Stress and Failure Analysis of Composite Prosthetic Leg

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Abstract. Prosthesis is an artificial substitute for body parts such as limbs, eye, tooth, etc. Generally, the prosthesis is referred to as a fabricated substitute used to assist the damaged part of the body. The devices are made up of light materials like plastics, aluminium, and composites materials. The prosthetic technology is aimed to replicate the body part which is damaged irreversibly due to unfortunate incidents. The present work deals with creation of an optimized design for the prosthetic leg proposed by Saito et al. [2]. The material of prosthetic leg proposed here is made up of Carbon Fiber Reinforced Polymer (CFRP) composite laminate, having unidirectional and cross-ply stacking sequence, which is analyzed for static stress and failure loads. From the results, it is evident that, while a uni-directional laminate can withstand a failure load of 4910 N, a cross-ply laminate withstands 4282 N. Also, the individual ply versus stress is studied in this work.

Keywords: Prosthesis legs, static stress, failure load, ply.

1. Introduction

Several people all over the globe require lower leg prosthetic legs. But due to the high cost of the prosthesis component, people are not able to offer the high-cost prosthesis leg. Thus, people were forced to resort to crude limitations constructed from wood or bamboo without regard to comfort or safety standards. The reasons for this high-cost prosthesis limbs are due to the very small production of the prosthesis and custom-made designs. Hence the mass production of these prosthesis and optimization of design that incorporates low manufacturing costs, high strength, great durability, and smooth walking will be the key in reducing the manufacturing cost of the prosthetics.

Saito et al.[2] had developed a low-cost transtibial prosthesis made of fiber-reinforced plastic (FRP) which is as shown in figure 1.
The design consisted of a foot component, an axial structural member, and a cosmetic cover. Later the prosthesis' cosmetic cover is attached to the foot component to give the regular shape of the foot. The prosthetic leg is so designed that, it can reproduce the motion of the intact leg adequately and also ankle of the prosthetic leg should follow the same path of the biological joint during walking. The axial member can be adjusted for the optimum fit. The two aluminium stiffeners were incorporated into the foot as shown in figure 1 which are used to increase the strength and load-bearing capacity of the prosthetic leg.

Jill Hahl et.al [3] performed a failure test on the fabricated prototype; it showed that it is capable of withstanding 6,600 N load before failure. It surpasses the failure load of 5,500 N of the original prosthesis and also satisfies the static test outlines in the ISO standard 10328. They found that the optimized design provides sufficient strength and also reduced the cost of manufacturing.

Jill Hahl et.al [4] studied the design developed by Saito et al. (1). They modified it and proposed an optimized design by performing FE analysis on various modified prosthesis models and it was tested by using FEA software. The model has the maximum von-Mises stress and maximum shear stress of 56.3MPa and 3.6MPa respectively. Also, the failure analysis was performed and the results obtained were congruent with the ISO standard 10328 of the prosthesis.

Glen K et.al [5] studied the influence of multiple factors viz., abnormal loading of the residual-limb soft tissues, abnormal or excessive musculoskeletal loading of the residual-limb proximal structures, and/or abnormal or excessive loading of the intact limb musculoskeletal structures, on biomechanical performance of the prosthesis and resultant loading impact on to the residual limbs. Also, mechanical properties of the vertical shock-absorbing pylons and prosthetic foot ankle systems and the impact on amputee gait were discussed.

Priya Sharma et. al [8] performed numerical analysis of Jaipur (JP) foot and Polyurethane (PU) foot to test the stress bearing capacity, and to compare the displacement, crack propagation and durability of both the foot and concluded that JP Foot has a better stress bearing capacity and material strength than PU Foot.
2. Stress and failure analysis

The main objective of this study is stress and failure analysis of the low-cost transfemoral prosthesis leg. The numerical analysis is performed to determine the stress concentration on the FRP foot and determine the onset of failure load at which the failure takes place. Finite element Modelling is done and analysis is performed using commercial FEA software.

Stress analysis can be performed by adopting any one of the following techniques, such as classical mathematical techniques, analytic mathematical modelling or computational simulation, or experimental methods. The technique adopted here is based on classical mathematical technique i.e classical laminated plate theory. The design of composite structures requires the prediction of the maximum load that a laminate can withstand before it fails. For this purpose, usually, first ply, the second ply, and last ply failure criteria are mostly used for failure analysis of composite structures. The entire process of failure prediction helps in finding the maximum stresses, maximum strains, maximum load, or the failure load that a composite structure can withstand. To determine the safe life of a composite structure, designing below the failure load values is important. Thus failure analysis is the preliminary investigation to be carried out before proceeding to any kind of analysis. Thus, the present study deals with linear static stress analysis for composite laminate made of carbon epoxy material for stacking sequences of {0}20s,{0/90/0/90/0/90/0/90/0/90}s on the basis of last ply failure adopting Tsai-Wu composite failure criteria [3] and failure loads for different lamina are obtained.

2.1 FE model development

The analysis of the prosthesis leg is done using ABAQUS/CAE software, a finite element program. The number of elements in a 3D FE model is around 3300 elements. The element type used was a 3D shell element. This was a 4 node, doubly curved general-purpose shell, reduced integration, hourglass control, finite membrane strains (S4R) elements.

2.2 Geometry

![Figure 2 Proposed optimum geometry of the prosthetic leg.](image-url)
The model mainly consists of a composite foot, aluminium pipe, and a rigid part (ground surface). The model was used to investigate a series of loadings and boundary conditions, intended to simulate the stages of loading during the stance phase of gait. The composite foot possesses a single integrated stiffener. The optimum stiffener placement was positioned at 39.5 mm from the toe with a clockwise base rotation of 12° as shown in figure 2. The foot component is made of a laminated composite structure. The total number of plies in the composite foot is around 20. Each ply is of thickness 0.25 mm/ply, having a total thickness 5 mm. The foot has a width of 60 mm. A 6061-T6 aluminium pipe of diameter 28 mm and a height of 300 mm was inserted and fitted into the hole cut at the top of the prosthetic composite foot.

2.3 Material Properties

The prosthetic model shown in figure 2 is having mainly 3 parts, composite foot, aluminium pipe and a rigid part. The composite foot is made of Carbon Fibre Reinforced Polymer (CFRP) laminate with 20 plies, each ply having thickness of 0.25 mm, total of 5 mm thick. The axial member is made of 6061-T6-aluminium pipe of dia 28 mm. The material properties are shown in table 1 and table 2.

| Material     | Engineering constants for laminate |
|--------------|-----------------------------------|
| CFRP         | E₁ (GPa)  | E₂ (GPa)  | E₃ (GPa)  | G₁₂ (GPa) | G₂₃ (GPa) | G₁₃ (GPa) | ν₁₂ | ν₂₃ | ν₁₃ |
|              | 170       | 9         | 9         | 4.8       | 4.5       | 4.8       | 0.34 | 0.5 | 0.34 |

| Table 2: Material properties for Aluminium 6061 T6 |
| Material | Engineering constants for isotropic material |
|----------|---------------------------------------------|
| Aluminium 6061 – T6 | E (GPa) | ν |
|              | 68.9       | 0.35       |

2.4 Loading and Boundary Condition

Figure 3 Loading and boundary conditions used in the finite element model.

A rigid surface is used as a ground surface and a rigid surface contact condition was used to simulate the ground surface. The height of the prosthetic model is fixed at 300 mm from the
ground surface. The maximum weight of the patient is assumed to be 100kg. Hence a force of 1000N is applied on the top of prosthesis. Horizontal displacement ranging from 0 to 110 mm with 5mm thickness is used to simulate walking

2.5 Interaction Property

![Figure 4](image)

Figure 4 Interaction properties in the FE model

Figure 4 shows the various interaction properties in the FE model. A rigid contact was fixed at a height of 300 mm from the ground surface. A tie constraint is used to give contact between the ground surface and the foot surface.

2.6 Meshing

![Figure 5](image)

Figure 5 Meshed FE model

The element type used is a 4 node doubly curve general shell element, with reduced integration, hourglass control, and finite membrane strains. Figure 6 shows S4R element and location of integration point. The total number of elements and nodes in the FE mode are 3363 and 3432 respectively.
3. Results and Discussion

The FE model was developed and subjected to stress and failure analysis. The static load [3] is applied on each ply (for both unidirectional and cross ply orientations) and the stresses developed on each ply is found and recorded. Graphs are plotted for on the recorded values and ply number as shown in figures 7 and 8 respectively. It is found that, individual ply is able to withstand the static load as evident from table 3 or in other words, the composite prosthesis model is able to withstand the failure load and hence the design is safe for the specified purpose. The material used in static analysis are CFRP laminate with unidirectional and cross-ply orientations.
Figure 8 Stresses $\sigma_i$ at each ply for a cross ply laminate

All the values obtained in the analysis for both unidirectional and cross-ply orientation of CFRP laminate are less than the values of lamina strength shown in table 3.

| Table 3 Values of lamina strengths |
|-----------------------------------|
| $\sigma_x$ (MPa) | $\sigma_y$ (MPa) | $\sigma_{xy}$ (MPa) |
| Tension            | 2050             | 62               | 81               |
| Compression        | 1200             | 190              | 81               |

Where $\sigma_x$, $\sigma_y$, $\sigma_{xy}$ are the ultimate strengths in the longitudinal, transverse, and shear directions, respectively.

Figures 9 and 10 shows static failure analysis for CFRP composite laminate having 20 plies with the unidirectional sequence was performed using Tsai-wu failure criteria [3]. The maximum load that unidirectional CFRP laminate can withstand is around 4910N. Similarly, maximum load that the cross-ply CFRP laminate can withstand is around 4282N.

Figure 9 Ply number Vs failure load per ply for CFRP laminate with unidirectional orientation
4 Conclusion

Static stress analysis and static failure loads were performed for a prosthetic leg made of CFRP laminate having unidirectional and cross-ply stacking sequences. As per the failure results, the maximum load that unidirectional CFRP laminate can withstand is around 4910N and the maximum load that cross-ply CFRP laminate can withstand is around 4282N respectively, which is congruent with ISO standard 10328 for the prosthesis respectively, which is congruent with ISO standard 10328 for the prosthesis.

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