, J. S. Chiad, and A. M. Takhakh, in IOP Conference Series: Materials Science and Engineering (IOP Publishing, 2018). p. 012078.
50. B. A. Miller, R. J. Shipley, R. J. Parrington, and D. P. Dennies, *ASM International Handbook* (USA, ASM International, 2002).

خصائص الكلال والشد للمواد المركبة المستخدمة في وقب الطرف الاصطناعي

زهير سالم خميس[1] و أسماء شوقي خليل[1]
[1]قسم الفيزياء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة

نظرًا للحاجة المتزايدة للأطراف الصناعية ومواد التصنيع الخاصة بها، فقد ركز هذا البحث على المواد الطبيعية مثل الصوف والقنب كتعزيز وسيط بدلاً من المواد الاصطناعية نظرًا لمزايا الألياف الطبيعية كونها مريحة ورخيصة ومتوفرة محليًا ونجاحها كبديل مقبول للألياف الصناعية. تم اقتراح مجموعتين: مجموعة (Y) 4 بيرلون 1 صوف 4 بيرلون، ومجموعة G، 4 بيرلون، 1 قنب 4 بيرلون، ومقارنة المجموعتين بمقبس مصنوع من البولي بروبيلين. تم استخدام اختبار الشد لتحديد الخصائص الميكانيكية للمآخذ. تحتوي المجموعة Y على إجهاد خضوع قدره 17 ميجا باسكال، واقصى قوة شد تبلغ 18.75 ميجا باسكال، ومعامل المرونة (يونك) يبلغ 4.021 جيجا باسكال، على التوالي، بينما بالنسبة للمجموعة G، كانت هذه القيم 12.75 ميجا باسكال، و 18.84 ميجا باسكال، و 4.76 جيجا باسكال. تم استخدام اختبار التعب لتقييم خصائص فشل المقبس. كان عامل أمان الفشل للمواد المركبة للمجموعة Y 1.26 . لوحظ الحد الأقصى من الإجهاد وعامل الأمان والتشوه الكلي باستخدام تقنية العناصر المحدودة (ANSYS Workbench 14.5)لتحليل وتقييم خصائص التعب.

الكلمات المفتاحية: وقب الطرف الاصطناعي، المواد المركبة، الخواص الميكانيكية، الصوف، القنب.