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Finite Element Design and Manufacturing of a Woven Carbon Fiber Prosthetic Foot

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Abstract— This paper presents design, analysis and manufacturing of an energy storing-releasing prosthetic foot that can be used for walking and running. The designed factors were estimated to gain the required specifications for above knee patient weight 62kg wearing spring type heel foot prosthesis. A combination between CAD and CAE is helpful towards achieving this goal because of geometry, material and loading complexity. Thus, the foot parts are designed and assembled via Solidworks version 15.0 and the analysis was performed by means of Ansys version 18.0. In addition to strength, the weight is a significant factor to minimize the labour of the user, so the composite material, specifically carbon woven fiber and epoxy resin are selected. The human gait is classified to three main phases which are: heel strike, mid stance and forefoot, thus a corresponding static tests were conducted depending on ISO 10328. The foot thickness is increased gradually until reach the required specifications according to AOPA in the permissilmble strength limit. The foot is deflected 11.4 mm under 900N at standing phase, the keel is deflected 55 mm under the same load whereas the heel is deflected 13.22 mm by the effect of 300N load. Since the keel deflection is more than 25mm and the heel more than 13mm, the design is considered dynamic foot. The finite element results are considered for manufacturing the required foot.

Keywords— Prosthetic foot, Finite element, Composite materials, 3D printing

1. Introduction

People may lose a lower limb for various troubles, for instance cardiovascular diseases, trauma, malignancy or congenital limb defects. Indeed, the number of amputees are constantly increased, It is obvious that transfemoral amputates, are extremely challenging as two joints are lost. This need to increase the metabolic energy to walk and perform other job like climbing stairs. , and also the load essential to this task[6].

Researchers have produced many various designs of prosthetic feet. They can be classified into three major categories: conventional, energy storing and powered foot. A conventional one is a solid ankle cushioning heel, which does not undergoes a natural gait style such as SACH foot. Energy return foot, such as, Pro-Flex, provide natural progression through the periods of natural gait. The deflection of the foot, and its response to load, can be controlled via the thickness profile of the structure, as well as its configuration. Furthermore, a spring may be added to the heel to provide further shock absorption. In the third category are powered active prosthetics, for instance, bionic and robotic ankle foot. This type is an adaptive to nearly mimics natural foot motion[15]. Recently, active and semiactive ankle joints have been developed to help amputees to imitate the normal walk. However, there are multiple factors that limit the general use of them such as actuators and energy transmission devices[9].

Figueroa and Müller in [4] conducted a numerical test on a novel design of a flexible keel foot. Comparing to the commercial feet, their new design is capable of storing and returning energy. The foot has typically stiffer heels and softer toes. Kadhim et al in [12] compared their new model with the SACH foot. Namely, dorsiflexion angle, force transmitted at impact heel and life of the foot. Furthermore, a conceptual foot with spherical ankle joint permits planter flexion and dorsiflexion during gait on flat surface as well as uneven terrain was presented, as in [11]. Joshua et al in [3] developed a hand-manufactured low-cost foot with varying carbon layers stiffness at the toe section.

Moreovere, two unilateral amputees tested the performance of the foot during gait. A regular roll-over shape and good result to energy recover, by means of a twisted beam shape in ankle-foot prosthetics, was achieved in [7]. Juan et al developed numerical and experimental models for four different layup glass fiber foot to cover a total range of body weight from 55 kg to 110 kg[14]. Gabert et al described the design and control of an actuated four bar ankle joint foot prosthesis .They proved that their design is lighter, lower build height and consume less power comparing to single axis ankle joint foot[5]. Alleva et al manufactured a carbon and epoxy skin prosthtic foot with foam core.Moreover, the ankle movement was controlled by linear actuator and shock observer [1].

This work aims to design and manfucturing a prosthtic foot for above knee amputee weights 62kg. The foot is size 26 accordimg to Ottobock. FEM was used to perform the theortical tests with reference to AOPA·s prosthetic foot project. The analysis process was done repeatedly with increasing the foot thickness until reaching the design thickness.

2. Design Spesifications

2.1 *Iso 10328 Standared*

In this international standard, the term prosthetic means any externally applied device used for replacing whole, part or lost limb segment.During use, the prosthesis is subjected to a various force actions, each varying specially with time. The test methods specified in this Standard include static and cyclic strength tests [8].

2.2 *Biomechanics of ankle foot*

The main periods of the human gait cycle are the stance phase, about sixty percent, and swing phase represents the remaining rate. The stance phase begins when the heel touches the floor and ends at toe-off when the same foot rises from the ground surface, while the swing time is the foot off the ground. Furthermore, we can subdivide the stance phase into: controlled plantarflexion, controlled dorsiflexion, and powered plantarflexion as illustrated in **Figure (1)**.

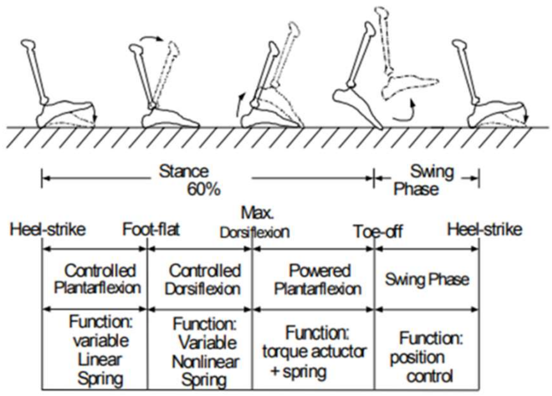


Figure 1 : Biomechanics of a normal human ankle during level-ground walking[12].

3. Effective load locations

ISO standared was adopted for locating the point of applied distributed load at the center of ankle joint and the point of keel contact with support. In addition, this standared is used for locating Cartesian axis of the foot and the convienent status in vertical load application. More information is picted in **Figure (2)**.

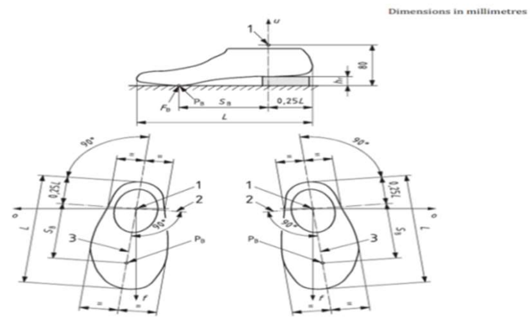


Figure 2: Longitudinal axis location and effective joint center [8]

4. CAD Modeling

The case adopted in this study is Ottobock size 26 foot. By concern with important properties in foot design specially, strength, weight, damping and energy absorbation and recover, a calculation of the suggested design was created keel and heel profile. Solidworks version 2015 is used as a powerful tool to create and then assembling all parts. Parasolid option was selected for analysis with the FEM software for stress and deflection calculation. **Figure (3)** shows the whole model rested on a rigid support and **Table (1)** shows the dimensions of the geometry.

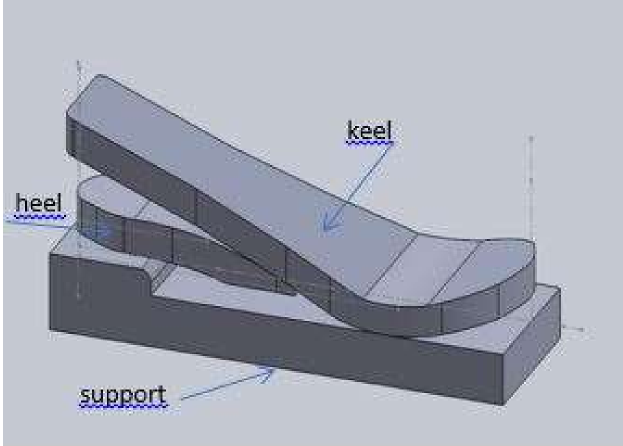


Figure 3: Cad modeling

Table 1: structure dimensions.

component	Dimension(mm)
Keel length	240
Maximum keel width at contact with support	80
Keel width at ankle region	50
Keel thickness	14
Heel length	150
Heel width at the root	60
Heel width at the tip	40
Heel thickness	14

5. FEM Analysis

5.1 Boundary conditions

The CAD model is imported to ANSYS version 18.0 where three necessary tests are performed. Four element types used in the analysis for modeling fixed support, composite foot, contact and target surfaces, namely, SOLID185, SOLSH190, CONTA174 and TARGET170 respectively. Element size effect was considered, so it is refined gradually pending no significant change in results when it is less than (4mm) **Figures (4,5)**. The mechanical properties were calculated experimentally. All degrees of freedom are constrained for the fixed support. Contact and target surfaces between (heel and support), (keel and support) and (heel and keel) are specified carefully as bonded contact. According to ISO **Figure(6),** the range of load is P_3,P_4 and P_5 used for person's weight 65kg and less, between (65-75)kg and athletic foot respectively. The present case study for person weight 62 kg, so maximum load P3(900N) was applied as distributed load on the location of the ankle joint as stated in **Figures (2,5)**. The foot thickness is the proper design factor, therefor it is increased gradually until reaching the permissible stress and deflection at thickness (14mm) for both heel and keel.

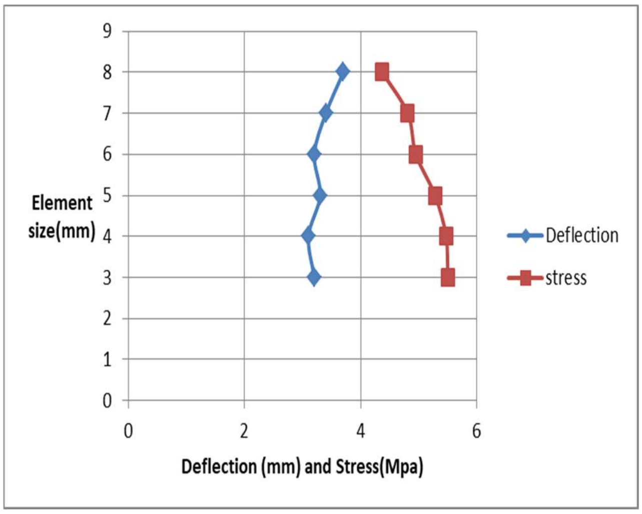


Figure 4: FEM results convergence at minimum load

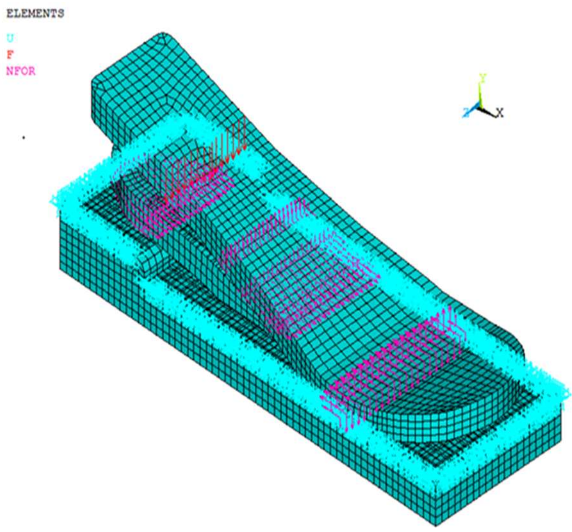


Figure 5: Meshing and loading of the process

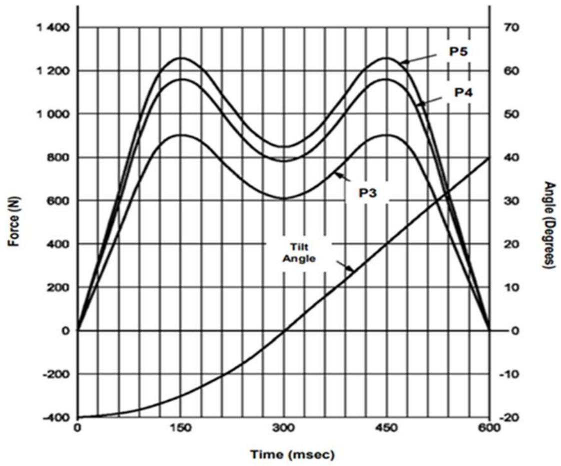


Figure 6: ISO load

5.2 Keel test

The keel test emulates t he toe off stage of the gait stance period, it is responsible for providing the required forward energy to the human body. In this test the keel was inclined by 20^0 to the support . The distributed load is increased gradullay until the maximum 900N was applied at the ankle joint.

5.3 Heel test

The purpose is to simulate the heel touch on the ground during the human gait cycle. The inclination between the heel and support is 15^0 in this analysis. The value of the maximum load was 300N applied at the heel tip.

5.4 Vertical loading test

The objective of this test is mimicking the stand condition of the human gait. The foot position is horizontally with the support. The loading case is the same as the keel test.

6. Expiremental work

6.1 Preparing composite plate for material testing using vacuum infusion method

Woven carbon fiber and epoxy resin are choosen for foot manufacturing for many resons such as high strength and light weigt. A steel mold was prepared to produce two composite plate with 0^0 and 45^0 fiber direction. The method of production depend on vacuuming air from the mold to permit the resin to spread entirely on the fiber without air bubbles. **Figure (7)** shows the necessary materials used and **Figure (8)** picted the compoite plate in the mold.

Figure 7: Materials

Figure 8: Composite plate in the steel mold

6.2 Tensile specimens

For testing the mechanical properties of composite, tensile specimens were prepared according to ASTM D3039 as obvious in **Figures (9,10)**.

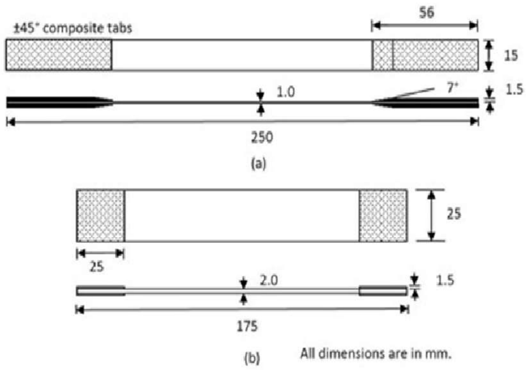


Figure 9: ASTM D3039 standared dimensions (a) fiber direction 0^0 (b) fiber direction 45^0 [16]

(a)

(b)

Figure 10: Tensile specimens (a) fiber direction 0^0, (b) fiber direction 45^0

Then, the shear modulus was calculated from the following equation[10].

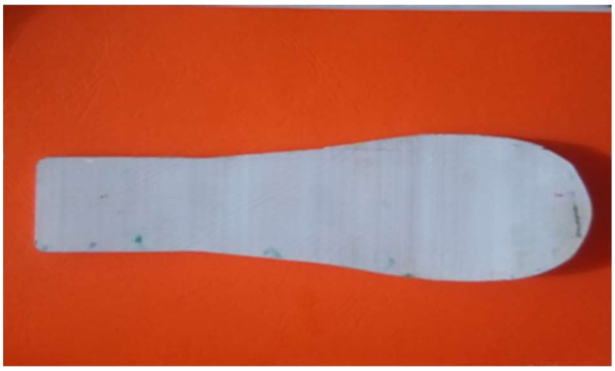
$$G_{12} = \frac{1}{\frac{4}{E_x} - \frac{1}{E_1} - \frac{1}{E_2} + \frac{2v_{12}}{E_1}} \qquad (1)$$

Where

G_{12} : shear modulus(Mpa).
E_x : Young modulus(Mpa) when the load 45^0 to the fiber direction.
E_1 : Young modulus when the load parallel to the fiber directin(0^0).
E_2 : Young modulus when the fiber dirction perpendicular to the fiber direction(90^0).
v_{12} : Poisson's ratio.
For woven fiber E_1=E_2 .

6.3 *3D printing*

To produce accurate keel and heel profiles, 3D printing technique was used. In addition, it is low cost, fast and programmable. It enables the user to control the printed product stiffness, weight and speed of production. In **Figure (11)** it is shown the printed structures by Blackwidow 3D printer.



(a)

(b)

Figure 11: Printed foot parts, (a) Keel, (b) Heel

6.4 *Lamination of foot*

The samples obtained from 3D printing were used to make the required shape in cement mold to be used for keel and heel lamination. The obtained groove were accurate and smooth as shown in **Figure (12)** . After that these grooves were filled by 28 carbn fiber layers and epoxy resin.

(a)

(b)

Figure 12: (a) Keel and (b) heel imprints in cement mold

7. Results and discussion

7.1 *Tesnsile test results*

Table (2) summrizes the mechanical properties of composite were calculated experimentally and used in FEM analysis. The failure of the spicemens in the tensile rig are picted in **Figure (13)**.

Table 2: mechanical properties of woven carbon fiber and epoxy resin.

E(Mpa)	G(Mpa)	σ_u(Mpa)
2738	14.83	83

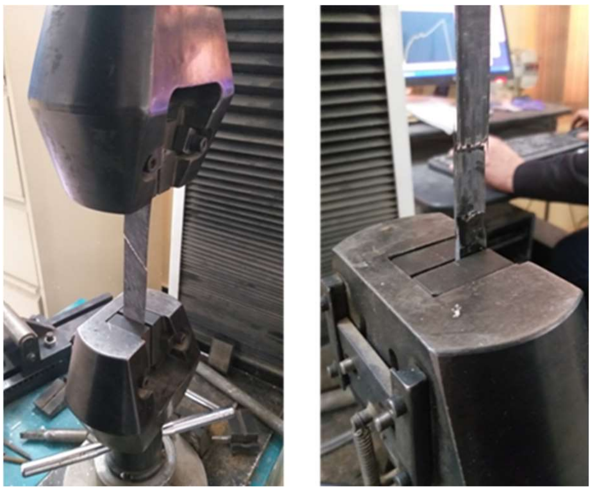


Figure 13: Specimens testing

7.2 *Keel result*

Figures (14,15) show the maximum stress and displacement counters respectively, while **Figure (16)** shows the load deflection curve.

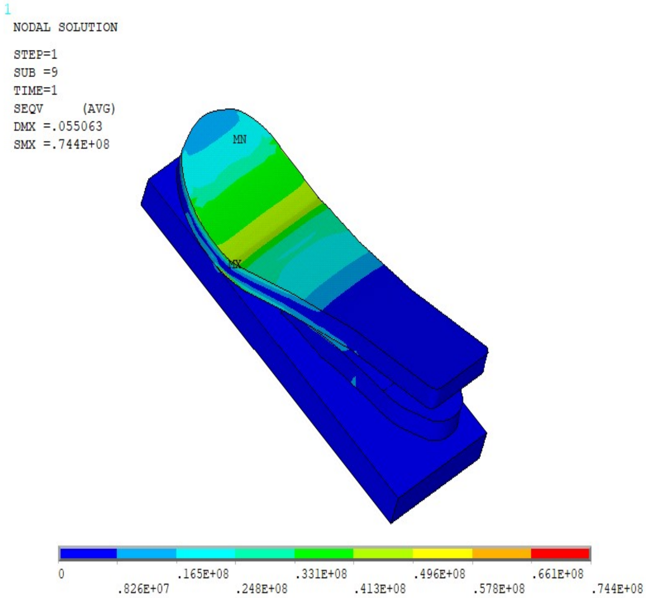


Figure 14 : Stress(Pa)in the keel part under maximum load

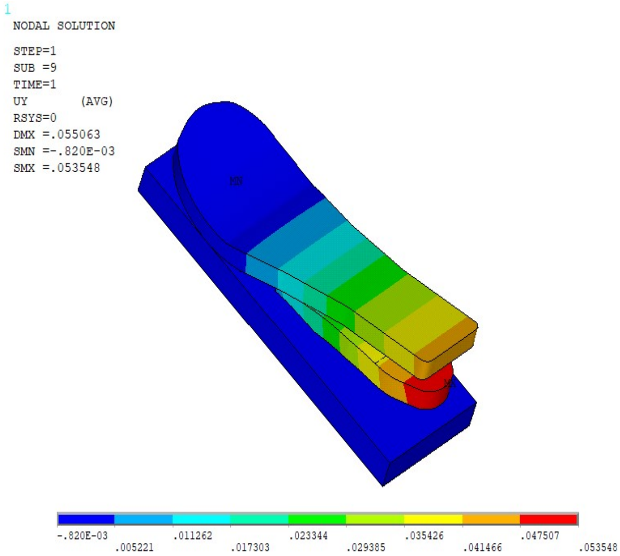


Figure 15 : Displacement (m) of the keel under maximum load

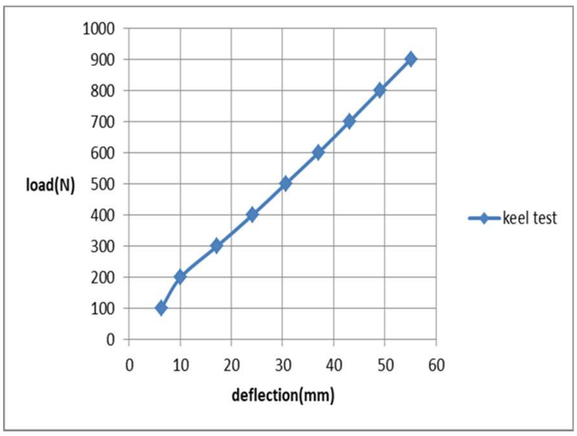


Figure 16: Load deflection curve of the keel

Mainely, the analysis concern on attaining a suitable keel thickness to withstand the generated stress with required displacements. To minimize weigt, we tried with small value of thickness, after multi trails it is found that thickness(t=14mm) can be sufficient for this task. Reffering to **Figure (14)** the maximum stress was 74 Mpa at the point of keel contact with ground and the maximum deflection was (55mm) at the point of applying load at the ankle joint as shown in **Figures (15,16)** .Thus, the keel pass the test as dynamic foot as it deflect more than 25mm according to [2].

7.3 *Heel result*

Figure (17) shows the values of stress distribution in the heel part and the displacement in **Figure (18)**. Moreover, **Figure (19)** shows the load defletion curve.

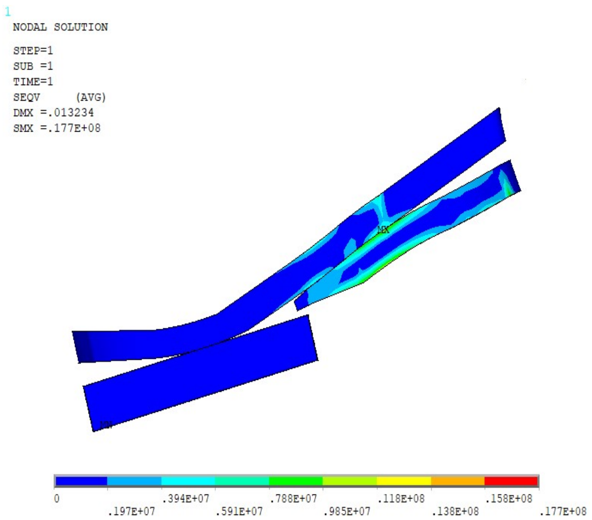


Figure 17 : Stress(Pa) in the heel under maximum Load

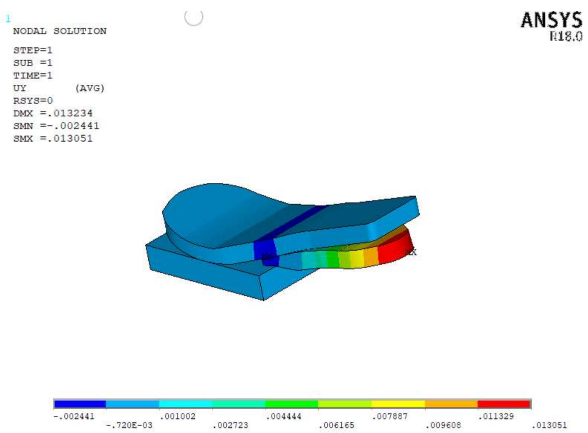


Figure 18: Displacement (m) in the heel under maximum load

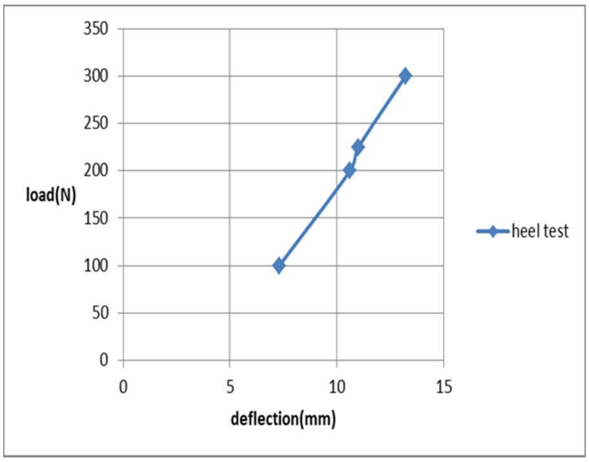


Figure 19: Load deflection curve of the heel

Comparing to the keel, the stress in the heel is less as it obvious in **Figure (17)** where the value of stress recorded 17.7 Mpa, also the induced deflection was less 13.2 mm as indicated in **Figures(18,19)** . The dynamic heel foot must deflect more than or equal to 13mm as stated in [2].

7.4 *Vertical loading test*

The maximum stress and its location can be seen in **Figure (20)** and the displacement in **Figure (21),** the relation between the resulting deflection and applied load is indicated in **Figure (22).**

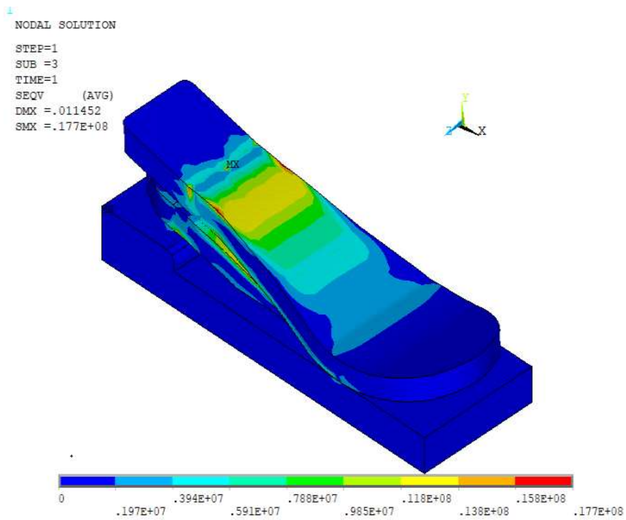


Figure 20: Stress (Pa) in in vertical load test under maximum Load

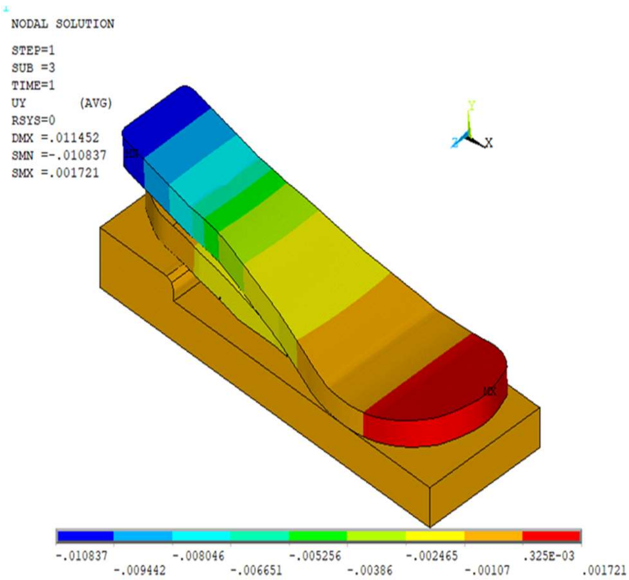


Figure 21: Displacement (m) in vertical load test under maximum load

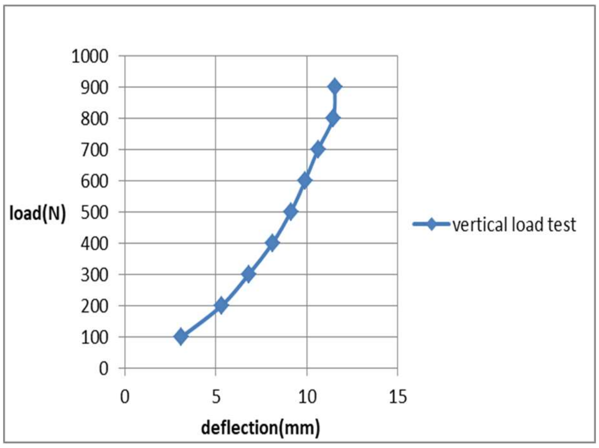


Figure 22: Load deflection curve in vertical load test

Finally, the value of stress is low compared to permissible stress which is 17.7 Mpa as picted in **Figure (20)**. Wheres the value of displacement is 11.4mm as clear in **Figures (21,22).** Since the displacement more than 10mm, the foot is pass this test[2].

7.5 *Lamination of foot*

The keel and heel were laminated by hand-lay up process by 28 layer of woven carbon and epoxy resin and then assembled by two bolts, the final shape of the product is shown in **Figure (23)**.

Figure 23: The designed foot

8. Conclusion

The objective of this work was to design and manufacturing of a prosthic foot for amputee's weight 62kg. The present study leads to conclude the following facts:

1. The maximum stress occurs in the dorsiflexion phase, at the region of keel contact with ground. Also the maximum displacement occurs in the keel at the same phase.
2. The stress value may be near or the same in the heel and vertical loading test.
3. Linear behavior is between the load and displacement in the keel part, whereas it is nonlinear in the heel.
4. The weight of the manufactured foot is only 0.4 kg. Thus the carbon fiber is preferable because of light weight and robust product.
5. The structure can be classified as a dynamic foot type. For future work, we can suggest the following:

1. Comparing the finite element results with the expiremental results.
2. Modifying the foot profile.
3. Study the effect of using unidirectional and random fiber.

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تصميم وتصنيع قدم صناعي باستخدام طريقة العناصر المحددة

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الخلاصة – هذا العمل يهدف لتصميم وتحليل وتصنيع قدم صناعي يتميز بقابليته على خزن الطاقه وارجعها اثناء الجري لشخص يزن 62 كغم يستخدم طرف صناعي ذو قدم من النوع الذي يحتوي على سبرنك معدني في كعب القدم. تم استحدم برنامج solidworks2015 لغرض الرسم والتصميم والتجميع بعد ذلك اجري التحليل باستخدام برنامج Ansys 18.0 فبعد عدة اختبارات تم استنتاج سمك الكعب ومشط القدم المناسب لمقاومة الاجهاد الناتج والحصول على الاستطالة المطلوبه لحمل تصميمي بالاعتماد على المواصفات والمقاسات العالميه المتبعه في تصميم الاقدام. استخدمت خصائص الكاربون فايبر المنسوج مع الايبوكسي المتوفر في الاسواق المحليه من خلال حسابها عمليا. نتائج الاختبارات الثلاثه تم مقارنتها مع شروط و مقاسات AOPA وكانت مطابقه حيث ان الاستطاله باختبار الحمل العمودي 11.4ملم واختبار مشط القدم 55 ملم بواسطة قوه مقدارها 900 نيوتن حسب شروط ISO ومقدار الاستطاله في الكعب كانت 13.22 ملم لحمل تصميمي مقداره 300 نيوتن وضمن اقصى اجهاد مسموح به لمادة التصتيع. بما ان الاستطاله في مشط القدم اكبر من 25 ملم وفي كعب القدم اكبر او يساوي 13ملم فان التصميم ضمن المقاسات المطلوبه لتصنيع الاقدام. تم الاعتماد على نتائج التحليل في تصنيع القدم عمليا.

الكلمات الرئيسية – قدم صناعي, طريقة العناصر المحددة, المواد المركبه, الطباعه الثلاثيه الابعاد