A Simulation Study of E-Glass Reinforced Polyurethane Footbed and Investigation of Parameters Effecting Elastic Behaviour of Footbed Material

Berkay Ergene, Çağın Bolat

Abstract**—**In this study, we mainly focused on a simulation study regarding composite footbed in order to contribute to shoe industry. As a footbed, e-glass fiber reinforced polyurethane was determined since polyurethane based materials are already used for footbed in shoe manufacturing frequently. Flat, elliptical and rectangular grooved shoe soles were modeled and analyzed separately as TPU, 10% glass fiber reinforced, 30% glass fiber reinforced and 50% glass fiber reinforced materials according to their properties under three point bending and compression situations to determine the relationship between model, material type and mechanical behaviours of composite model. ANSYS 14.0 APDL mechanical structural module is utilized in all simulations and analyzed stress and strain distributions for different footbed models and materials. Furthermore, materials constants like young modulus, shear modulus, Poisson ratio and density of the composites were calculated theoretically by using composite mixture rule and interpreted for mechanical aspects.

Keywords**—**Composite, elastic behaviour, footbed, simulation.

I. INTRODUCTION

DURING recent years it is obviously noticed a fast growth and interest in the development, practice and usage of fibre-reinforced thermoplastic polymer composite materials. Apart from this important enlargement and interest, the effect of parameters and the mechanism of matrix-fibre relationships have been investigated considerably by researchers working on different application areas [1]-[3]. Polyurethane is a very useful engineering material that can be found as different types of polymer like thermosets and thermoplastics. Owing to its low viscosity, superior coherency with the fibres and low cost, polyurethane is a promising and a tough rival for conventional engineering materials in several applications especially in lightweight designs [4]. This versatile material is also utilized in shoe sector as a footbed. In some earlier studies, researchers carried out detailed finite element analysis about footwear properties and its interaction with human foot comfort and they also checked up the strain distribution on footbed in different usage conditions [5]-[7].

In our study, we performed a numeric model work in order to contribute to textile engineering literature and shoe production sector. In addition to this, we analyzed the mechanical behavior of e-glass reinforced thermoplastic polyurethane (TPU) footbed in varied loading situations like compression and three point bending.

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II. METHOD

A. Finite Element Modelling

Finite element models are created as their length, width and height 270, 70 and 12 mm, respectively. The base of the shoe is made up of 3 different shapes as flat, rectangular grooved and elliptical grooved. The main length of the grooves on shoe sole 10 mm and their height is 2 mm. As material type; pure TPU, 10% e-glass reinforced TPU, 30% e-glass reinforced TPU, 50% e-glass reinforced TPU were used. TPU and e-glass were considered as general materials and composite materials obtained by mixing them in various e-glass percentages (10%, 30% and 50%). In the analyzes, the material data were obtained from composite mixing rule and they were entered as anisotropic material type in the material model part at Ansys finite element analysis program. The material properties of the composite materials formed based on the principle of composite mixing rule.

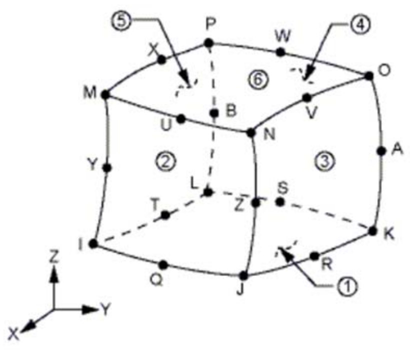


Fig. 1 View of the Solid186 element

In our analysis, in structural analysis mode, 20 node Solid186 element type was used. SOLID186 element is a higher order 3-D 20-node solid element that exhibits quadratic displacement behavior. Also this element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. This element supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities [8], [9]. This element type can be seen at Fig. 1.

In the analyzes, the modulus of elasticity, E, poisson ratio, v, shear modulus, G, and density, ρ constants of the composite structure, respectively, were obtained by the equation of mixture and given in Table I which also shows the e-glass reinforcement ratio in the composite structure with details. Table II gives the material constants used in the composite mixture rule [10], [11].

TABLE I
CONSTANT VALUES OF COMPOSITE MODEL CALCULATED ACCORDING TO COMPOSITE MIXTURE RULE

	E_x (GPa)	E_y (GPa)	E_z (GPa)	v_{xy}	v_{xz}	v_{yz}	G_{xy} (GPa)	G_{xz} (GPa)	G_{yz} (GPa)	P (g/cm^3)
TPU	1.5	1.5	1.5	0.48	0.48	0.48	0.7	0.7	0.7	1.2
%10	9.35	1.66	1.66	0.45	0.08	0.08	0.77	0.77	0.77	1.33
%30	25	2.125	2.125	0.40	0.034	0.034	0.99	0.99	0.99	1.60
%50	40.75	2.944	2.944	0.35	0.025	0.025	1.368	1.368	1.368	1.87

TABLE II
MATERIALS COMPOSING THE COMPOSITE MODEL AND ITS MECHANICAL PROPERTIES [10], [11]

Material	E (GPa)	v	G (GPa)	ρ (g/cm^3)
E-glass	80	0.22	30	2.55
TPU	1.5	0.48	0.7	1.2

The modulus of elasticity of the fiber E_f is calculated from the longitudinal elastic modulus (E_x), the longitudinal elasticity modulus (E), the plane shear modulus (G_{xy}) using the following composite modulus constants, V_f, the modulus of elasticity of the matrix Em and the volume ratio Vm of the matrix, Major Poisson ratio v_{xy} values are calculated [12]

$$E_x = E_f V_f + E_m V_m \quad (1)$$

$$E_y = \frac{E_m . E_f}{V_f . E_m + V_m . E_f} \quad (2)$$

$$v_{xy} = v_m Vm + v_f V_f \quad (3)$$

$$G_{xy} = \frac{G_m . G_f}{V_m . G_f + V_f . G_m} \quad (4)$$

$$v_{xy} / E_x = v_{yx} / E_y \quad (5)$$

Three different solid models can be seen in Figs. 2-4. These models have been created in Ansys finite element analysis program and their dimensions are 270 mm. length, 70 mm width and 12 mm height. Besides, flat shoe sole (Fig. 2) contains no groove. However, rectangle and elliptical models contain 10x2 mm grooves. In analysis, element type solid186 has been selected and as material properties, anisotropic module has been used because of the material properties obtained by mixture of TPU and e-glass fiber in various ratios (10%, 30% and 50%).

Fig. 2 Flat shoe sole

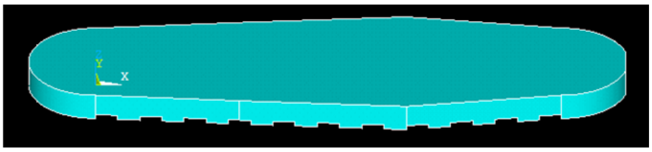


Fig. 3 Rectangle grooved shoe sole

Fig. 4 Elliptical grooved shoe sole

Fig. 5 shows the boundary conditions and loading conditions applied to all models and materials for compression and three point bending situations. In Fig. 5 (a), the finite element model was fixed supported (all rotation and displacement values equal to zero) from the nodes at the right and left ends, and on the upper area of the shoe sole, 0.021 MPa pressure has been applied. In Fig. 5 (b), the shoe sole was fixed supported from the nodes at the bottom, 0.021 MPa pressure was applied to upper area of the shoe sole. The stress value of 0.021 MP was determined as a pressure value applied to a single shoe sole of 270 mm length and 70 mm width by an average person weighing 80 kg.

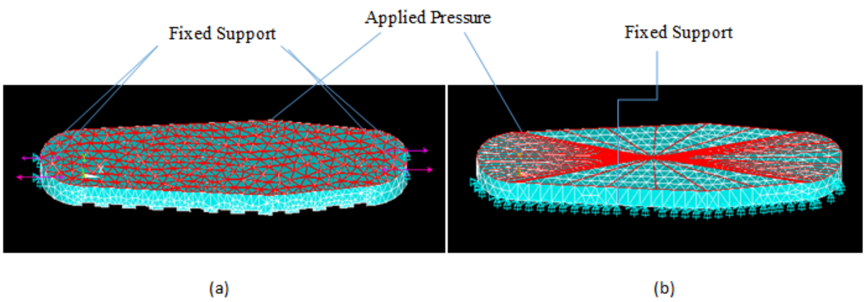
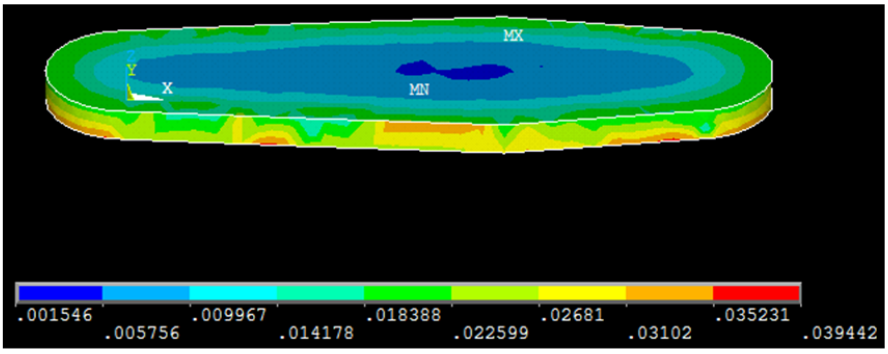


Fig. 5 Boundary Conditions and Applied Loads on Models for (a) 3 point bending and (b) Compression



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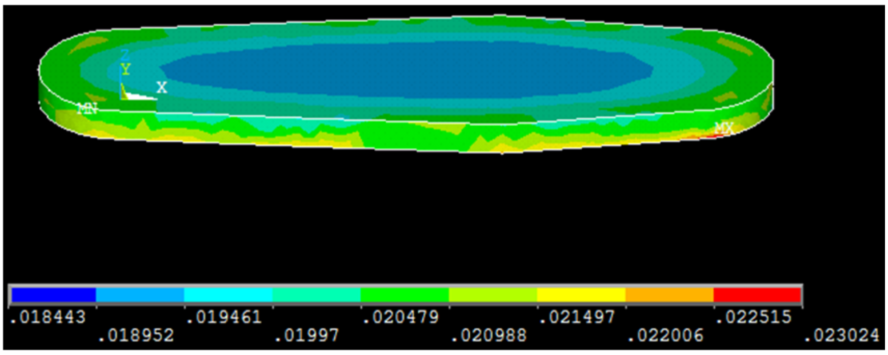

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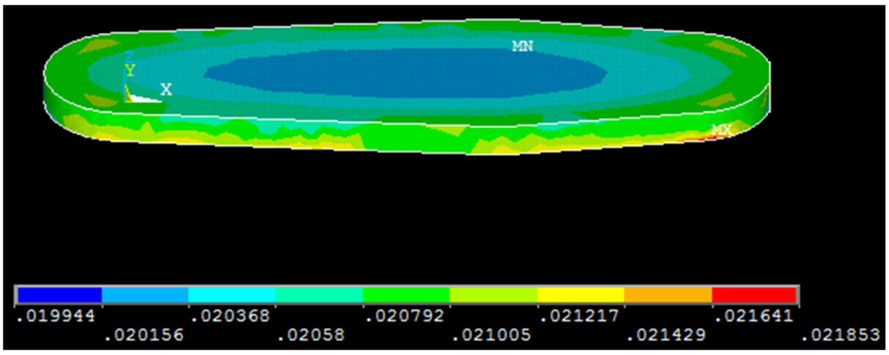

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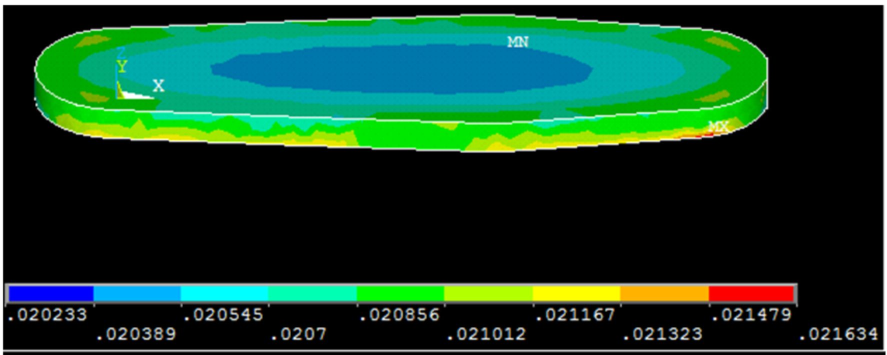
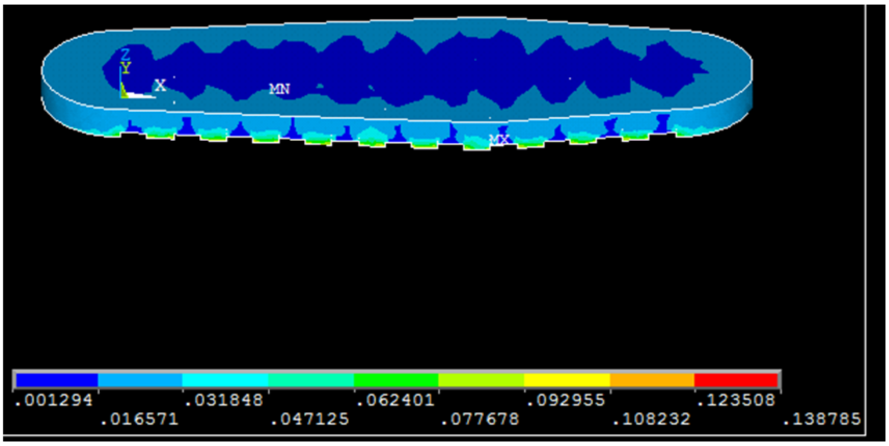


(d)

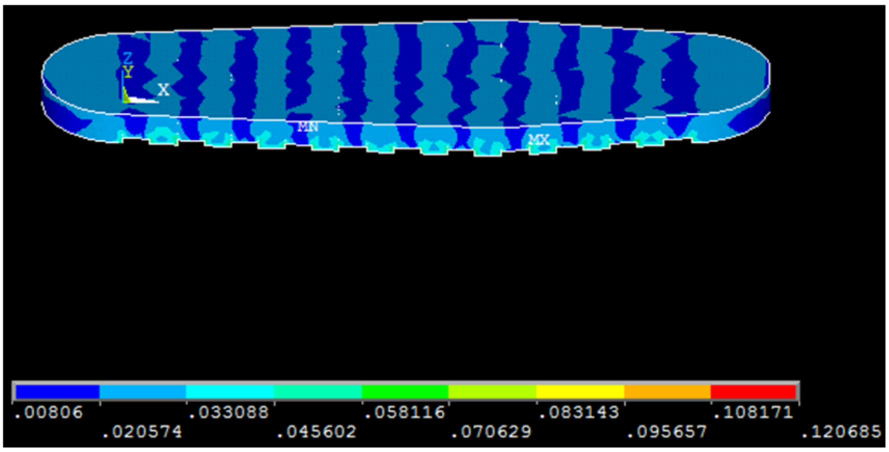
Fig. 6 Compression results for flat shoe sole (a) TPU, (b) 10% e-glass reinforced, (c) 30% e-glass reinforced, (d) 50% e-glass reinforced

III. Analysis Results

Based on the results of the finite element analysis, the stresses and strains of the composite shoe sole under three different bending and compression conditions were investigated according to the percent fiber ratio and model, besides the mechanical behaviors. In the study, totally 24 analyses have been done which include 4 different materials (TPU, 10% e-glass reinforced, 30% reinforced and 50% e-glass reinforced) and 3 different shoe sole geometries (flat, rectangle grooved and elliptical grooved) and 2 main analysis types (three point bending, compression). In Figs. 6-8 for different shoe sole models, stress distribution and values can be seen respectively.



(a)



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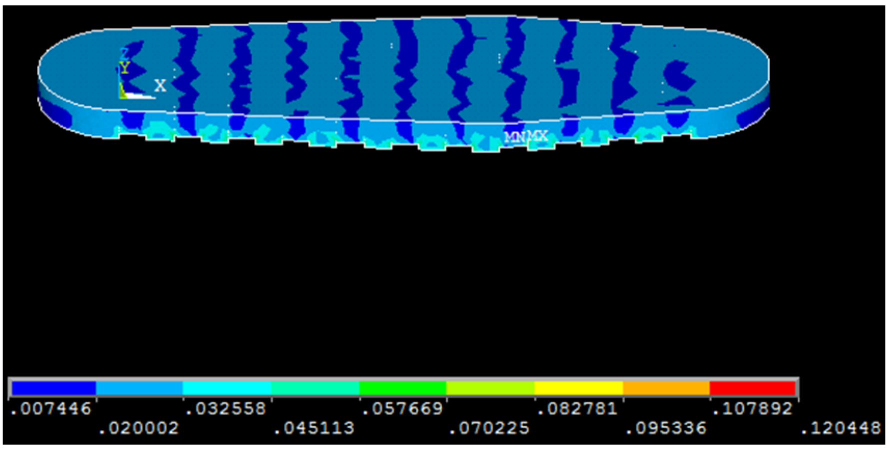

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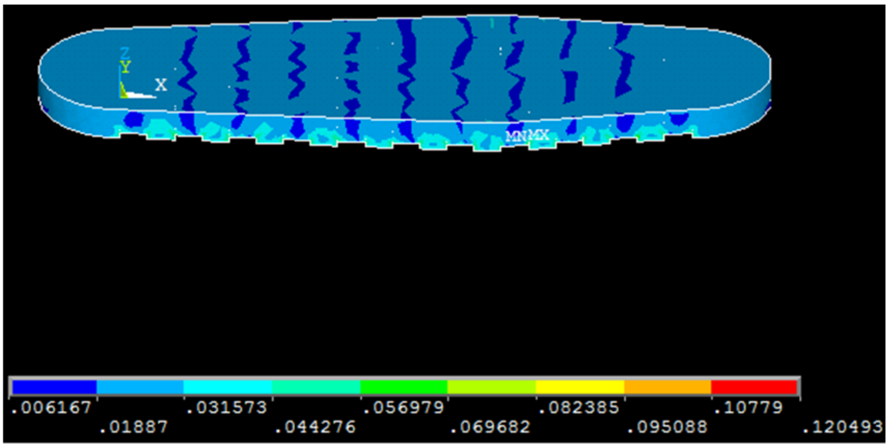
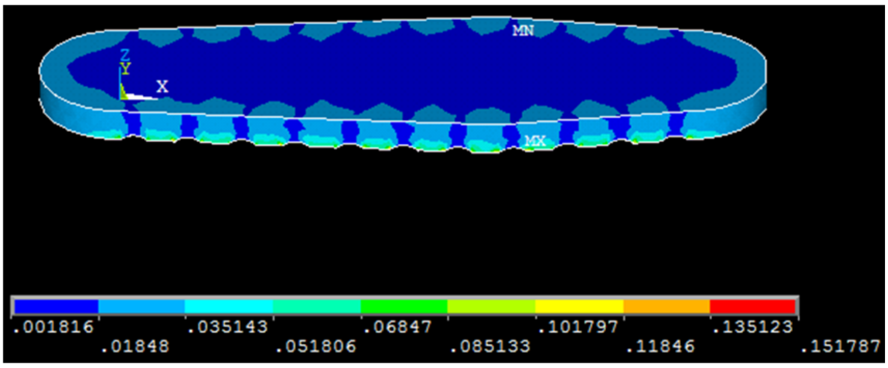


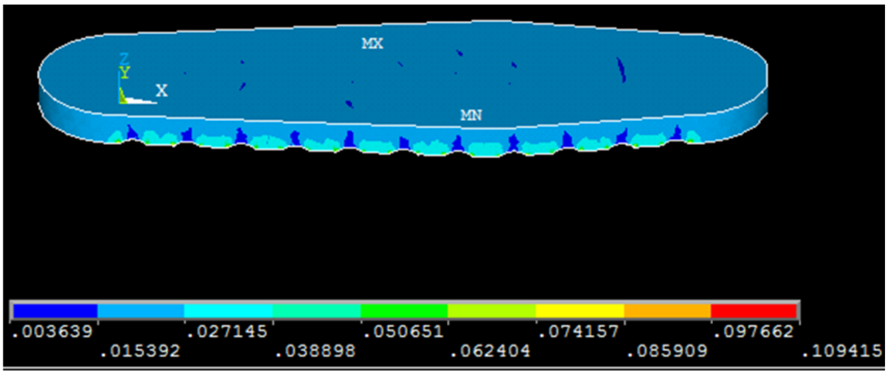
(d)

Fig. 7 Compression results for rectangular grooved shoe sole (a) TPU, (b) 10% e-glass reinforced, (c) 30% e-glass reinforced, (d) 50% e-glass reinforced

Fig. 9 shows that how model has been deformed during 3 point bending. At the left and right edge, displacement value is zero as predicted. At the middle of the shoe sole, 135 mm from the left side maximum displacement value was obtained for all models and materials.



(a)



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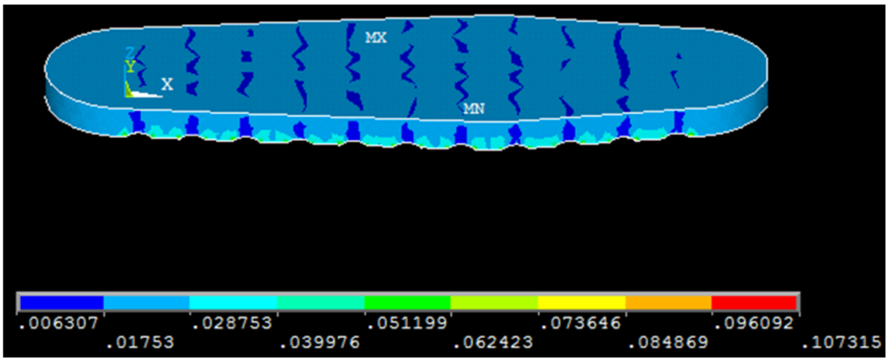

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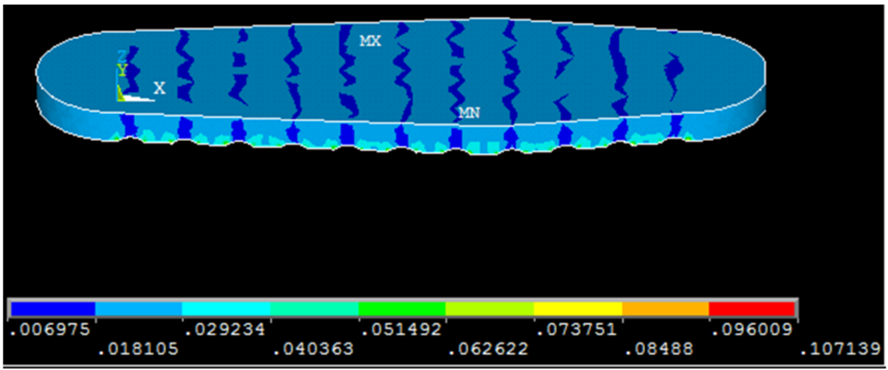

(d)

Fig. 8 Compression results for elliptical grooved shoe sole (a) TPU, (b) 10% e-glass reinforced, (c) 30% e-glass reinforced, (d) 50% e-glass reinforcement

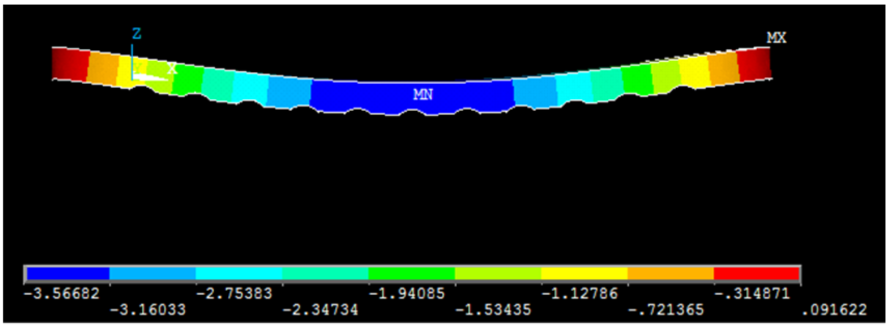

Fig. 9 A general deformation state for three point bending conditions

Fig. 10 shows that, 3 point bending analysis has been done for 3 different shoe sole model and 4 material types like TPU, 10%, 30% and 50% e-glass fiber reinforced by applying boundary conditions and loading which was mentioned in Fig. 5 (a) earlier. According to 3 point bending results, first of all, for the all models, maximum displacements has been determined at the middle of shoe sole (135 mm. from the left and right side) as predicted. When we have a look at material types and shoe sole models as general, it can be seen that maximum displacement along thickness occurs on TPU material and flat as geometry. Maximum displacement along thickness at TPU material and flat geometry has 4.399 mm value and the minimum displacement of 0.338 mm along thickness for elliptical and 50% e-glass fiber reinforced. Furthermore, it can be expressed that TPU material type has maximum and 50% e-glass fiber reinforced has minimum values for all models. Besides, if we compare the models in order to determine the displacement values, maximum and minimum displacement along thickness can be observed for flat and elliptical model respectively. That's why, if we want to create a shoe sole which should have minimum displacement during 3 point bending (for example, for the shoe sole which are used in heavy industrial departments) elliptical grooved shoe sole model should be used with %50 e-glass reinforced. On the other hand, if a shoe sole is desired to have maximum displacement (it means we need a ductile material), we might choose the TPU material with flat sole geometry.

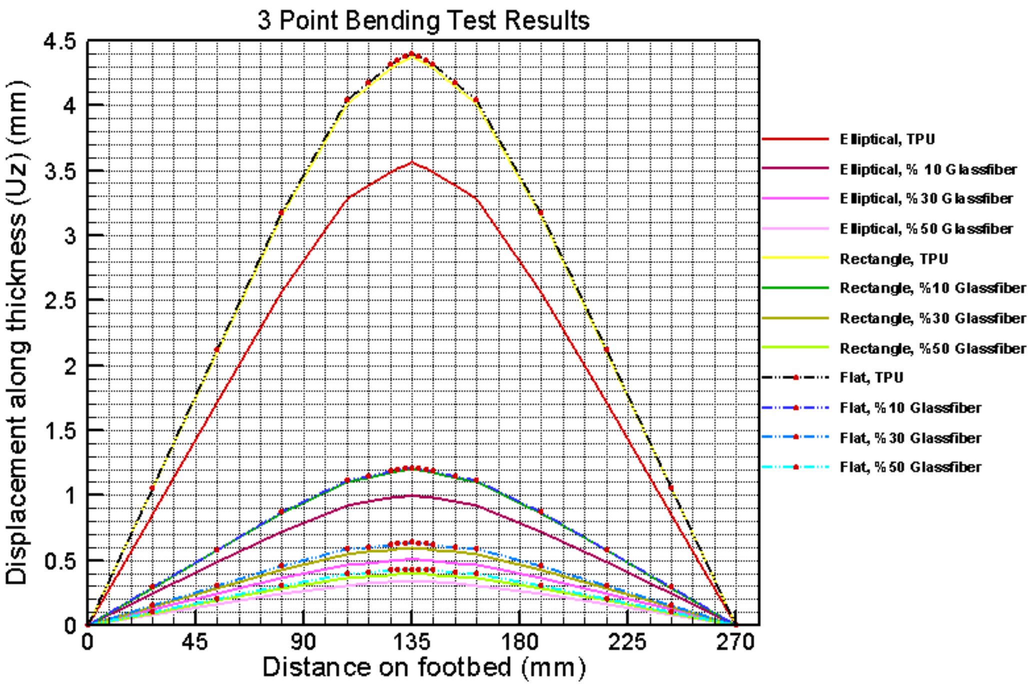

Fig. 10 3 point bending test results (displacement values along thickness by change of distance on footbed)

Fig. 11 shows the relationship between e-glass % and maximum Von Mises stress on footbed under compression with the boundary condition and loading status which were mentioned in Fig. 5 (b) earlier. For the compression status, maximum Von mises stress was obtained in elliptical grooved sole model for TPU material and has 151.78 KPa. On the other hand, minimum stress value has been detected at flat sole model for 50% e-glass reinforced and it is 21.6 KPa. By changing the fiber reinforcement ratio from zero to 10%, it makes a great decrease in all type of models. However, after 10% reinforcement ratio till 50% reinforcement ratio, also there is a decrease in all models, but it differs from others about amount of changing. Moreover, it can be said that, increasing the e-glass fiber reinforcement ratio leads to stress values on footbed decrease. The biggest change in stress value by changing the ratio of fiber reinforcement has been seen between pure TPU-elliptical and 10% fiber reinforcement-elliptical. Pure TPU-elliptical has 151.78 KPa and 10%-elliptical has 109.4 KPa stress value. It means 27.8% stress value changing by making it 10% reinforced instead of pure TPU.

IV. Conclusion

- Maximum displacement along thickness at TPU material and flat geometry has 4.399 mm value and the minimum displacement of 0.338mm along thickness for elliptical and 50% e-glass fiber reinforced under three point bending.
- It can be expressed that TPU material type has the maximum and 50% e-glass fiber reinforced has minimum values for all models under three point bending status.
- When we compare the models in order to determine the displacement values, maximum displacement along thickness at flat and minimum displacement at elliptical model were determined.
- For the compression status, maximum Von Mises stress was obtained in elliptical grooved sole model for TPU material and has 151.78 KPa. On the other hand, minimum stress value has been detected at flat sole model for 50% e-glass reinforced and it is 21.6 KPa.
- By changing the fiber reinforcement ratio from zero to 10%, it makes a great decrease in all type of models for compression.
- Pure TPU-elliptical sole model has 151.78 KPa and 10% e-glass fiber reinforced elliptical sole model has 109.4 KPa stress value. It means 27.8% stress value changing by making it 10% e-glass fiber reinforced instead of pure TPU.

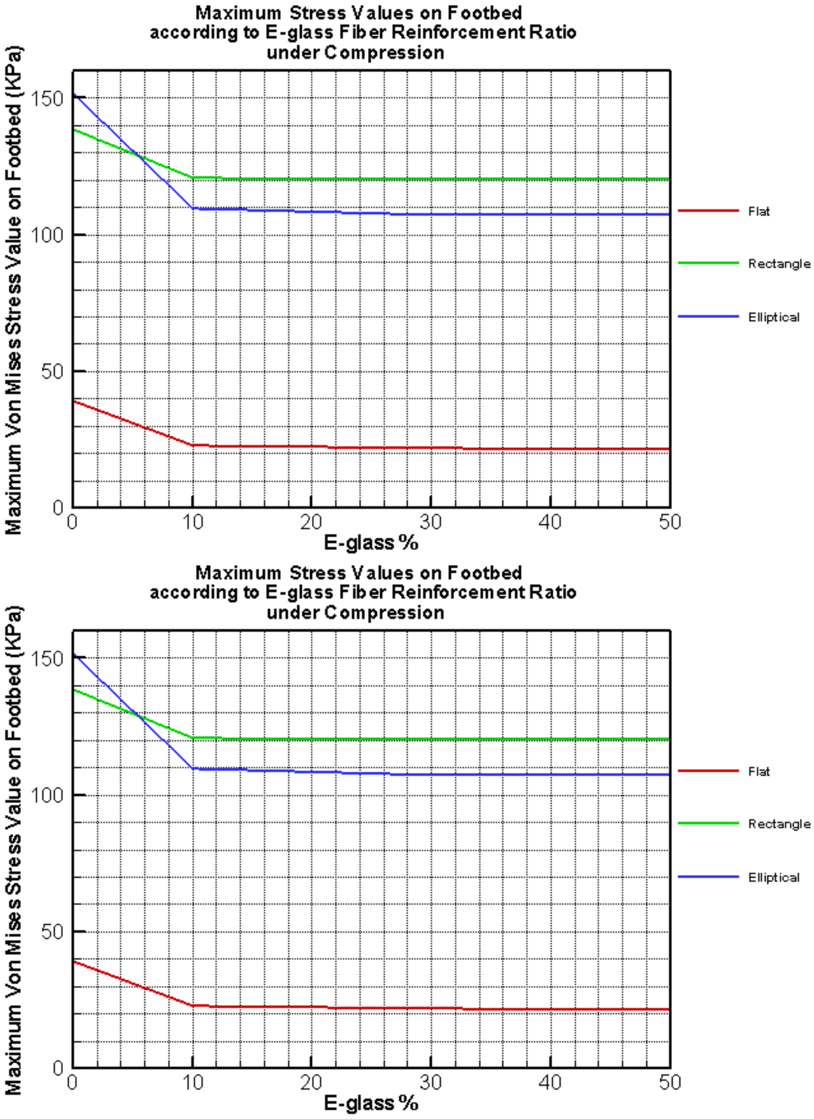

Fig. 11 Maximum stress values on footbed according to E-glass fiber reinforcement ratio under compression

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