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FINITE ELEMENT ANALYSIS ON PROSTHETIC LEG UNDER DIFFERENT LOADS AND FLEXION ANGLES FOR MEDICAL APPLICATIONS

Naresh Kumar KONADA[1*], Suman KOKA NAGA SAI[2]

[1*]Asst Professor, Mechanical department, Anits Engineering College, Andhra Pradesh, India,
E-mail: nareshkonada@gmail.com
[2]Associate Professor, Department of mechanical Engineering, Andhra University Andhra Pradesh, India

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Abstract: Prosthetic legs are mainly used to perform leg amputations more easily and sometimes the appearance is similar to a real leg. Different types of legs have been developed in recent days to be used in specific fields like running, cycling in sports and normal walking. The selection of materials and load bearing capacity of a leg determines its usage for any field of application. The behavior of prosthetic legs can be assessed properly by performing a finite element analysis on it with varying material properties and loads before it undergoes a designing and manufacturing stage. In the current study, Al alloy, Ti alloy, unidirectional Carbon fiber epoxy (UDCFE) and combined composite material which include (CF, UDCFE and Ti alloy) are used as materials for the prosthetic leg. A prosthetic leg model of C Type with its main parts being the sleeve, the rod and the base foot was designed initially by using the Solid Works 2010 software and the assembled file was imported to Ansys Workbench 2020 to perform a static and fatigue analysis. The static analysis was performed under four different load conditions, i.e. 60 kg, 70 kg, 80 kg and 90 kg, considering the different human weights of the body. A fatigue analysis was done by using the Soderberg method and applying a sinusoidal varying load for low cycle fatigue conditions. Theoretical calculations were also performed at various inclinations of foot 10°, 20°, and 30° with the ground and stresses were evaluated using finite element equations. The results obtained theoretically were compared with the analytical results. The best material which provided the lesser value of deformation and sustaining more loads with a lower value of the damage factor was selected for the design. Further experimental studies were suggested based on the results obtained from this work.

Keywords: prosthetic leg, Al alloy, Ti alloy, UDCFE, combination material (CF, UDCFE and Ti alloy), static and fatigue analysis

1. INTRODUCTION

People who have lost their legs due to injury or birth have the option to use prosthetic legs for performing the functional requirements of the limbs [1]. The legs developed should be resistant to wear, comfortable, reliable, and moisture resistant, and they should be capable of withstanding high loads. These characteristics can be achieved by a proper selection of materials for manufacturing a prosthetic leg. The main parts of a prosthetic leg include a socket, a residual limb and a base foot [2]. The materials selected for these parts have to sustain the loads acting on it. Since 1980s, there has been a significant development in the usage of materials for sockets ranging from wood, leather, and aluminum to plastics in the present generation. A few authors have worked on alternative materials and manufactured a cost effective prosthetic leg. Steven Chen [3] conducted a study to design a cost effective prosthetic leg using aluminum and polypropylene materials. The Author observed that prosthetic legs are fabricated using a vacuum molding process are durable, reliable and easy to assemble and dismantle, and the production cost is also very low. The designed prosthesis can also bear a load of 8 kg and a hooking angle of 53.5°. M I Awad [4] developed a semi-active prosthetic leg for a preliminary assessment and testing which works under both active and passive modes. The mechatronic system designed by the author yields good results for a back driving mechanism to restore the negative energy and to provide the positive power based on the requirement. Kadhim K Resan [5] designed and analyzed a new prosthetic foot for special needs people. The author used wood, steel, cast iron and designed a dorsiflexion foot tester. Based on the results of an impact and fatigue analysis performed on the newly designed leg, it was observed that the new foot offers a high fatigue life, a high dorsiflexion angle of 7.8°. The developed foot also exhibits high flexibility compared to such a foot. V. Vijayan [6] designed and analyzed a prosthetic foot using an additive manufacturing technique using a poly lactic acid material. The model was printed by using a 3D printer. The foot was optimized for a weight of 230 g and a finite element analysis was performed. This technique of additive manufacturing can reduce the cost of the foot in mass production. Ganapathi Shastry [7] conducted his study on a simulation and optimization of the materials used for the prosthetic leg for above-knee amputees using mr fluid. In this study, the author used Mr Damper consisting of Mr Fluid and smart materials which change their behaviour according to the magnetic field around it. This methodology of introducing the damper changes the performance of a semi active prosthetic leg to a natural leg and it is less expensive. The author suggested an aluminum material compared to steel for achieving a high relative permeability and a factor of safety greater than one. Qahtan [8] performed a tensile test on a laminated composite prosthetic socket reinforced by different fibers. The fabrication was done by using a vacuum bag molding technique with polyester resin reinforced with jute, glass, carbon and perlon fibers. The results showed that the best combination is observed for three layers of jute and four layers of carbon fiber. The tensile strength and modulus of elasticity was observed to be 162 MPa and 3.6 GPa, the specific strength reaches to 134 MPa.

Jiann-jong liau [9] investigated the effect of misalignment on stresses in a polyethylene prosthetic knee. The finite element model of a knee prosthesis was studied under three medical translations (0.25, 0.5 and 1 mm), internal rotation (1°, 3° and 5°) and various tilt (1°, 3° and 5°) under a load of 3000 N at 0° flexion angle. The maximum contact stresses are reported to be 67.6%, 14.3% and 145.9% and an increase of the maximum Von Mises stress were 92.5%, 22.7% and 120.6% in mistranslation, internal rotation and various tilt. Based on the results, it was observed that an increase of the contact and Von Mises stresses occurred in flat on the flat design prosthesis. Therefore, the polyethylene material presents a high conformity curve on the curve design and there is minimal risk of misalignment by using this material. M Hamzah and A. Gatta [10] designed a novel carbon fiber ankle prosthetic foot and performed a finite element analysis for heel and keel deflections. The heel deflected by 29.18 mm under a load of 300 N, while the keel deflected more than 25 mm under 1230 N, and the deflection under a vertical load of 1230 N was ca. 8.1 mm. The strain and stress are observed to be within the safe limits. As there is limited research that has been performed in the area of an analysis of the prosthetic leg for medical applications, it was observed that several authors used alternate polymer materials like polypropylene, polyethylene and polyester for manufacturing the prosthetic leg. Several authors used alternative natural fibers for manufacturing the socket of a prosthetic. It was also observed that there is very limited research that has been taken place in using the FEA tool for the prosthetic leg. It was also observed that carbon fiber materials occupy a better position to replace many metal components in the field of aerospace, sports and automobiles. Hence, within this work, an attempt was made to use an alternative material of carbon fiber epoxy for prosthetic leg applications and to compare these results with metals. A static and fatigue analysis was performed for all the materials of the prosthetic leg. A theoretical analysis was also performed under different loads and flexion angles and compared with the analytical results.

2. SELECTION OF MATERIALS

A selection of materials plays a vital role for any component to withstand the loads acting on it and to exhibit fewer deformations. The materials selected for performing a static and fatigue analysis on the prosthetic leg include the Al alloy, the Ti alloy, UDCFE and a combination of the materials. The inbuilt mechanical and physical properties of all the selected materials are taken from the properties present in Ansys 2020. These properties are listed in Tables 1 to 3.

Tab. 1. Properties of Al Alloy

Material Property	Value
Young's Modulus	7.1×10^{10} Pa
Poisson's Ratio	0.33
Bulk Modulus	6.9608×10^{10} Pa
Shear Modulus	2.6692×10^{10} Pa
Isotropic secant coefficient of thermal expansion	2.3×10^{-5} /°C
Compressive ultimate strength	0 Pa
Compressive yield strength	2.8×10^{8} Pa
Tensile ultimate strength	3.1×10^{8} Pa
Tensile yield strength	2.8×10^{8} Pa
Density	2770 Kg/m^3
Specific heat at constant pressure	875 J/Kg°C

3. DESIGN AND ANALYSIS OF PROSTHETIC LEG

The design of the prosthetic leg was done by using SolidWorks 2015 software. The standard dimensions of a C type leg are considered for the current study having a total length of the leg as 586 mm and the foot length of 250 mm and the pylon height of the foot 120 mm shown in Fig 1.

Tab. 2. Properties of Ti alloy

Material Property	Value
Young's Modulus	9.6×10^{10} Pa
Poisson's Ratio	0.36
Bulk Modulus	1.1429×10^{10} Pa
Shear Modulus	3.5294×10^{10} Pa
Isotropic secant coefficient of thermal expansion	9.4×10^{-6} /°C
Compressive ultimate strength	0 Pa
Compressive yield strength	9.3×10^{8} Pa
Tensile ultimate strength	1.07×10^{8} Pa
Tensile yield strength	9.3×10^{8} Pa
Density	4620 kg/m^3
Specific heat at constant pressure	522 J/ kg°C

Tab. 3. Properties of uni-directional CF- Epoxy (395GPa)

Material Property	Value
Young's Modulus X direction	2.09×10^{11} Pa
Young's Modulus Y direction	9.45×10^{9} Pa
Young's Modulus Z direction	9.45×10^{9} Pa
Poisson's Ratio XY	0.27
Poisson's Ratio YZ	0.4
Poisson's Ratio XZ	0.27
Sshear Modulus in XY	5.5×10^{9} Pa
Shear Modulus in YZ	3.9×10^{9} Pa
Shear Modulus in XZ	5.5×10^{9} Pa
Tensile in X direction	1.979×10^{9} Pa
Tensile in Y direction	2.6×10^{7} Pa
Tensile in Z direction	2.6×10^{7} Pa
Compressive in X direction	(-) 8.93×10^8 Pa
Compressive in Y direction	(-) 1.393×10^8 Pa
Compressive in Z direction	(-) 1.39 × 10^8 Pa
Density	1540 kg/m^3
Specific heat at constant pressure	522 kg°C

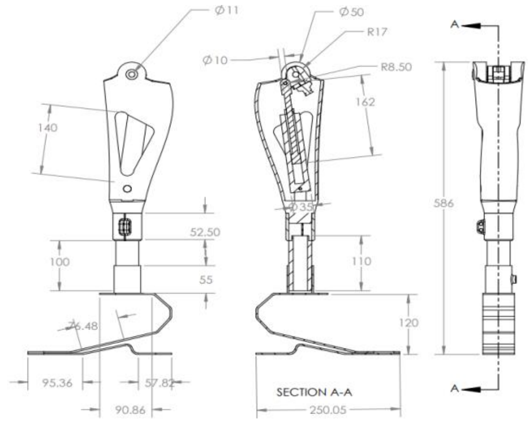

Fig. 1. Dimensions of prosthetic leg

The various parts of the prosthetic leg socket, limb, foot and joining elements are designed with the standard dimensions individually and made to match all these individual parts to form an assembled prosthetic leg. The designed components using Solid Works are represented in Fig. 2 and assembled they are represented in Fig. 3.

Fig. 2. Assembled prosthetic leg

The assembled model developed by using the Solid Works software is saved in the format of .iges. The saved file was then imported to Ansys Workbench 2020 to perform a static and fatigue analysis on the component. Initially, a static analysis was performed by considering the different weights of the human body, i.e. 60 kg, 70 kg, 80 kg and 90 kg loads acting on the component and noting down the values of Von Mises stresses and deformations for different configurations.

A fatigue analysis was performed under a finite life condition of up to 10^6 cycles. The details of the meshing for the analysis possess a minimum edge length of the element as 1.0083×10^{-4} m and a surface area of 1.4247×0^{-3} m^2. In order to obtain the results with smaller time intervals, coarse type mesh sizing is provided to the component. The imported component of the prosthetic leg, i.e. the meshed part is shown in Fig. 4 and Fig. 5.

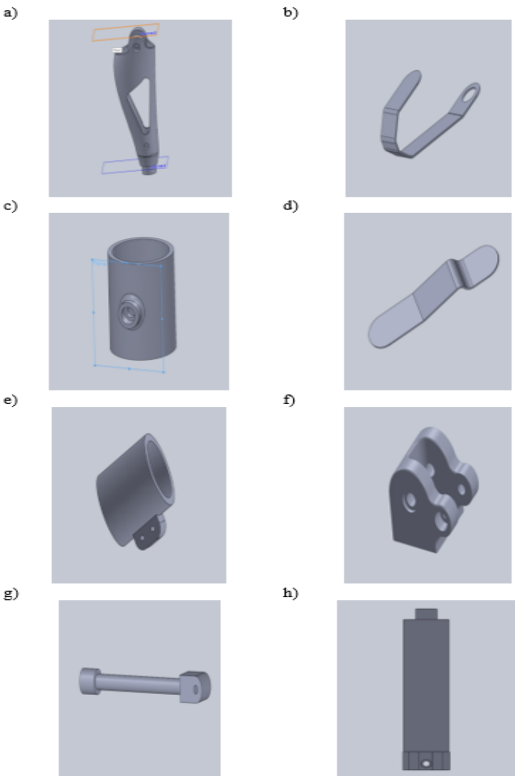

Fig. 3. Individual parts of prosthetic leg

4. RESULTS AND DISCUSSIONS

4.1. Static analysis

A static analysis was performed on the prosthetic leg which is under rest condition. This analysis will provide the ability of the material to sustain loads. The more the ability of the material to sustin the loads, the greater the strength of the material is. In the present study, four loads, i.e. 60 kg, 70 kg, 80 kg and 90 kg loads are acting on the centroidal axis of the prosthetic leg at the limb position shown in Fig. 6.

Fig. 4. Prosthetic leg imported to ansys

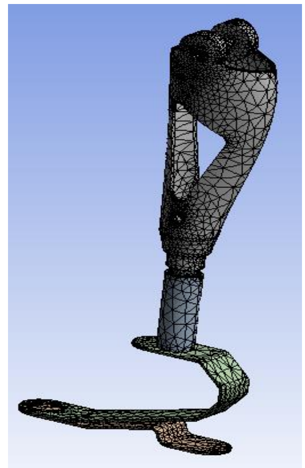

Fig. 5. Prosthetic leg after performing meshing

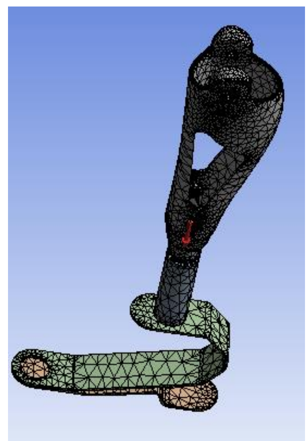

Fig. 6. Location of applied load on prosthetic leg

The base foot of a prosthetic is made to fix in all the directions. The values of deformations and Von Mises stresses are noted by varying the material properties of a prosthetic leg. The results of all the materials at a load of 90 kg are represented in Figures 7 to 14 below.

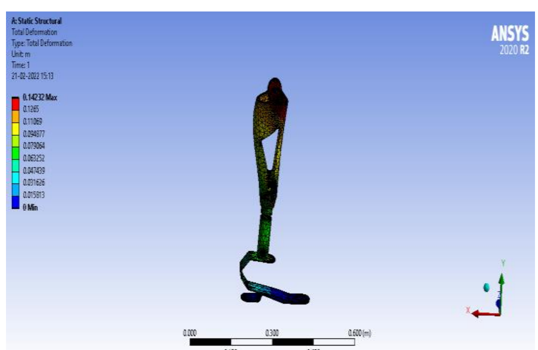

Fig. 7. Deformation of Al Alloy

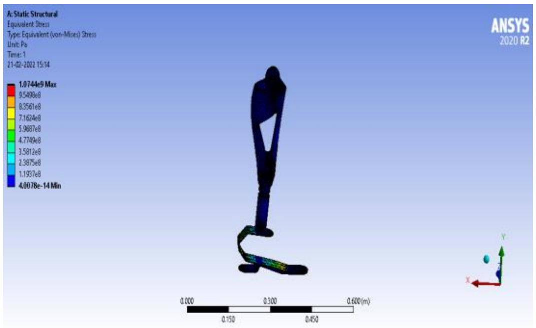

Fig. 8. Von Mises stress of Al Alloy

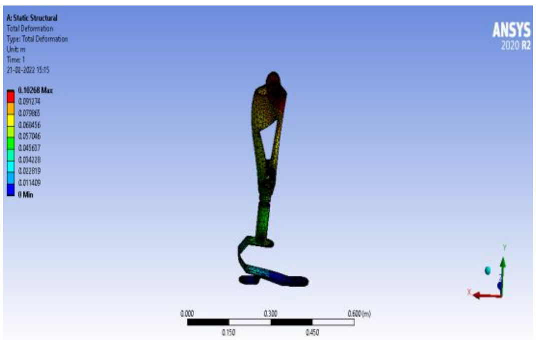

Fig. 9. Deformation of Ti Alloy

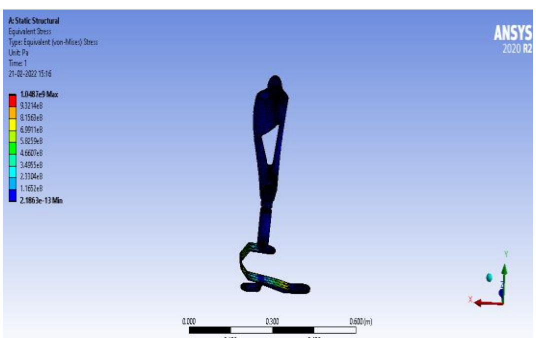

Fig. 10. Von Mises stress of Ti Alloy

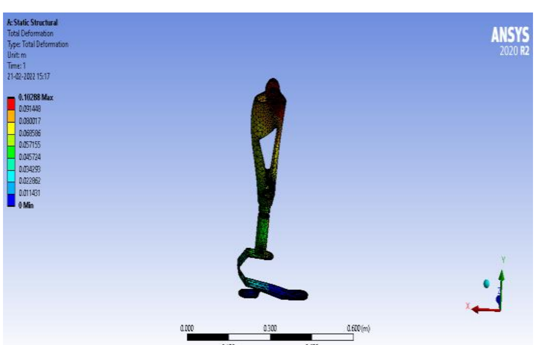

Fig. 11. Deformation of UDCFE

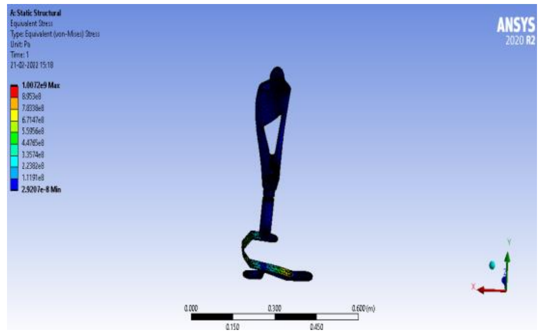

Fig. 12. Von Mises stress of UDCFE

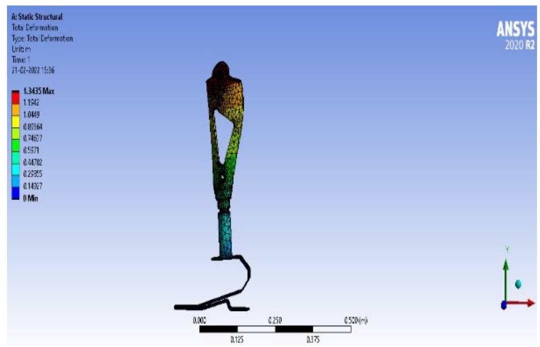

Fig. 13. Deformation of combined material

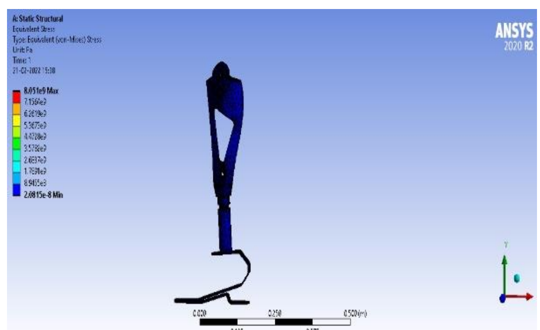

Fig. 14. Von Mises stress of combined material

Tab. 4. Values of deformation and Von Mises stress at a load 60 kg for all materials

Material	Von Mises Stress (Pa)	Deformation (m)
Al Alloy	7.16×10^{8}	0.094877
Ti Alloy	7.22×10^{8}	0.094088
Carbon fiber epoxy UD	7.33×10^{9}	0.03442
Combination (CF+CEPoxy+Ti alloy)	5.37×10^{9}	0.89564

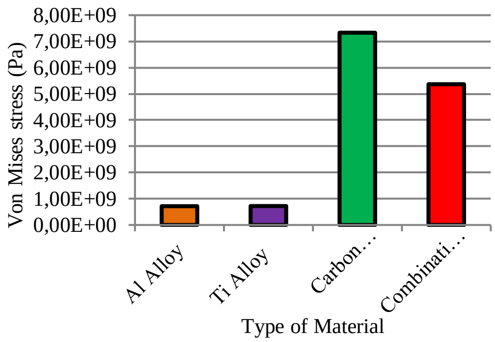

Fig. 15. Graphical representation of Von Mises stress values at a load of 60 kg

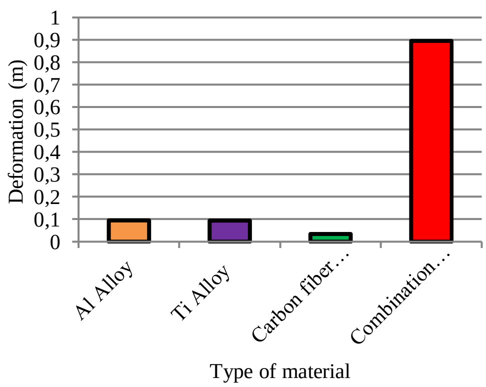

Fig. 16. Graphical representation of deformation values at a load of 60 kg

Tab. 5. Values of deformation and Von Mises stress at a load 70 kg for all materials

Material	Von Mises Stress (Pa)	Deformation (m)
Al Alloy	8.36×10^{8}	0.11069
Ti Alloy	8.16×10^{8}	0.079865
Carbon fiber epoxy UD	3.42×10^{9}	1.0669
Combination (CF+CEPoxy+Ti alloy)	6.26×10^{9}	1.0449

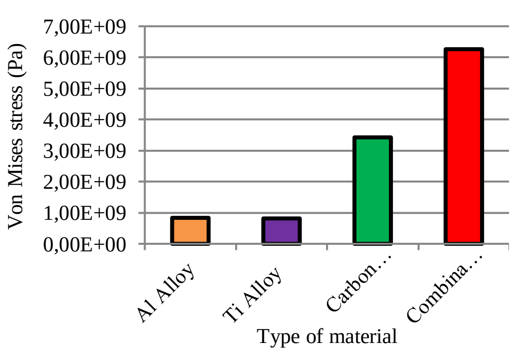

Fig. 17. Graphical representation of Von Mises stress values at a load of 70 kg

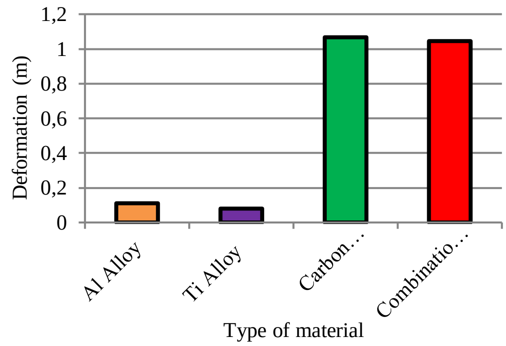

Fig. 18. Graphical representation of deformation values at a load of 70 kg

Tab. 6. Values of deformation and Von Mises stress at a load of 80 kg for all materials

Material	Von Mises Stress (Pa)	Deformation (m)
Al Alloy	9.55×10^{8}	0.1265
Ti Alloy	9.32×10^{8}	0.0912
Carbon fiber epoxy UD	3.91×10^{9}	1.2193
Combination (CF+CEPoxy+Ti alloy)	7.16×10^{9}	1.1942

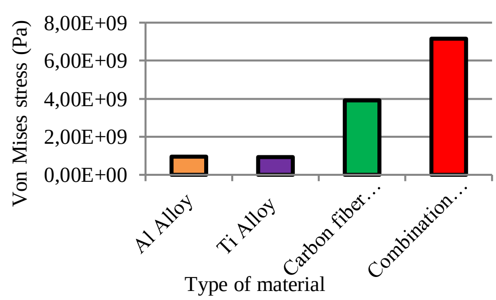

Fig. 19. Graphical representation of Von Mises stress values at a load of 80 kg

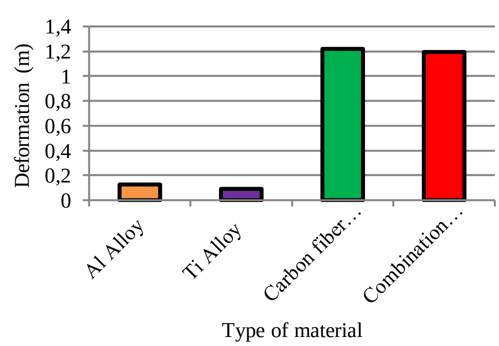

Fig. 20. Graphical representation of deformation values at a load of 80 kg

Tab. 7. Values of deformation and von Mises stress at a load 90 kg for all materials

Material	Von Mises Stress (Pa)	Deformation (m)
Al Alloy	1.07×10^9	0.14232
Ti Alloy	1.05×10^9	0.10298
Carbon fiber epoxy UD	1.01×10^9	0.10288
Combination (CF+CEPoxy+Ti alloy)	8.05×10^9	1.3435

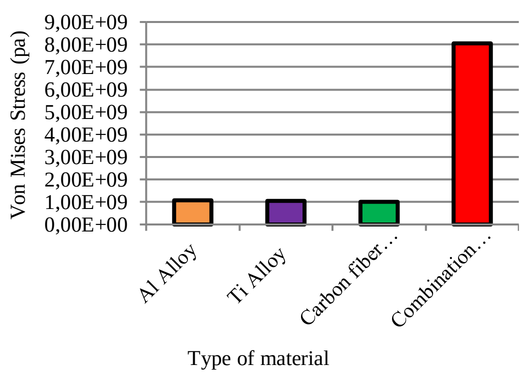

Fig. 21. Graphical representation of Von Mises stress values at a load of 90 kg

It was observed from Fig. 15 that the Al alloy exhibits a lower value of von Misses stress (7.16×10^8 Pa) compared to the remaining materials at a load of 60 kg. The value of the deformation is observed to be less for UDCFE (i.e 0.034 m) at lower loads. With increase of load to 70 kg, it was observed from Fig. 17 that Ti alloy exhibits lower values of Von Mises stress (7.16×10^8 Pa) and deformation of (0.0798m) compared to the remaining materials. At a further increase of the load to 80Kg, it was observed that the Ti alloy shows better values of Von Mises stress (9.32×10^8 Pa) and deformation values of (0.091m).

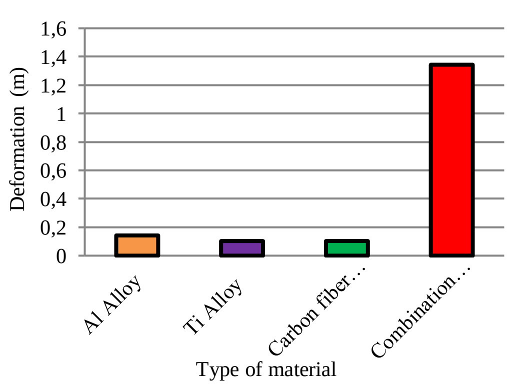

Fig. 22. Graphical representation of deformation values at a load of 90 kg

At higher loads i.e 90 kg load, it was observed that uni-directional carbon fiber epoxy UDCFE exhibits a lower value of von Mises stress (1.021×10^9 Pa) and a lower value of deformation (0.102 m) compared to the remaining materials. Hence, based on all these observations, it was evident that the Al alloy material exhibits good results at lower load values of 60 kg applied on the prosthetic leg. With an increase in the load to 70 kg, 80 kg and 90 kg, the Ti alloy exhibited good values of Von Mises stress and deformation. At higher load conditions, i.e. the 90 kg load, UDCFE exhibited a lower value of von Mises stress and deformation, and it was also observed that this composite material has higher chances of replacing the conventional metals like the Ti alloy and the Al alloy.

4.2. Fatigue analysis

In this analysis, a sinusoidal load curve is generated in Ansys 2020 by providing the predetermined cycles and alternating stress values considering the finite life behavior of the component up to 10^6 cycles shown in Table 8. The determination of the behavior of the component under cyclic loads is a herculean task for the designer to analyze the damage of the component and to estimate the value of the endurance limit of the component. Ansys 2020 provides a tool for determining the damage of the component against the applied variable loads acting on the component. This analysis can be taken as the basis for evaluating the performance of the component under fatigue loads before the component proceeds to the design and manufacturing stages.

It was observed from Fig. 26-29 and from the Tables 9 to 12 that the damage values of Ti Alloy and CF Epoxy are significantly smaller compared to the remaining materials selected for the prosthetic leg. The main reason for exhibiting better properties is the addition of Ti alloying element which provides a higher strength to the steel. At lower load conditions, i.e. 60 kg, the fatigue load applied on the material, it was observed that the Ti alloy exhibits a damage value of (2.03×10^6) and UDCFE exhibits (5.39×10^7) which are smaller than the Al alloy and the combination material. It was also observed that the damage resistance of the Ti alloy and UDCFE was greatly improved with an increase of the load from 70 kg and 80 kg.

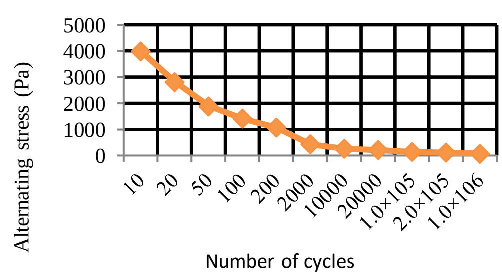

Fig. 23. S-N Curve of Number of cycles vs. alternating stress acting on the component

Tab. 8. Sinusoidal alternating stress acting on the component

Cycles	Alternating stress (Pa)
10	3999
20	2827
50	1896
100	1413
200	1069
2000	441
10000	262
20000	214
1.0×10^{5}	138
2.0×10^{5}	114
1.0×10^{6}	86.2

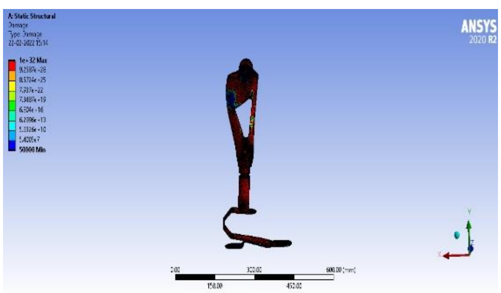

Fig. 24. Damage of Ti Alloy at load 90 kg

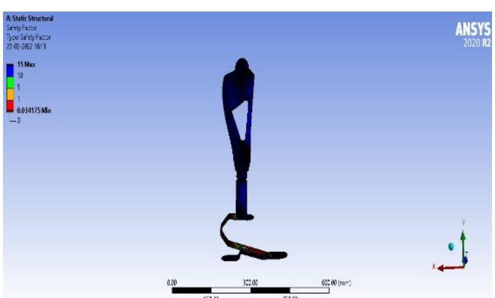

Fig. 25. Factor of safety for all materials

Tab. 9. Values of damage for all the materials at 60 kg load

Type of material	Damage
Al Alloy	1.0×10^{32}
Ti alloy	2.03×10^{6}
Carbon-Epoxy	5.39×10^{7}
Combination (CF+Epoxy +Ti Alloy)	1.0×10^{32}

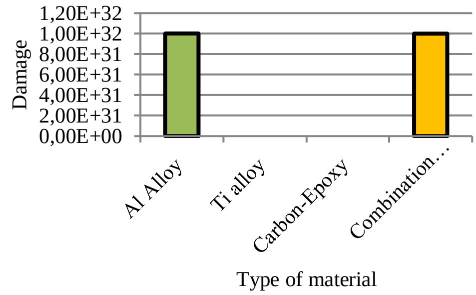

Fig. 26. Graphical representation of damage values at a load of 60 kg

Tab. 10. Values of damage for all the materials at 70 kg load

Type of material	Damage
Al Alloy	1.0×10^{32}
Ti alloy	2.81×10^{6}
Carbon-Epoxy	7.33×10^{7}
Combination (CF+Epoxy +Ti Alloy)	1.0×10^{32}

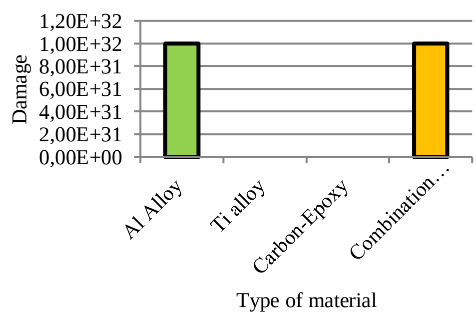

Fig. 27. Graphical representation of damage values at a load of 70 kg

Tab. 11. Values of damage for all the materials at 80 kg load

Type of material	Damage
Al Alloy	1.0×10^{32}
Ti alloy	3.74×10^{6}
Carbon-Epoxy	9.57×10^{7}
Combination (CF+Epoxy +Ti Alloy)	1.0×10^{32}

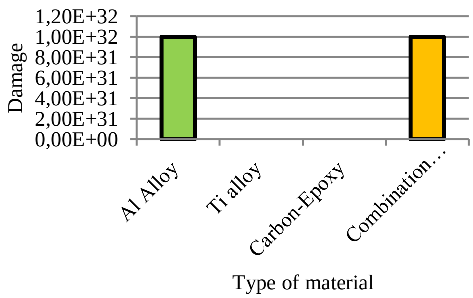

Fig. 28. Graphical representation of damage values at a load of 80 kg

Tab. 12. Values of damage for all the materials at 90 kg load

Type of material	Damage
Al Alloy	1.0×10^{32}
Ti alloy	4.80×10^{6}
Carbon-Epoxy	1.0×10^{32}
Combination (CF+Epoxy +Ti Alloy)	1.0×10^{32}

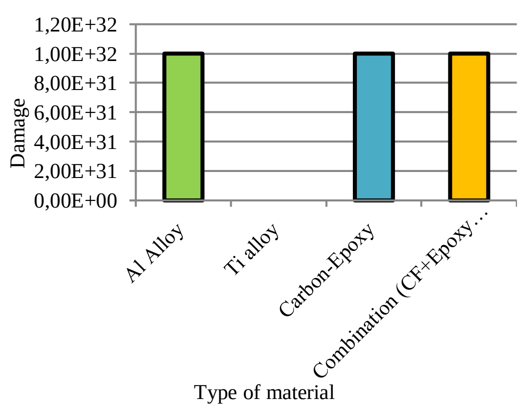

Fig. 29. Graphical representation of damage values at a load of 90 kg

The damage resistance of UDCFE is observed to be (1×10^{32}) at a load of 90 kg, which is equal to the damage resistance observed for the Al alloy and the combination material. Therefore, at a higher sinusoidal load of 90 kg applied on UDCFE, the material possesses a possibility of a degradation of the material which further leads to failure at high cycles fatigue conditions greater than 10^6 cycles. Hence, the composite material UDCFE has closer results to those of the Ti alloy material and a greater chance to sustain fatigue loads acting on it for low cycle fatigue conditions. Further, proper fabrication of the composite and the methodology adopted and ingredients selection during manufacturing of the component will decide about the ability of the material to sustain more variable loads.

5. VALIDATION AND COMPARISON OF RESULTS BY VARYING THE BASE FOOT ANGLE

A theoretical analysis was performed of the prosthetic leg to determine the stresses induced in each member by varying the inclination of the base foot with the ground. The behaviour of the foot at three inclinations, i.e. 10°, 20° and 30° was analyzed by considering the dimensions of the members, the areas of each member and the Young's modulus of each member. Finite element equations are developed to calculate the individual stiffness matrix and the global stiffness matrix. After imposing the boundary conditions, the stresses induced in each member for different materials with varying inclination angles are calculated and tabulated. The theoretical results obtained by using the finite element equations are compared with the analytical results observed using Ansys 2020.

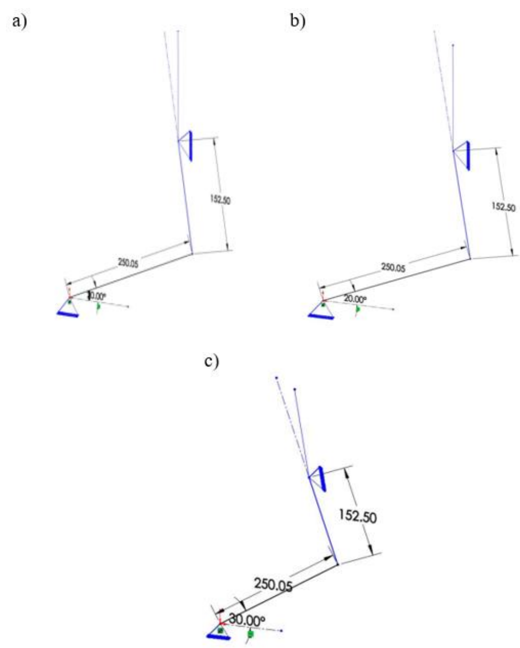

Fig. 30. Dimensions of prosthetic leg by varying the inclinations of base foot with ground

A theoretical analysis was performed for two materials, i.e. Ti alloy and UDCFE and the results obtained are compared with the analytical results**.** Case (i) Sample calculation for UDCFE at 80 kg load and 10° base foot inclination.

The ability of the material to sustain the loads by varying the base inclination angles was analysed by applying the finite element equations on two members of a prosthetic leg. The sample calculations performed on UDCF Epoxy at an inclination of 10° was shown in case(i). The values of all the calculated stresses of the two materials, i.e. UDCFE and Ti Alloy with varying inclinations of the base foot are presented in Table 15.

Tab. 13. Node coordinates table

Position	*X*	*Y*
1	0	0
2	246.25	43.42
3	246.25	195.2

Tab. 14. Direction cosine table

Element	*le*	*L=(X2-X1)/le*	*M=(Y2-Y1)/le*
1	250.05	0.984	0.173
2	152.5	0	0.999

$$A_1 = 115\ \text{mm}^2\ \text{E} = 130\ \text{GPa} = 12 \times 10^3 \text{N/mm}^2 \quad (1)$$

$$K^1 = \frac{A_1 E_1}{L_e}\begin{pmatrix} l^2 & lm & -l^2 & -lm \\ lm & m^2 & -lm & -m^2 \\ -l^2 & -lm & l^2 & lm \\ -lm & -m^2 & lm & m^2 \end{pmatrix} \quad (2)$$

$$K^1 = 10^3\begin{pmatrix} 57.87 & 9.83 & -57.87 & -9.838 \\ 9.83 & 0.28 & -9.83 & -0.28 \\ -57.87 & -9.83 & 57.87 & 9.838 \\ -9.83 & -0.28 & 9.83 & 0.28 \end{pmatrix} \quad (3)$$

$$K^2 = 10^3\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 601.36 & 0 & -601.36 \\ 0 & 0 & 0 & 0 \\ 0 & -601.36 & 0 & 601.36 \end{pmatrix} \quad (4)$$

$$K = 10^3\begin{pmatrix} 57.87 & 9.83 & -57.87 & -9.83 & 0 & 0 \\ 9.83 & 0.285 & -9.83 & -0.285 & 0 & 0 \\ -57.87 & -9.83 & 57.87 & 9.83 & 0 & 0 \\ -9.83 & -0.285 & 9.83 & 0.285 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.99 & 0 & 0.99 \end{pmatrix} \quad (5)$$

$$[F] = [K][q] \text{ since f1,f2,f3,f4,f5,q1,q2,q5} = 0 \quad (6)$$

$$10^3(57.87q_3 + 9.83q_4) = 0 \rightarrow eq1 \quad (7)$$

$$10^3(9.83q_3 + 1.28q_4 - 0.998q_6) = 0 \rightarrow eq2 \quad (8)$$

$$10^3(-0.998q_4 + 0.998q_6) = 0 \rightarrow eq3 \quad (9)$$

By solving eqations 1, 2 and 3

$$q_3 = -0.0961{=}0.096\text{mm}$$
$$q_6 = -0.220{=}0.220\text{mm}, q_4 = 0.5652mm \quad (10)$$

$$\sigma_1 = \frac{E}{l_e}[\text{-l -m l m}]\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \quad (11)$$

$$= \frac{130\times10^3}{250.05}[-0.98\ \text{-}0.17\ 0.98\ 0.17]\begin{bmatrix} 0 \\ 0 \\ 0.096 \\ 0.220 \end{bmatrix} \quad (12)$$

$$\sigma 1 = 6.8x107\ Pa \quad (13)$$

$$\sigma_2 = \frac{E}{l_e}[\text{-l -m l m}]\begin{bmatrix} q_3 \\ q_4 \\ q_5 \\ q_6 \end{bmatrix} = \quad (14)$$

$$\frac{130\times10^3}{152.5}[0\ \text{-}0.999\ 0\ 0.999]\begin{bmatrix} 0.096 \\ 0.220 \\ 0 \\ 0.220 \end{bmatrix} \quad (15)$$

$$\sigma_2 = 0 \quad (16)$$

Based on the theoretical calculations performed by using finite element equations on the members, it was observed that the stresses induced in the second member are zero for all the inclination angles of the base foot with the ground. It was also observed that the theoretical stresses induced in the materials for UDCFE is (6.8×10^7 Pa) and Ti alloy is (11.7×10^4 Pa). At 80 kg load, the stresses observed by using the analytical results for the UDCFE and the Ti alloy are (3.9×10^9 Pa) and (9.32×10^8 Pa) observed to be more than the theoretical permissible stresses for the two materials. At lower inclinations, there may be chances of failures taking place in both materials at the load value of 80 kg.

Further, it was also observed from results that the theoretical stresses obtained for the UDCFE and Ti alloys at 20° base foot angle amounted to (4.53×10^7 Pa) and (98.85×10^9 Pa). The analytical values of the stresses are observed to be more than the theoretical calculated stresses for the UDCEF material. However, the Ti alloy material possesses an analytical value of (9.32×10^8 Pa) and it sustains the load at 20° base foot angle and 30° base foot angle. When a load of 70 kg is applied to the prosthetic leg, it was observed from Table 2 that the von Mises stress stresses calculated analytically for the UDCFE and Ti alloy are observed to be (3.42×10^9 Pa) and (8.16×10^9 Pa). Based on the results present in Table 16, it was observed that the Ti alloy material possess good results at an inclination of 10°, 20° and 30°. The values observed using an analytical method are lower than the calculated theoretical values.

Tab. 15. Stress values in members 1 and 2 by varying the base foot inclination at 80 kg load

Material	At 10° Inclination		At 20° Inclination		At 30° Inclination	
	σ1(Pa)	σ2(Pa)	σ1(Pa)	σ2(Pa)	σ1(Pa)	σ2(Pa)
CFE	6.80×10^7	0	4.53×10^7	0	76.60×10^7	0
Ti alloy	11.70×10^4	0	98.85×10^9	0	15.56×10^7	0

Tab. 16. Stress values in members 1 and 2 by varying the base foot inclination at 70 kg load

Material	At 10° Inclination		At 20° Inclination		At 30° Inclination	
	σ1(Pa)	σ2(Pa)	σ1(Pa)	σ2(Pa)	σ1(Pa)	σ2(Pa)
CFE	5.95×10^7	0	3.96×10^7	0	67.02×10^7	0
Ti alloy	10.23×10^4	0	86.49×10^9	0	13.61×10^7	0

Hence, the Ti alloy material withstands the load more easily with an inclination of the base foot from 10° to 30° for a sinusoidal load of 70 kg. It was observed that when a sinusoidal load is acting on the component with a varying inclinations of the base foot from 10°, 20° and 30°, the chances of a failure are more in UDCFE compared to the Ti alloy material. Hence, further experimental studies need to be conducted to understand the degradation mechanism, the manufacturing methods, the ingredients' selection for UDCFE to replace metals under inclination angles, which plays a primary role especially in running competitions, sports etc. This composite material UDCFE exhibits better results in static and fatigue loads.

6. CONCLUSIONS

Prosthetic legs are used by many people in various fields like sports, normal walking and performing their daily activities with ease. With the advancement of composites in various industries, an attempt was made in the present work to study the behaviour of a prosthetic leg by varying the material properties and analysing its performance under different loads. The conclusions drawn from this analysis can be used to estimate the materials, loads and manufacturing methods suitable to design a prosthetic leg for medical applications.

It was observed from static analysis results that with an increase in the load from 60 kg to 90 kg, the Ti alloy exhibits good properties compared to the remaining materials. It was also notice that at higher loads of 90 kg under a static condition, the UDCFE composite material exhibits a lower value of von Mises stress (1.01×10^9 Pa) and small deformation (0.10288 m) compared to the remaining materials followed by the Ti alloy material.

After performing a fatigue analysis, it was observed from the results that at a cyclic load of 60 kg and alternating stresses values acting on the component, the damage of the Ti alloy is observed to be (2.03×10^6 Pa) and that of UDCEF is observed to be (5.39×10^7 Pa). The damage resistance of CFE is closer to the Ti alloy material compared to the Al alloy and the combination material considered in the study. Finally, the theoretical values of the two main members present in a prosthetic leg are evaluated at three different angles, i.e. 10°, 20° and 30°. Based on these results, it was observed that the stresses produced analytically for the Ti alloy material are smaller than the theoretical values for almost all the angles. nevertheless, UDCFE has the chances of failure at inclined angles. Hence, a proper methodology of the fabrication of the UDCFE composite with necessary reinforcement ingredients will further enhance the strength closer to the Ti alloy metal. Therefore, in the future applications, there is a large scope to replace the conventional metals with composites like UDCFE for manufacturing a prosthetic legs suitable to medical field applications, sports and normal walking conditions.

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Biographical notes

Naresh Kumar Konada is presently working as an Assistant professor in the department of mechanical engineering, Anits, Visakhapatnam, India. He is in teaching and research since 2010. He published 22 international journals in various fields. He was awarded doctorate degree PhD in the department of mechanical engineering, Andhra University in the year 2020. His area of research interests includes machine design, nano composites, friction materials, vibrations and vehicle dynamics.

K.N.S. Suman is working as an Associate professor in the department of mechanical engineering, Andhra University, Visakhapatnam, India. He received his doctorate in the year 2006 from Andhra University, in the field of research on under water vehicles in collaboration with naval science and Technological laboratory (NSTL). He received best thesis award during that year by Andhra University. He received senior research fellowships from UGC and CSIR. His area of research interests includes mechanical behavior of composites, nano materials and manufacturing.