Study and Analysis of Failure Mechanism of Bolt Adapter in Prosthetic SACH Foot

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ABSTRACT

This paper presents is the study and analysis of failure mechanism of non-articular prosthetic foot (SACH) in the region (Bolt Adapter). The tests of mechanical properties and fatigue behavior were carried for material of which the bolt manufacture from it is a region where the failure occurs out and inserted of these properties to the program of engineering analysis (Ansys) to calculate the safety factor of fatigue and stress equivalent (Von-Mises).The results that both, showed the maximum equivalent stress and the minimum safety factor of fatigue are located in bolt at interface region between the adapter and the foot at notch, however, in static case, the effect was on the ground reaction force at toe off phase more than heel strike phase.

Keywords:SACH,prosthetic,foot,bolt,adapter,failure,mechanism,analysis.

دراسة و تحليل الية الفشل لبرغي الطرف الاصطناعية نوع SACH

الخلاصة

في هذا البحث يتم دراسة و تحليل الية الفشل في الطرف الاصطناعي غير مفصلي (SACH) في منطقة البرغي,اجريتاختبارات الخواص الميكانيكية و الكلال للمادة المصنع منها البرغي,وهي المنطقة التي يحدث فيها الفشل و ادخال هذه الخواص لبرنامج التحليل الهندسي(Ansys) لحساب عامل الامان للكلال و الاجهاد المكافئ (Von-Mises). النتائج اظهرت ان اعظم اجهاد مكافئ و اقل عامل امان للكلال ظهر في منطقة البرغي عن المنطقة الفاصلة بينAdapter و القدم عند السن و في حالة السكون,كان تاثير رد فعل الارض عن طورtoe off اكبر مما علية عند طورheel strike.

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INTRODUCTION

The human ankle joint is a unique design that makes the joint stable and is capable of withstanding 1.5 times the body weight during normal ambulation and eight times the body weight during running [1], but the prosthetic SACH foot is incapable of withstanding 1.5 times the body weight during normal ambulation for long time because of the fatigue failure at ankle joint due to alternative loading.

In the development of prostheses, allprosthetic assemblies and components aresubjected to structural acceptance tests whichinclude static and fatigue tests. Static tests arerequired to determine the structural strength ofthe foot to ensure performance and safety.These are carried out on a universal testingmachine. Also, fatigue test must be performed to define the fatigue strength of the bolt material. Fatigue tests aredesigned to study performance under dynamic load forthe equivalent of the expected service lifeduring normal use [2].

To study the fatigue failure of the SACH foot the gait cycle and ground reaction force should be studied for patient to know the forces act on the foot during motion.
In this study the gait cycle and ground reaction force, will be investigated in order to calculate the life of SACH foot calculate by using the fatigue criteria due to alternative loading and suggesting a model for fatigue analyses in Ansys program.

Previews works

The gait cycle is defined as the period from heel contact of one foot (for example, the left foot) to the next heel contact of the same foot. This cycle is broken into two parts, stance phase and swing phase. On the average, the gait cycle is about one second in duration with 60 percent in stance and 40 percent in swing. The stance phase is further divided into an initial double stance, followed by a period of single stance and then a final period of double stance. Double stance indicates that both feet are in contact with the ground; single stance is the period when only one foot is in contact with the ground. When walking, there must be a period of double stance and when running, this period is replaced by a flight phase during which neither foot is in contact with the ground.

The failure occurs as a result of load that be in heel and toe of foot in intermittent periods and regular during the phases of gait and that lead to alternating moment and opposite directions about the point A .Where at heel strike phase as shown in figure (1), the ground reaction force is applied on the heel of the foot upward vertically and the axis of the foot is italic so that the force analyze to two components, the first one is parallel to the axis of the screw which produces moment in clockwise about the point A in distance L_1 and the second one is perpendicular to the axis of the screw and produces small shear which can be neglected.While at toe off phase as shown in figure (2) the force will be vertical upward to the foot is analyzing to two components, the first parallel to the axis of the screw and producing moment in anticlockwise about the point A in distance L_2 and the second produces small shear which can be neglected too. From figures (1) and (2) the distance isL_2 larger than L_1 so that the moment in toe off phase is larger than the moment in heel strike phase.

The Numerical Analysis by Ansys

In order to conduct the finite element analysis, all of the components needed to be modeled in Pro/AutoCAD 2011.

The SACH foot was more difficult to model due to the complex geometry of the foot. It was modeled as an assembly of two parts, the polypropylene inner keel and polyurethane foam outer cover. The two parts were modeled separately, then assembled together and used to modify the construction of the outer cover. The final created model of keel is shown in figure (3)

The complex outer SACH foot shell was created using the loft order in AutoCAD program between several cross sections creating by close curves and then cut the inner keel space from it to producte the final foam outer cover as shown in figure (4).

The bolt and adapter were modeling separately as shown in figure (5) and finally they are combined to obtain the final model of bolt adapter.

Having obtained the final model of SACH foot and the bolt adapter, the data are exported to the Ansys program.

Finite Element Analysis

ANSYS Workbench was chosen as the FEA soft ware package because of its ability to accept a 3Dcomputeraideddesign (CAD)model.

In the finite element analysis, the element type was chosen based on the geometry of the prosthetic foot, the information are available to input, from which the results that are to be extracted. Each element type has different available degrees of freedom, real constants, material properties, allowance of surface, body loads, and other special features(ANSYS).This analysis required element types that have three degrees of freedom, can undergo potentially large deflections and model constraints that include the loading and boundary condition. Lastly, the material properties that affect the results [3].The automatic size control was used to mesh the model as shown in figure (7),with refined meshing at the notches of the bolt. The total number of elements was (46889 elements) with total a number of nodes of (81263 nodes.).

In this work SOLID 185 as shown in Figure (8) is used. SOLID185 is used for 3-D modeling of solid structures. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities.

In fatigue solution, the fatigue tool is used to find the equivalent stress and safety factor at particular loads [4].Apply the same boundary conditions (constraints and loads) that are taken from the GRF test. The tip of the adapter was selected as fixed support for the four sides at all time. a vertical upward pressure of 310 Kpa was applied to the bottom surface of the heel from 0% to 21% of gait cycle and 310 was applied to the bottom surface of the toes from 69% to 100% of gait cycle as shown in Figure (9).

Experimental Work

Chemical analysis of the alloy was carried out at the Specialized Institute using x-rays method. The results, which are compared to the American Society for Testing and Materials specifications (ASTM) (A 479 316 stainless steel), are listed in the table (1)[8]. The tensile test was achieved by using the tensile test machine the tensile specimen's geometry and dimensions knew by using standard (A370)[5] which was specified for metals (Stainless steel) .

The specimens used in tensile test are machined from bolt that use in SACH foot. The test is achieved on 3 specimens and adopting the average value of the results. Figure (10) showsthe specimens before test.

A fatigue–testing machine that applied a rotating bendingthat used to execute all fatigue tests, with constant and variable amplitude. The specimen is subjected to an applied load from the right side perpendicular to the axis of specimen, developing a bending moment .Therefore; the surface of the specimenwill be under tension and compression stress during rotation.

The specimens used in the fatigue tests are machined from bolt that used inmanufacturing SACH foot to a suitable geometry for the testing [7].

The test was achieved on two groups of specimens without laser peeningand the third group for fatigue test after laser peening. The specimens before test were as shown in Figure (11).

After machining the specimens, they are polished using the following steps:

1-The surface of the specimen is smoothed using different wet silicon carbide papers.

2- The specimen is polished by using wool .The results of the surface roughness for selected specimens are given in Table (2).

Results and Discussion

Tensile specimens had been examined at room circumstances conditions The results, which are compared to the American Society for Testing and Materials specifications (ASTM), are listed in the table (3)[7].

Fatigue failure occurs when the specimen fractures under cyclic loading. The readings recorded by the fatigue tester represent the number of cycles until fracturethe specimens. The test was carried to 18 specimens. The fatigue results are presented in the form of curve as shown in figure (12).

i. The Result of the Numerical Analysis and Discussion

The fatigue and static properties of prosthetic SACH foot are investigated using finite element method (ANSYS 14).

a. Static Analysis

The aim of this analysis is to investigate the stresses and safety factor of SACHfoot at maximum pressure that are taken from ground reaction force measurements.

Figures (13) and (14) show the distribution of Von-Mises stresses in the prosthetic SACH foot at toe off phase and heel strike phase, respectively.It is clear that amaximum stress is located in bolt at interface region between adapter and foot at notch because the cross section is minimum at that region.

The maximum Von-mises stress is at the toe off phase not at the heel strike phase because of that the normal distance at the toe off phase more than at the heel strike phase, that makes the maximum stressoccure at the toe off phase.

Figures (15) and (16) show the equivalent stress-safety factor for the prosthetic SACH foot. It can be seen from the figure that the maximum equivalent stress-safety factor is located in bolt at interface region between adapter and foot at notch and the equivalent stress-safety factor at toe off phase is less than that at heel strike phase because of that the maximum Von-Misses stress at toe off phase is more than at heel strike phase.

b. Fatigue Analysis.

The aim of this analysis is to investigate the equivalent (Von-Mises) stress and safety factor of fatigue of prosthetic SACHfoot.

The safety factor for fatigue will be safe in design if the safety factor is about or more than (1.25) [9].

Figure (17) shows the equivalent stress-safety factor for the prosthetic SACHfoot. It can be seen from the figure that the minimum equivalent stress-safety factor is located in bolt at interface region between the adapter and foot at notch because of the minimum cross section at notch.

It was observed that the minimum equivalent stress-safety factor is at the toe off phase not at the heel strike phase because of the perpendicular distance at the toe off phase is more than that at the heel strike phase, that makes the minimum equivalent stress-safety factor occurs at the toe off phase and this make the crack initiation at the side of heel first and the failure initiation at this side.

CONCLUSIONS

1. The maximum equivalent Von-Misesstress and the minimum equivalent stress-safety factorare located in bolt at interface region between adapter and foot at notch because of the minimum cross section at notch.
2. At static, the effect of ground reaction force at toe off phase is more than the heel strike phase.

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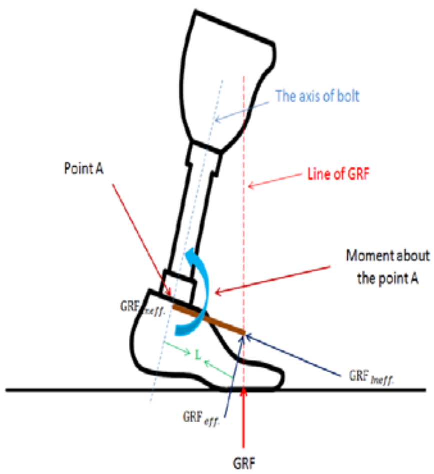
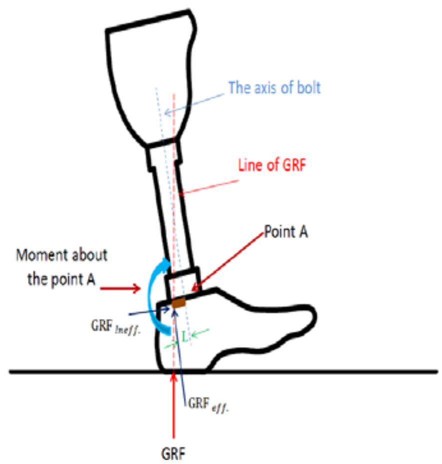


Figure(1) GRF at heel strike phase.



Figure(2) GRF at toe off phase.

Figure (4) Simplified SACH Foot.

Figure (3) Final Solid Model of KEEL OF SACH Foot.

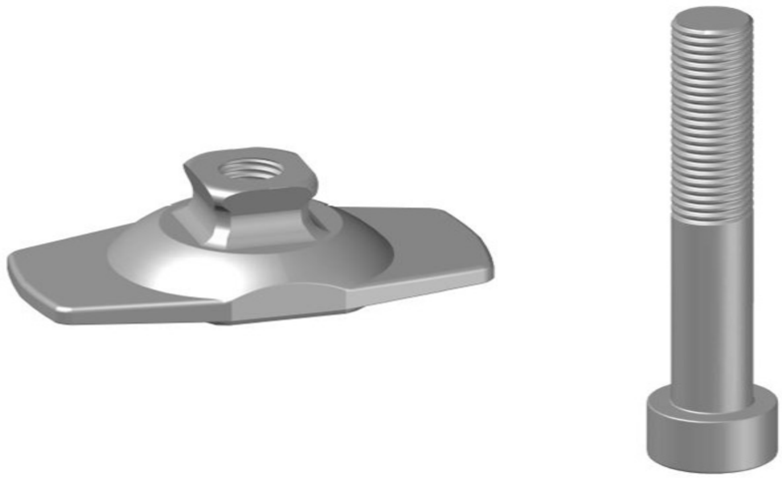


Figure (5).models of bolt and adapter each one alone.

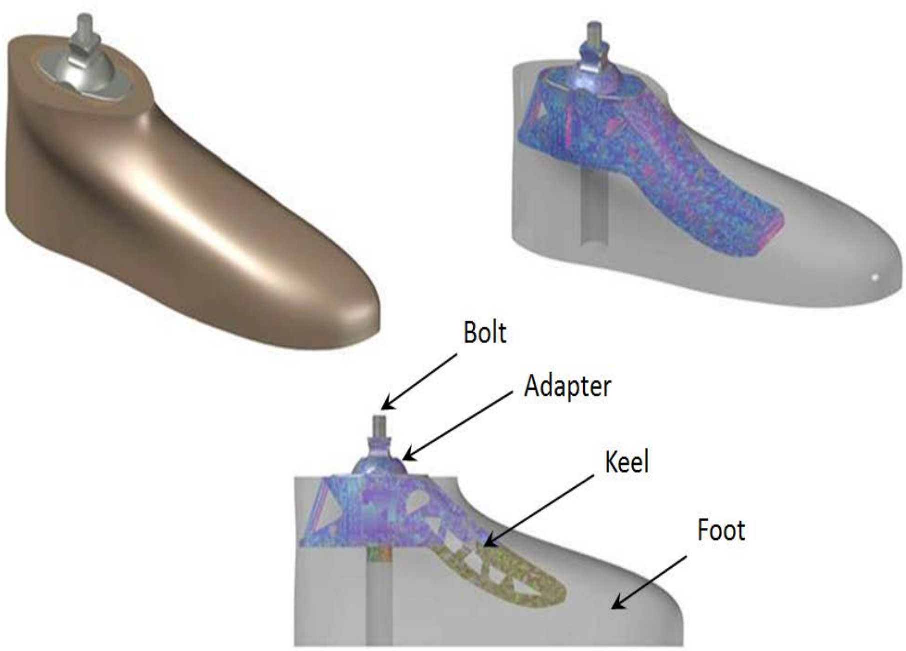


Figure (6). Multiple Views of final model of SACH foot and bolt adapter.

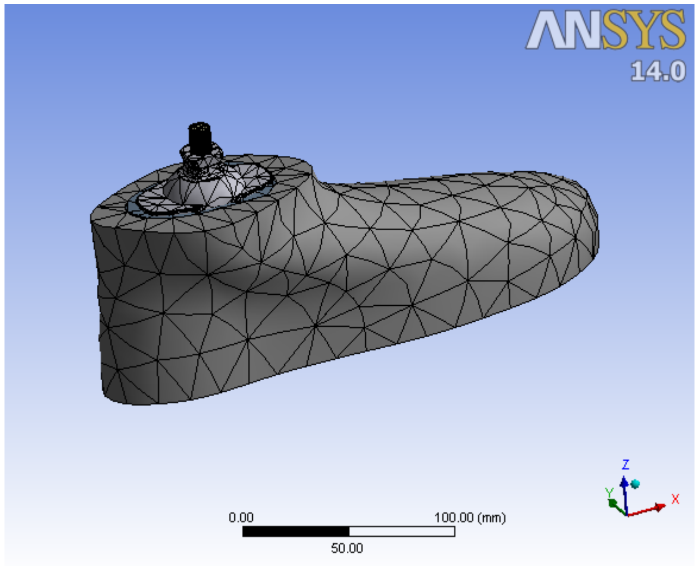


Figure (7).Meshed SACH Foot Models.

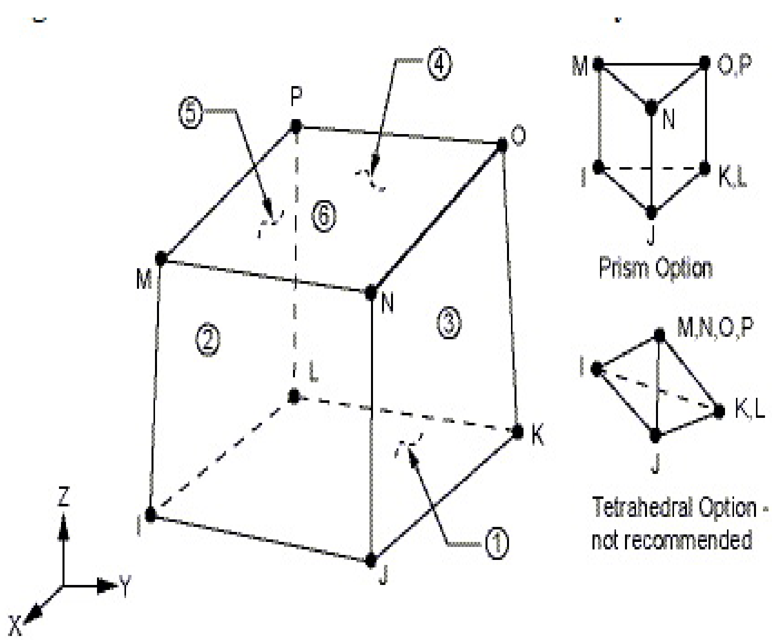


Figure (8) Solid 185.

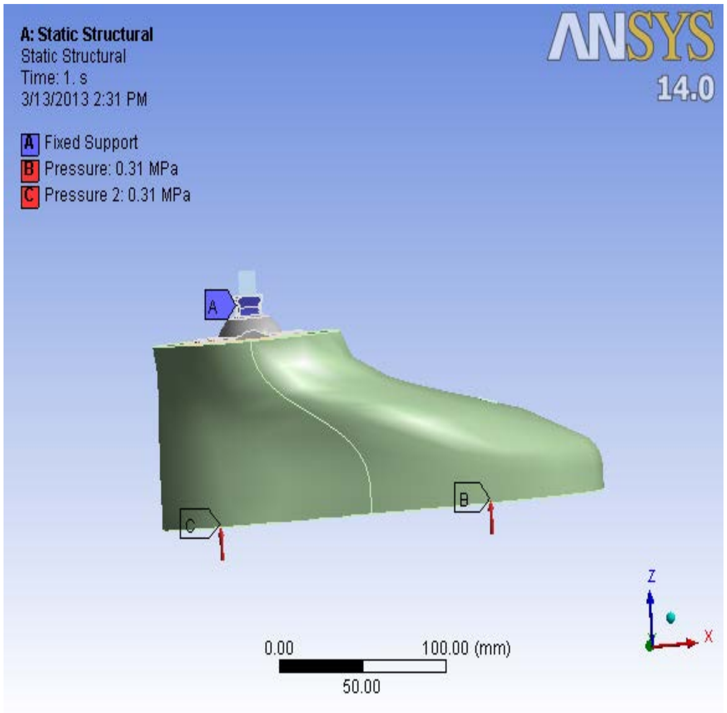


Figure (9) FEA Model Constraints and Loads.

Figure (10) Tensile test specimens before test .

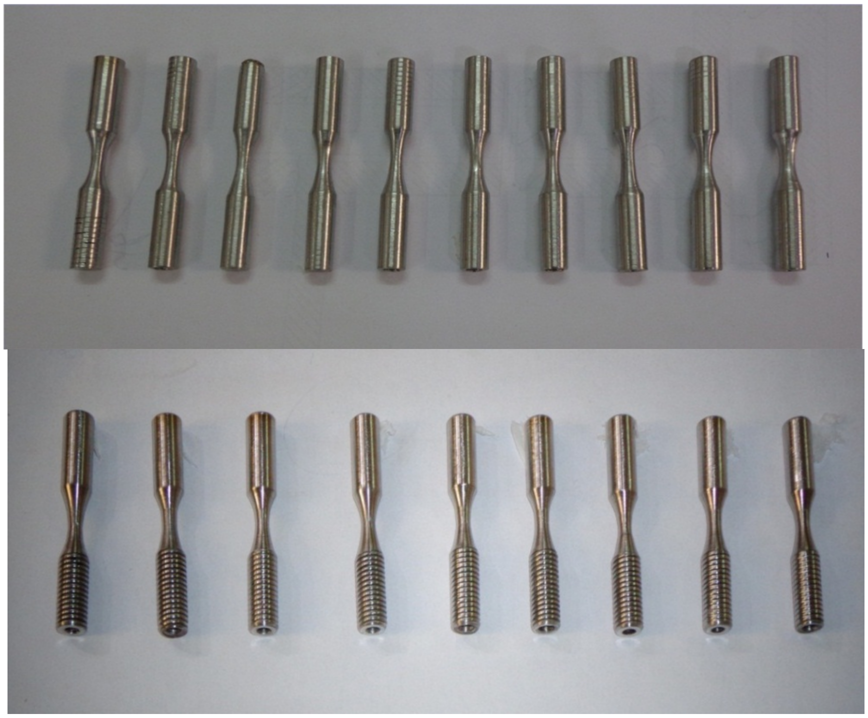


Figure (11) Fatigue specimens before test.

Table (1) Chemical composition wt%

material	C	Si	Mn	Cr	Ni	Other elements
bolt (experimental)	0.0089	0.867	0.475	13.48	3.6	----
Key to steel (standard)[7]	0.008	1	2	16	10	----

Table (2) The results of the surface roughness test

Specimen No.	Peak Roughness Rt(μm)	Average Roughness Ra (μm)
7	1.2	0.3
3	1.4	0.42
2	0.9	0.72
8	1.7	0.92

Table (3) The mechanical properties of material bolt (stainless steel)

Material	Young's Modulus (GPa)	Yield Stress (MPa)	Ultimate Stress (MPa)
experimental	185	483	570
Standard [7]	95	450	585

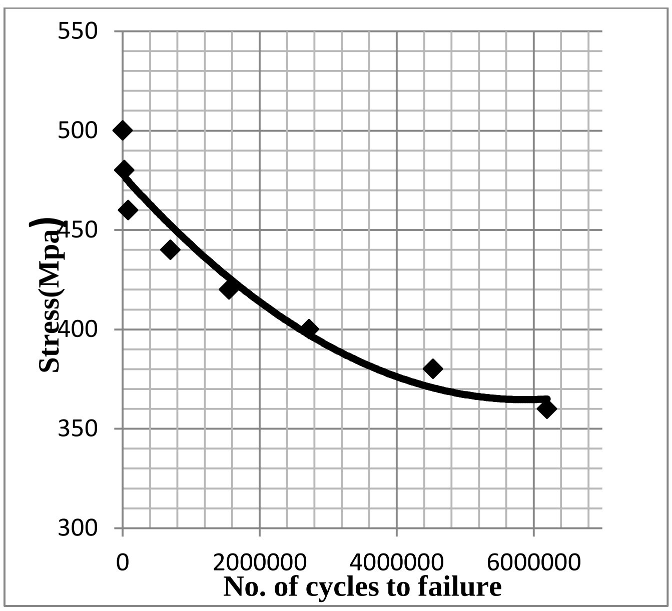
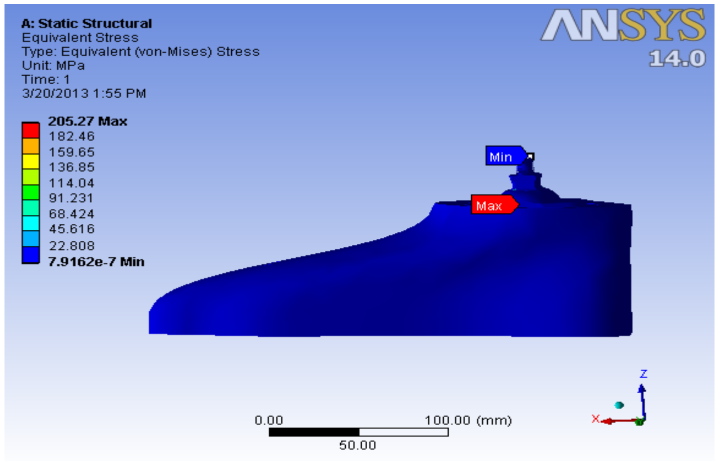
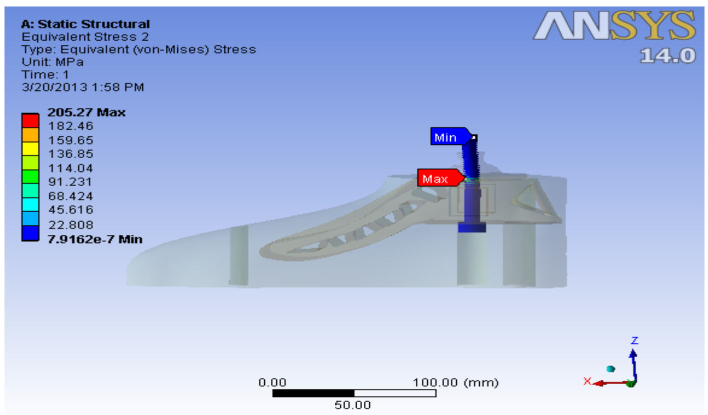


Figure (12) S-N fatigue tests curve.





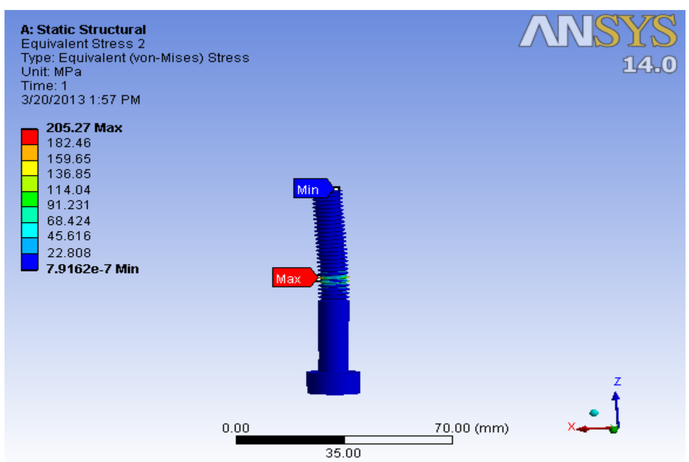
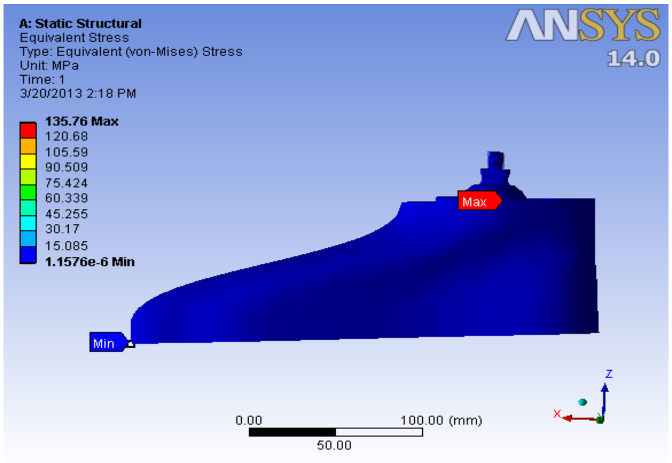
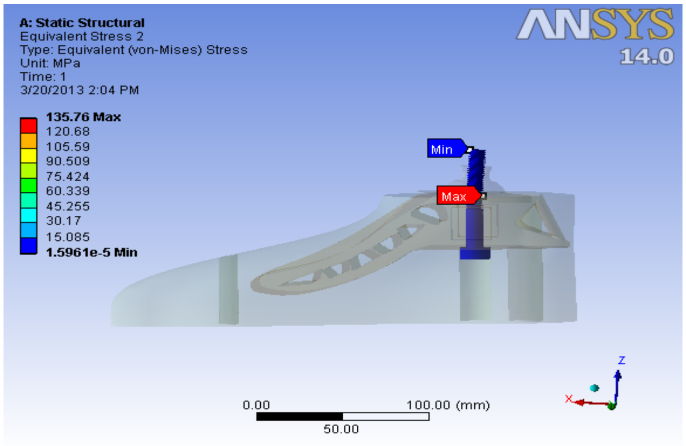


Figure (13) Von-Misses stress of prosthetic SACH foot (toe off phase).





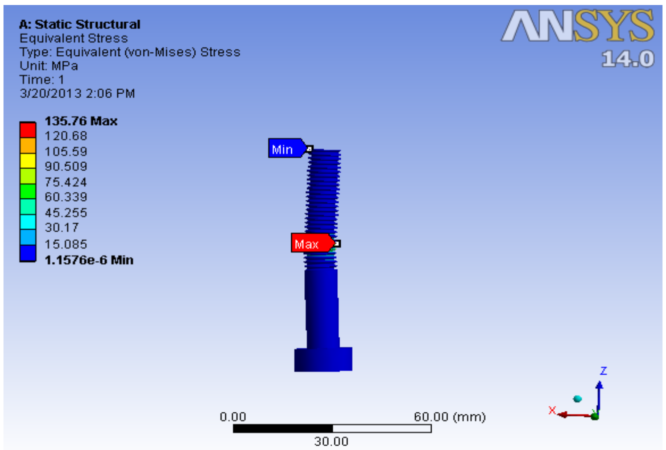
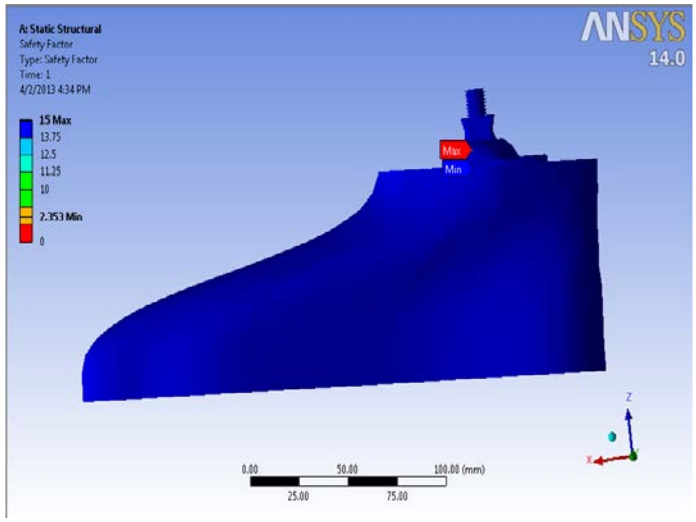


Figure (14) Von-Misses stress of prosthetic SACH foot (heel strike phase).



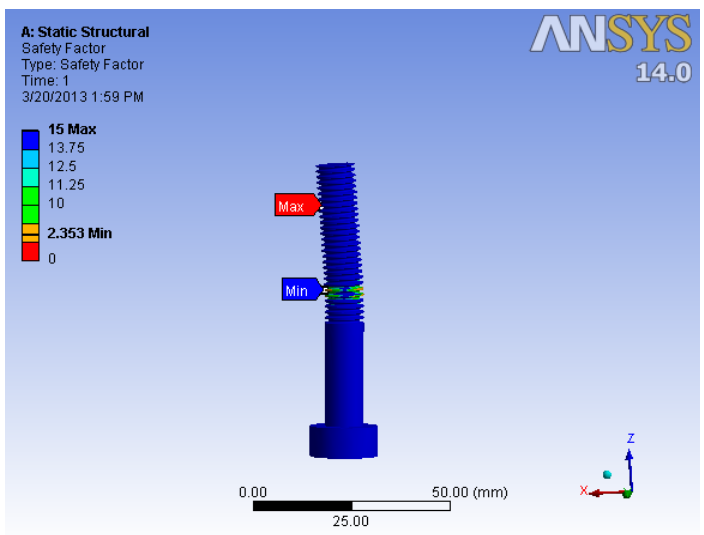
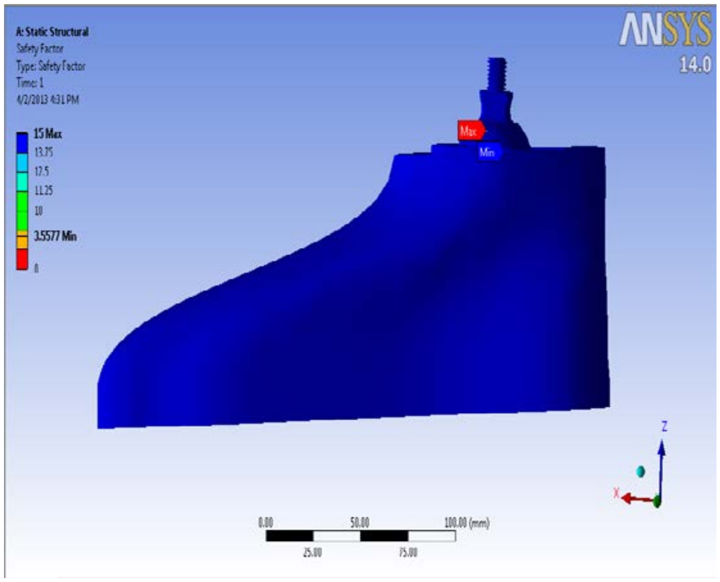


Figure (15) the equivalent stress-safety factorof the prosthetic SACH foot for static load (toe off phase).



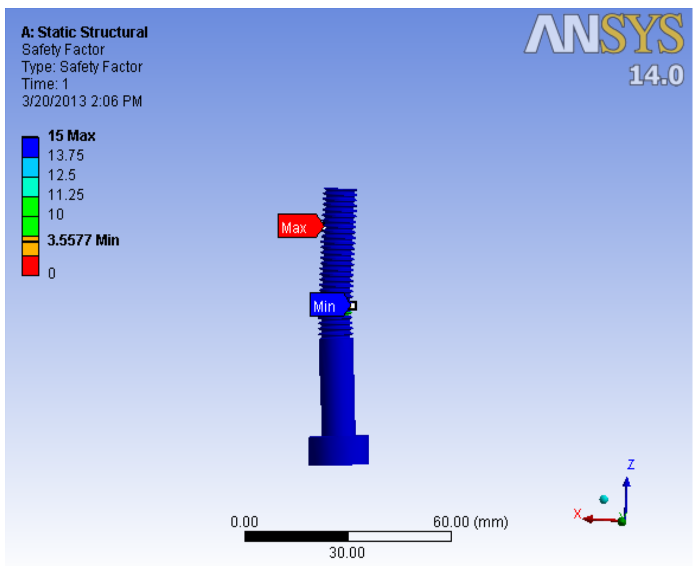
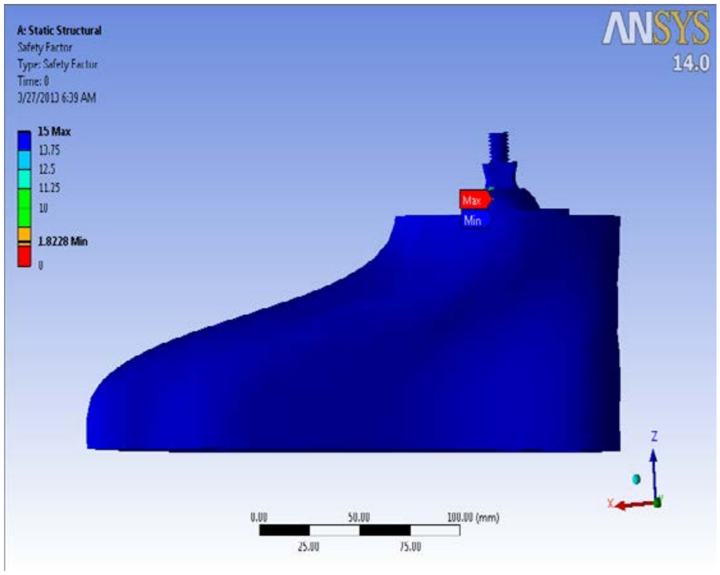


Figure (16).the equivalent stress-safety factorof the prosthetic SACH foot for static load (heel strike phase).



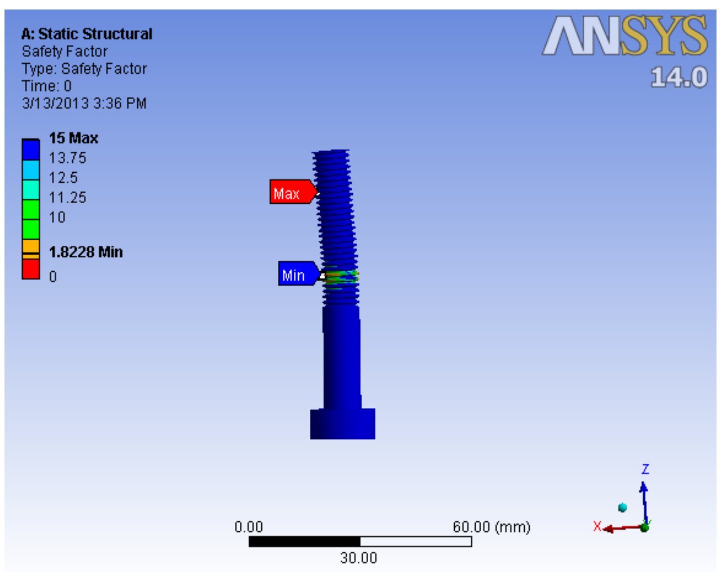


Figure (17)the equivalent stress-safety factor for fatigue of the prosthetic SACH foot