

Citation: Akankshya Priyadarshini, Mihir Kumar Sutar, Sarojrani Pattnaik. A finite element approach to enhance the performance of nano-reinforced prosthetic foot. *Journal of Harbin Institute of Technology (New Series)*. DOI: 10.11916/j.issn.1005-9113.2024013.

A Finite Element Approach to Enhance the Performance of Nano Reinforced Prosthetic Foot

Akankshya Priyadarshini, Mihir Kumar Sutar , and Sarojrani Pattnaik*

(Department of Mechanical Engineering, Veer Surendra Sai University of Technology, Sambalpur 768018, Odisha, India)

Abstract: Functionally Graded Materials (FGMs) are innovative advanced quality materials in the field of composites concerning their strength, mechanical, and thermal properties. Nowadays, the modern requirement of the industry in the fields of health care, aerospace, and power sectors needs the rapid evolution of new components, which allows researchers to invent new materials to satisfy the functional requirements of modern technology. Tissue engineering is one of the most concerned areas of the application of FGM in the healthcare sector, where the tailored properties of FGM play a significant role in building and growing an artificial structure that heals the damaged tissue of the body parts and meets the desired application that the part needs to perform. This paper highlights the suitability of the combination of a nano-structure enhanced epoxy functionally graded material, its properties, and applicability in the design of a prosthetic foot where it provides the mobility and comfort of the body part like natural tissue. The analytical study is done by designing an ANSYS model and simulating the results of equivalent stress and directional deformation. The Finite Element (FE) approach is used to optimize the output results of stress-strain analysis, different weight percentages of nano-filler are taken for performance enhancement. A comparative analysis is done with the previously established results taking carbon fiber-reinforced composites that offer a successful validation of the present results obtained. Furthermore, this study also provides a clear understanding of the justification of the composition considered for the effective application in the field of prosthetics field.

Keywords: FGM; FE; prosthetic foot; ANSYS model

CLC number: TB332

Document code: A

Article ID: 1005-9113(2024)00-0000-08

0 Introduction

The prosthetic foot serves as the major component of the lower limb providing the basic interfacial region between the limb and the ground. Based on various parameters like the weight of the human being, and ground reaction on the foot, several designs have been developed to model the prosthetic feet^[1-2]. A clear understanding of various prosthetic foot technologies with their advantages and disadvantages has been studied by researchers. Among those, one basic foot manufacturing is based on the principle of Resin Transfer Molding (RTM) where the materials chosen for such manufacturing are wet epoxy carbon woven with resin epoxy as the built-in materials^[3].

Many researchers have proposed different

processes for the optimal design of a prosthetic foot. Recent advances in the design of prosthetics involve the use of composites where the appropriate design parameters are required to be set using methods, such as metaheuristic algorithm, and at the end of the design process, the simulation is performed using ANSYS for the different deformation analysis^[4]. Hence, the design parameters are taken for Finite Element Analysis (FEA), and a comparative static analysis can be done between FEA results and experimental results. Researchers also manufactured non-articulated prosthetic feet using composite materials like High-Density Polyethylene (HDPE) and Date Palm Wood (DPW)^[5]. The main objective of experimental studies is to manufacture the foot to optimize the dorsiflexion angle to limit the bending capacity to an acceptable range and for longer fatigue life. Focusing on the biomechanical properties in

Received 2024-1-25.

Sponsored by the Science and Technology Department, Government of Odisha (Grant No.3724/ST, Bhubaneswar.dt.14.09.2022).

* Corresponding author. Mihir Kumar Sutar, PhD. Email: mihirsutar05@gmail.com.

prosthetic feet analysis, such as durability, stability, shock absorption improvement, fatigue enhancement, etc, the recently recommended one is SACH (Solid Ankle Cushion Heel) foot^[6]. Three types of SACH prosthetic feet have been studied and analyzed: two types are for active users with total energy return, and one type is based on partial energy return. Nowadays, prosthetics are designed to offer controlled mobility by utilizing the energy storing and releasing capacity.

Finite Element Analysis is being used in many developmental fields of advanced material to study the elastic stability, bending, and vibration response of Functionally Graded structures of porous plate^[7], sandwich plate^[8], porous beams^[9], etc. Researchers also have done Finite Element Analysis on Graphene nanoplatelets-reinforced FG structures, such as beams and panels^[10-11], etc., for better analysis of the dynamic responses^[12-14].

In addition to the recent research, besides designing and analyzing the foot with different geometrical modifications, one important task is to determine the material properties with advanced dynamic abilities. Various composite materials have been used in the manufacturing of the foot with good extracted results. The current analysis focuses on designing and analyzing a foot using functionally graded material with epoxy as the matrix polymer. Compared to the uniform dispersed material in many kinds of research, it was found that the mechanical properties such as wear, stiffness, strength, and energy absorption capacities, are superior in graded structure^[15-16]. The reinforcement is chosen as the GPL focusing on its properties of good mechanical strength and structural integrity^[17-18]. Hence, many applications require the use of FGMs that mechanically outperform the conventional composites with homogenous composition.

1 Material Property Selection

The polymer matrix is chosen as the epoxy resin with low viscosity to proceed with the material selection. GPL is used as the filler material in the matrix to analyze the FG structure. Varying the filler weight percentage, the material properties are selected based on the considered graded pattern and utilized as the input parameters in the simulation. The individual material properties of the matrix and filler are mentioned in Table 1.

Table 1 The material properties

Material	Modulus of elasticity (E) (GPa)	Mass density (ρ) (kg/m ³)	Poisson's ratio
Epoxy	3	1200	0.340
GPLs	1010	1060	0.186

1.1 Material Gradation

To model the Functionally Graded (FG) structure made by the nano filling of Graphene Nano-Platelets (GPLs) in the epoxy matrix where the reinforcement is dispersed non-uniformly in the transverse direction (z -direction). The gradation pattern of GPL, which varies from a minimum at the surface to the maximum at the center as a function of its volume fraction^[19], can be expressed as Eq.(1),

$$V_{GPL}(z) = V_{GPL}^* \cdot 2 \cdot \left(1 - \frac{2|z|}{h}\right) \quad (1)$$

where z is thickness direction of geometry, h denotes the total thickness of the model, V_{GPL} represents the volume fraction of GPL, and V_{GPL}^* describes the total volume fraction of GPLs and can be determined by the formula of Eq.(2),

$$V_{GPL}^* = \frac{W_{GPL}}{W_{GPL} + (\rho_{GPL}/\rho_m)(1 - W_{GPL})} \quad (2)$$

where W_{GPL} denotes the GPL Nano filler weight percentage which is considered for three different values to analyze every desired mechanical behavior more efficiently. ρ_{GPL} is the density of GPL, and ρ_m is the density of the matrix.

1.2 Properties Determination

For implementing the FG material properties in the ANSYS software simulation, the effective material properties for three different weight fractions of 1.0 wt. %, 1.5 wt. %, and 2.0 wt. % have been evaluated based on the rule of mixture using mathematical formulation.

$$E(z) = V_{GPL}(z) E_{GPL} + V_m(z) E_m \quad (3a)$$

$$v(z) = V_{GPL}(z) v_{GPL} + V_m(z) v_m \quad (3b)$$

$$\rho(z) = V_{GPL}(z) \rho_{GPL} + V_m(z) \rho_m \quad (3c)$$

where $E(z)$, $v(z)$, $\rho(z)$ denote the effective Young's modulus, poisson ratio, and density, and the subscript GPL and m are for nano-filler and polymer matrix respectively. E_{GPL} and E_m are Yong's modulus of rigidity of GPL and epoxy, respectively, V_{GPL} and V_m are Poison's ratio of GPL and epoxy, respectively.

2 Design Methodology

For the initial design, all the details about the

person for whom the design of the prosthetics is going to be done are gathered, and the design parameters are determined to model the desired foot in ANSYS 2020R1 software.

2.1 Material Selection

To initiate the design, the material properties must first be identified. All the property values are obtained by using the rule of mixture that is selected for the better suitable property of the foot. All the respective material properties of each weight fraction of reinforcements are presented in Table 2, such as density, Young’s modulus, and poison’s ratio, are obtained as per the previously mentioned property relations. These properties are used as the input parameters in the material selection steps.

2.2 Geometry of the Foot

The foot is designed according to the geometrical

parameters proposed by Al-Zubaidi and Al-Shammari^[20], which has been considered as ideal geometry for the design of the foot after several modifications, e.g., the thickness of the back arch of the foot was increased and subsequently the length was reduced, and the width was increased to the shape of final geometry. Fig.1 shows the isometric and side views of the proposed model.

Table 2 The mechanical properties

Weight fraction (wt%)	Property		
	Density P (Kg/m ³)	Young’s modulus E (GPa)	Poison’s ratio ν
2.0	1197.6	93.778	0.3261
1.5	1193.7	71.078	0.3374
1.0	1187.4	48.572	0.33

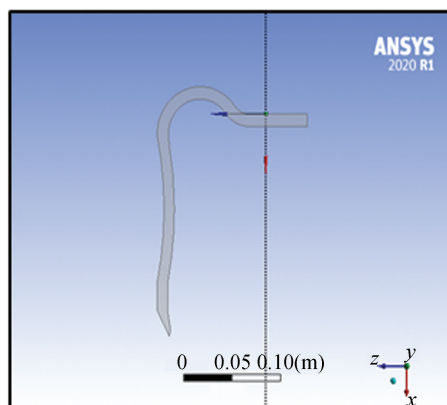
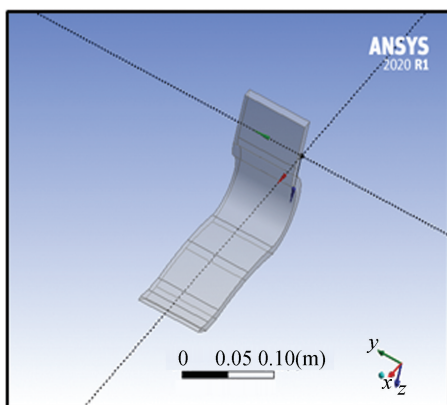


Fig.1 Geometry of the foot in ANSYS

2.3 Modelling

In modelling, first of all, the predetermined material properties are assigned to the considered geometry and then going for the next step, i. e. meshing. Meshing is completed by selecting the shape of the mesh element as a hexahedron with subsequent variations of the mesh size.

To perform the independent grid resolution test, the variations of several mesh finally were taken, the fine meshing of the best-selected mesh size, is shown in Fig. 2, where it has been noted that the results are constant and independent. Hence, the convergence test is completed to get the accuracy in the results, especially in the area of higher induced critical stress during normal functioning of the foot, aiming to reach a point of steady state or mesh independent state.

2.4 Boundary Conditions

The foot is designed fixed from the top and free

at the bottom part as shown in Fig. 3. It is thus designed so that the person feels free to move from one side at the bottom of the leg and from the side of the toes.

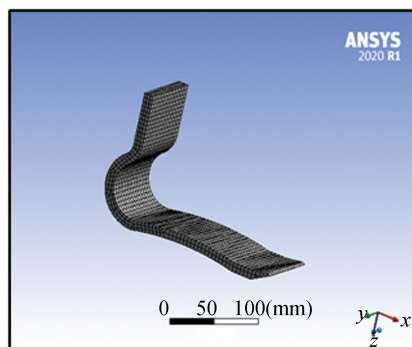


Fig. 2 Mesh geometry of the foot

2.5 Loading Conditions

The entire modeling and structural analysis of the

proposed prosthetic foot are done prominently for a person's need for walking and accordingly, the loading condition is taken based on the mid-stance phase while the person is walking. To represent the ground reaction forces on the foot, the forces acting on the foot are determined where the body mass is also assumed as the weight of a common adult of 80 kg i.e. $784.8 \text{ N}^{[20]}$.

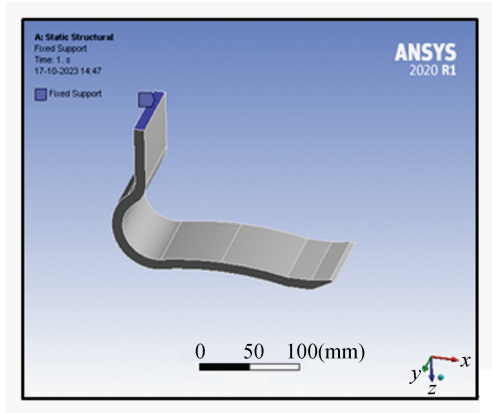


Fig. 3 Foot with fixed support

2.5.1 Gait Cycle

The gait cycle is the sequence of the limb movements in the dynamic condition, i.e. during walking or running. It mainly involves two phases which are the stance phase and the swing phase.

(a) Stance phase: During this phase, the foot is in contact with the ground and supports the body weight consisting of four different periods. The events corresponding to each period are summarised as follows.

- i. Loading response: It is the period between the events of initial contacts at 0% to the opposite toe-off at 10%.
- ii. Mid-stance phase: It is the period up to the event of heel rise at 30% of the gait cycle.
- iii. Terminal phase: It is the period of heel rise to opposite limb initial contact at 50% of the gait cycle.

(b) Swing phase: There is no contribution of GRFs on the lower limbs as the foot is not in contact with the ground as this is the phase of limb advancements.

The identification of gait cycle phases plays a vital role in controlling the dynamic equilibrium of a pedestrian by measuring and analyzing the force systems acting on the lower limbs, which can be stated as the Ground Reaction Forces (GRFs). Subject must equilibrate the forces consisting of the body weight components. Simultaneously, the three components of

GRFs are developed which are vertical forces, anterior-posterior shear, and medial-lateral shear. Among all these components, vertical forces have extreme peaks with 120% of BW (Body Weight) at 10% of the gait cycle and 80% of BW at 55% of the gait cycle. The shear components have negligible contribution to the gait cycle, i.e. of about 20% of BW in case of anterior-posterior shear and $\pm 5\%$ of BW in case of lateral shear, where BW corresponds to body weight.

2.5.2 Monitoring of Gait Cycle Events

The GRF diagram makes it possible to identify and analyse the forces acting on foot at different time instances during its dynamic mode considering the angle of inclination at that point. The major component of the GRF, i.e. the vertical force, has two peaks where the force is 120% of the body weight which shows its peaks at two instances. One instance is towards the end of 10% gait cycle completion and another one is the 50% of the gait cycle completion. All these instances are shown in Fig.4 incorporated during the gait cycle. It also shows a minimum value, i.e., 80% of body weight, in the middle towards the completion, and of the 30% gait cycle which is known as the mid-stance phase.

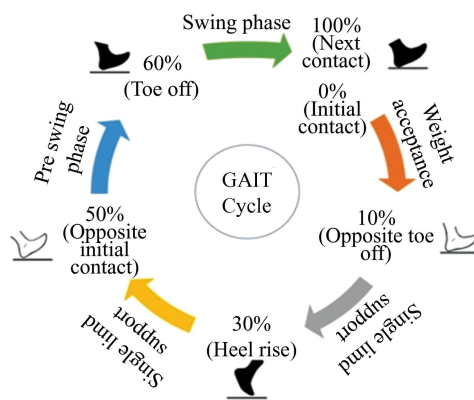


Fig. 4 The Gait cycle phases

The GRF vertical components, as a function of gait cycle percentage, are clearly illustrated in Fig.5. From Fig. 5, it can be seen that the force at the heel region represents 1.3 times of the body weight, and the force at the tips of the toes represents 1.25 times of the body weight, the force at the midstance position is 0.8 times of the body weight. In the biomechanical analysis, a normal foot is considered that an ideal walking condition that a person takes into consideration, the instance where the heel portion

force is inclined at an angle of $+20^\circ$ from the vertical axis, and the toe portion force is inclined at an angle of -15° from the vertical axis, as shown in Fig. 6.

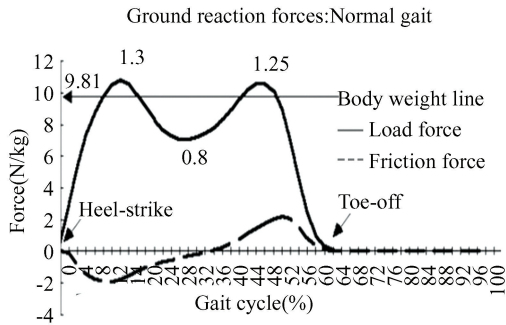


Fig. 5 Representation of force components on percentage of gait cycle^[20]

The forces of F_1 and F_2 are applied to the designed foot based on the corresponding angle of inclination to

plot in ANSYS software, as shown in Fig.7. Taking into consideration the angle of inclination, the force components are:

$$F_{1x} = F_1 \sin 20^\circ, F_{1y} = F_1 \cos 20^\circ$$

$$F_{2x} = F_2 \sin 15^\circ, F_{2y} = F_2 \sin 15^\circ$$

2.6 Solution Procedures

The solution part presents the stress and deformation pattern across the different components of the prosthetic foot which are chosen to evaluate the result. After the completion of the above solution procedures, the solver output gives the results that are selected for, i.e.

- 1) Maximum directional deformation
- 2) Maximum equivalent stress

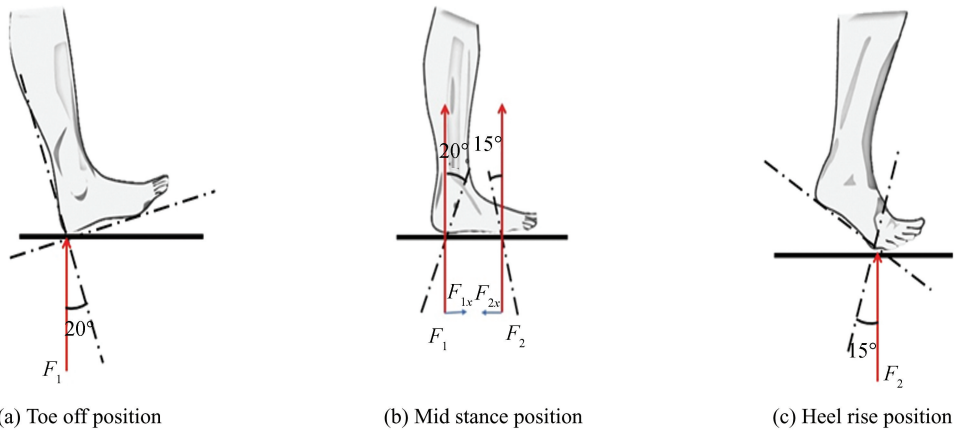


Fig. 6 Position of a pedestrian in dynamic condition

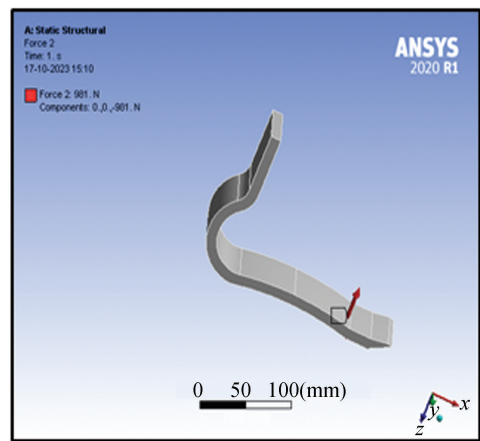
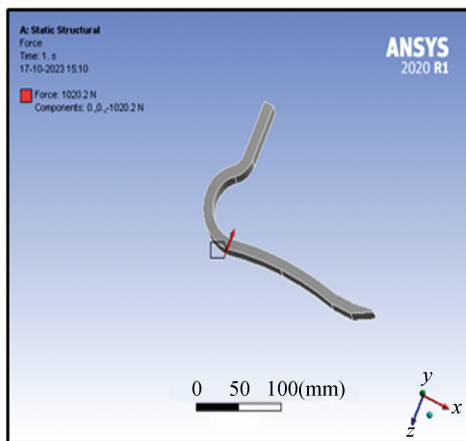


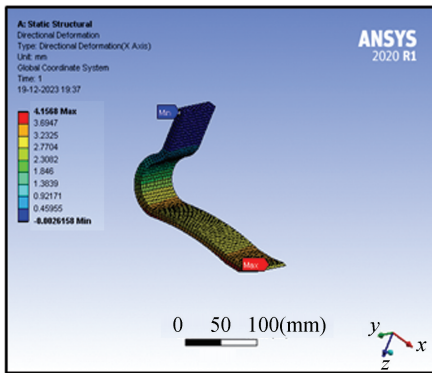
Fig. 7 Forces applied on the foot

From Figs. 8–10, it can be seen that the maximum equivalent stress occurs at the heel region,

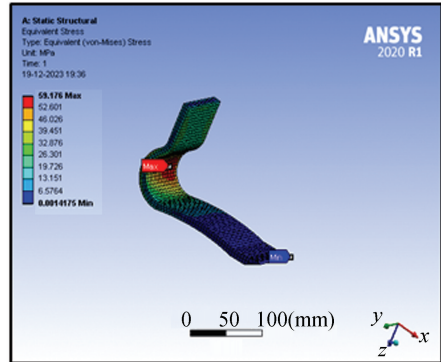
and at the same time, maximum directional deformation occurs at the toe region. It is because

during the heel strike phase to the toe-off phase, it almost covers the two extreme peaks of the vertical force component, i.e. the reaction force of the ground on the foot, as it is the primary contact area with the ground during these gait phases. Thus, and this concentrated force in this heel area leads to increased stress in the respective portion. On the other hand,

during the forward locomotion of the body, a gradual transfer of weight occurs from the heel to the toe region contributing to the increased deformation in that toe region. Also, the flexibility requirements of the toe area to accommodate the motion could contribute to the larger deformation.

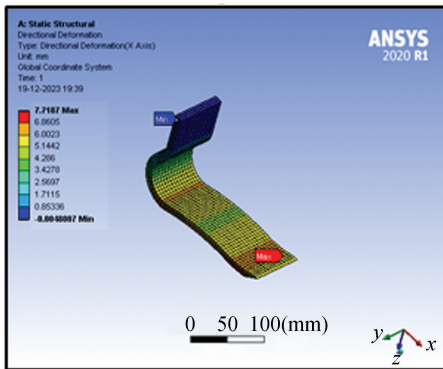


(a) Maximum directional deformation

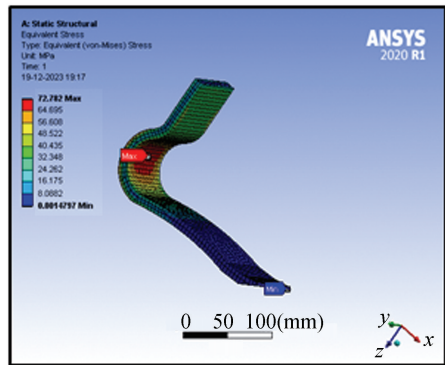


(b) Maximum equivalent stress

Fig. 8 ANSYS simulation results for 1.0 wt.% FG-GPL

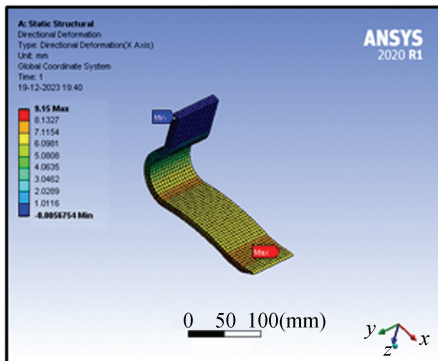


(a) Maximum directional deformation

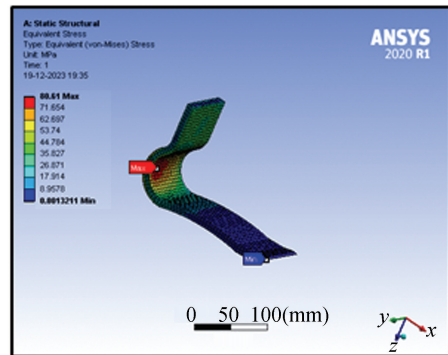


(b) Maximum equivalent stress

Fig. 9 ANSYS simulation results for 1.5 wt.% FG-GPL



(a) Maximum directional deformation



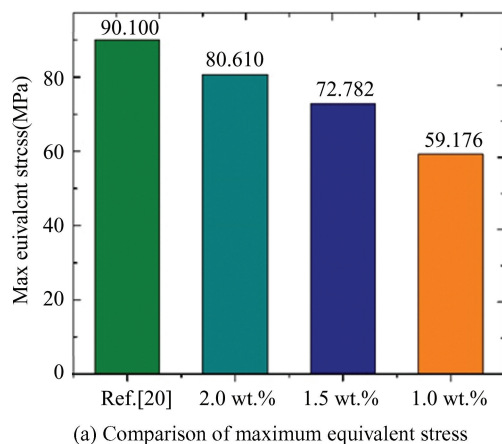
(b) Maximum equivalent stress

Fig. 10 ANSYS simulation results for 2.0 wt.% FG-GPL

3 Results and Discussion

The results thus obtained are compared with the acceptable results of stress and strain limits for the specific geometry to ensure the safety and durability of the present design model. Table 3 represents the results obtained from the ANSYS simulation for each fraction of nano-fillers along with the results of the reference model. The design mentioned is found to be satisfied with the proposed filler content and gradation pattern. The main objective of the current analysis is to design a prosthetic foot where the results show the reduction in the maximum equivalent stress and maximum directional deformation as compared to the existing prescribed model from Ref. [20].

A comparative plot for both the results of



maximum equivalent stress and maximum directional deformation is plotted using a bar chart in Fig. 11, where a continuous decrement pattern is observed in the maximum equivalent stress and maximum directional deformation from 2.0 wt.% GPL nanofiller to 1.0 wt.% of nanofiller with a noticeable differential order of 34.04 % and 78.48 % of reduction in the present model, while 1 wt. % FG-GPL compared to the model in Ref. [20].

Table 3 The results of the ANSYS simulation

Model	Maximum equivalent stress (MPa)	Maximum directional deformation (mm)
model in Ref. [20]	90.100	25.743
2.0 wt.%	80.610	9.150
Present model 1.5 wt.%	72.782	7.719
1.0 wt.%	59.176	4.157

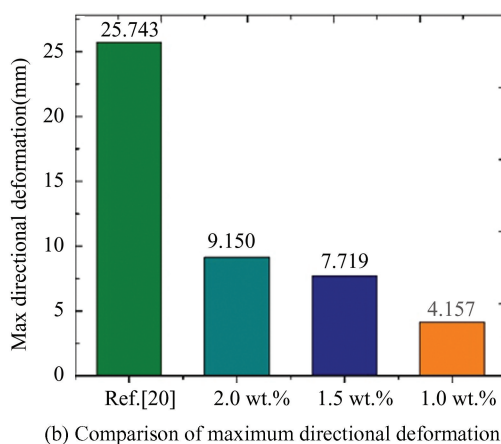


Fig.11 Comparative plots of results between the present and reference model^[20]

Replication of natural mobility, and better responsiveness of the wearer's to movements, could be addressed by reducing directional deformation. Also from an energy expenditure point of view, a prosthetic foot is designed to reduce the maximum directional deformation that could benefit the user in requiring less effort to move, which in turn improves the endurance and less fatigue for the prosthetic wearer.

Minimizing the maximum equivalent stress lowers the degree of structural failure, wear, and tear that otherwise improves its durability for long-term use. It also reduces the pressure sores of the user and provides more comfort, making daily activities less painful.

4 Conclusions

The present study focuses on the benefits

provided by the FE analysis of prosthetic foot based on the proposed material, which constituents to characterize the performance parameters, such as stress-induced, deformation, etc., and to understand its better adaptability in the biomedical field. In this paper, stress-strain analysis of the present model reinforced with nano GPL is done. It is found that the equivalent stress is reduced by 10.53% in 2.0 wt.%, besides, again decreases to 34.32% in 1.0 wt.%, whereas the directional deformation is reduced by 64.45% in 2.0 wt.% to 83.85% in 1.0 wt.% in comparison with the reference model. In the same way, another advantageous aspect lies in the higher Young's modulus that indicates higher material stiffness or resistance to elastic deformation. The proposed material in the analysis with lower density in comparison with the pre-existed model available in the

literature is found to be advantageous for the application where weight reduction is a major priority factor.

Hence, the present study is found to be useful in analyzing the proposed model for enhancing the flexibility, longevity, and making wearer movements more comfortable. The use of the proposed advanced material with a functionally graded structure provides the possibility of manufacturing tough and lightweight prosthetic feet.

References

- [1] Jiang M J, Zhang J X. An investigation into the effect of cross-ply on energy storage and vibration characteristics of carbon fiber lattice sandwich structure bionic prosthetic foot. *Science and Engineering of Composite Materials*, 2023, 30;20220206. DOI: 10.1515/secm-2022-0206.
- [2] Oshkour A A, Osman N A Abu, Yau Y H, et al. Design of new generation femoral prostheses using functionally graded materials; A finite element analysis. Part H; *J Engineering in Medicine*, 2012, 227(1): 3–17. DOI: 10.1177/0954411912459421.
- [3] Tan Q Y, Wu C C, Li L, et al. Nanomaterial-based prosthetic limbs for disability mobility assistance: A review of recent advances. *Journal of Nanomaterials*, 2022, 2022(1): Article ID 3425297. DOI: 10.1155/2022/3425297.
- [4] Elgamsy R, Awad M I, Ramadan N, et al. Localization of composite prosthetic feet; Manufacturing processes and production guidelines. *Scientific Reports*, 2023, 13; 17421. DOI: 10.1038/s41598-023-44008-7.
- [5] Mohammed H S, Salman J M. Design and modeling the prosthetic foot from suitable composite materials. *American Journal of Engineering and Applied Sciences*, 2020, 13(3): 516–522. DOI: 10.3844/ajeassp.2020.516.
- [6] Oleiwi J K, Hadi A N. Properties of materials and models of prosthetic feet; A review. *Materials Science and Engineering*, 2021, 1094; 012151. DOI: 10.1088/1757-899X/1094/1/012151.
- [7] Vinh P V, Nguyen V C, Tounsi A. Static bending and buckling analysis of bi-directional functionally graded porous plates using an improved first-order shear deformation theory and FEM. *European Journal of Mechanics-A/Solids*, 2022, 96; 104743. DOI: 10.1016/j.euromechsol.2022.
- [8] Bentra H, Chorfi S M, Belalia S A, et al. Effect of porosity distribution on free vibration of the functionally graded sandwich plate using the P-version of the finite element method. *Computers and Concrete*, 2023, 88(6): 551–557. DOI: 10.12989/sem.2023.88.6.551.
- [9] Belabed Z, Tounsi A, Al-osta M, et al. On the elastic stability and free vibration responses of functionally graded porous beams resting on Winkler Pasternak foundations via finite element computation. *Geomechanics and Engineering*, 2024, 36(2): 183–204. DOI: 10.12989/gae.2024.36.2.183.
- [10] Mesbah A, Khaled A, Zakaria B, et al. Formulation and evaluation a finite element model for free vibration and buckling behaviors of functionally graded porous (FGP) beams. *Structural Engineering and Mechanics*, 2023, 86(3): 291–309. DOI: 10.12989/sem.2023.86.3.291.
- [11] Xia L, Wang R, Chen G, et al. The finite element method for dynamics of FG porous truncated conical panels reinforced with graphene platelets based on the 3-D elasticity. *Advances in Nano Research*, 2023, 14(4): 375–389. DOI: 10.12989/.2023.14.4.375.
- [12] Cuong B M, Tounsi A, Thom D V. Finite element modeling for the static bending response of rotating FG-GPLRC beams with geometrical imperfections in thermal mediums. *Computers and Concrete*, 2023, 33(1): 91–102. DOI: 10.12989/cac.2024.33.1.091.
- [13] Tien D M, Thom D V, Van N T H, et al. Buckling and forced oscillation of organic nanoplates taking the structural drag coefficient into account. *Computers and Concrete*, 2023, 36: 553–565. DOI: 10.12989/cac.2023.32.6.553.
- [14] Katiyar V, Gupta A, Tounsi A. Microstructural/geometric imperfection sensitivity on the vibration response of geometrically discontinuous bi-directional functionally graded plates (2DFGPs) with partial supports by using FEM. *Steel and Composite Structures*, 2022, 45: 621–640. DOI: 10.1088/1757-899X/1094/1/012151.
- [15] Loh G H, Pei E, Harrison D, et al. An overview of functionally graded additive manufacturing. *Additive Manufacturing*, 2018, 23: 34–44. DOI: 10.1016/j.addma.2018.06.023.
- [16] Bai G, Chen S, Chen X H, et al. Mechanical properties and energy absorption capabilities of functionally graded lattice structures; Experiments and simulations. *International Journal of Mechanical Sciences*, 2020, 182: 105–735. DOI: 10.1016/j.ijmecsci.2020.105735
- [17] Liu D, Chen D, Yang J, et al. Buckling and free vibration of axially functionally graded graphene-reinforced nanocomposite beams. *Engineering Structures*, 2021, 249: 113327. DOI: 10.1016/j.engstruct.2021.113327.
- [18] Papageorgiou D G, Kinloch I A, Young R J. Mechanical properties of graphene and graphene-based nanocomposites. *Progress in Material Science*, 2017, 90: 75–127. DOI: 10.1016/j.pmatsci.2017.07.004.
- [19] Vo-Duy T, Ho-Huu V, Nguyen-Thoi T. Free vibration analysis of laminated FG-CNT reinforced composite beams using finite element method. *Frontiers of Structural and Civil Engineering*, 2019, 13(2): 324–336. DOI: 10.1007/s11709-018-0466-6.
- [20] Al-Zubaidi D H J, Al-Shammari M A. Theoretical analysis of a new design of dynamic prosthetic foot. *International Journal of Mechanical Engineering*, 2022, 7(1): 4667–4680.