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Computational Modeling of Metal Toe Caps to Reinforce Safety Footwear: A Finite Element Approach

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ABSTRACT

Toe caps in safety footwear improve protection against workplace injuries, and the commonly used toe cap materials are metal, plastic, and composite. Metal is used to strengthen the toe cap; however, increased thickness proportionally adds weight to the shoe. Adding flutings can strengthen the toe cap rather than increase the thickness, and a study is required to evaluate the impact of fluting height and direction on the strength of the toe cap. The objectives of this study were to optimize the strength of the toe caps by applying flutings along different directions with various fluting heights and toe cap materials. Toe caps with no flutings, longitudinal flutings, and transverse flutings were the three types of samples used to evaluate deformation. For both longitudinal and transverse directions, the heights of 2 mm, 3 mm, and 4 mm flutings were added to the toe cap surface, and those models of the toe caps were developed by SolidWorks software. Ansys software performed finite element analyses of all the toe cap models for different materials (steel, aluminum, titanium). The strength of the toe cap was determined through deformation analysis by applying a load to the surface. Compared to longitudinally fluted toe caps, transversely fluted toe caps displayed a lower deformation in this test. Furthermore, the 4 mm steel transverse fluted toe cap showed less deformation than the 2 mm and 3 mm steel transverse fluted toe caps. Moreover, steel has the lowest rate of deformation among the three materials. Therefore, the toe cap with 4 mm transverse flutings was considered the strongest among the analyzed toe cap models. This study may be helpful for footwear manufacturers to produce stronger toe caps for safety footwear for workers who need to carry heavy-weight objects in their workplace.

Keywords: Toe cap, Fluting, Safety footwear, Deformation analysis, Finite element analysis

1. Introduction

A safe workplace protects employees from injuries and health risks by reducing accidents, leading to an efficient workflow. Workplace accidents are also common in industrial and construction workplaces worldwide. In every 100,000 workers, the fatality rate was 9.6 from 2004 to 2018 in Alaska; in the southeastern, it was 5.2 in 2008, and in the USA, it was 3.6 in 2021 [1, 2]. In 2021, the European Union recorded more than 2.17 million work accident cases, of which 29.2% were lower extremity injuries [3]. Therefore, personal protective equipment is vital for reducing workplace injuries and illnesses and ensuring worker safety [4].

For safety purposes and to avoid any work-related injuries from falling objects and compressive loads on the foot, a structural reinforcement is placed at the front of the shoe, known as a toe cap. Toe caps in safety footwear are essential personal protective equipment that ensure safety, enhance comfort, and adapt to modern material innovations and designs [5]. The toe cap can be made of metal or non-metal. For example, metals such as steel, aluminum, and titanium, as well as non-metals such as high-density polyethylene, plastic composites, and layer glass fibers of composites. Metal is used for its mechanical strength, while having less thickness and geometrical volume than non-metal. Non-metallic toe caps are also used because of their specific properties, such as non-magnetic, non-electronic, and better thermal insulation. Non-metallic toe caps are easy to manufacture, feature addition, reshaping, free design, and decrease in weight from 40% to 56%. However, they require more volume than metals to achieve the same strength [5, 6].

Therefore, steel or steel-like metals are used in shoes for mechanical strength; however, they consume 35% of the total weight of the shoe [6]. This is because the lattice structure of the metal causes heaviness. The crystal structure and bonding increase the density, as the weight per unit depends on the density, which increases with it. Weight also depended on the volume parameter. With an increase in thickness, the volume mainly increases, so the weight increases while the thickness is extended [7].

Previous studies showed that flutings enhance the stability and strength of any material [8, 9]. Therefore, flutings in toe caps are also utilized to reinforce safety footwear [10, 11]. Recent studies have also demonstrated that different fluting designs for toe caps significantly increase their strength [10-12].

The deformation analysis technique can be used to determine the mechanical strength of the toe cap. The deformation analysis examines how structures or materials change in response to environmental influences or outside forces [13]. Previous studies used the deformation analysis to determine the strength of the toe cap [5, 6].

Moreover, Finite Element Analysis (FEA) has become an essential tool in engineering and physics because of its ability to solve complex problems. This allows us to evaluate the mechanical features of the designs without being

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physically presented. The application of FEA in the footwear sector has tremendous potential. A recent review study provided an updated overview of the physical and mechanical features of different shoe parts through FEA [14]. The strength of the toe caps of various designs and materials has also been evaluated in recent studies using FEA [15]. However, there is a lack of studies to determine the impact of fluting direction and height of the flutings on toe cap strength. This study aimed to optimize the strength of toe caps by applying flutings along the longitudinal and transverse directions with different fluting heights and toe cap materials.

2. Materials and methods

In this study, toe cap models with different fluting directions and heights were developed using CAD software. The strength of the toe cap was determined by evaluating the deformation of the models using simulation software assigning different materials.

2.1 CAD models of toe caps

SolidWorks software version 2022 was used in this study to develop toe cap models. A toe cap with no flutings, three toe caps with longitudinal flutings, and three toe caps with transverse flutings were modeled. The fluting heights were 2 mm, 3 mm, and 4 mm. All toe caps were modeled with 2 mm thickness for proper comparison. The toe cap models are shown in Fig.1, and the features of the toe caps are presented in Table 1.

Fig.1 CAD models of toe caps.

Table 1 Sample toe caps, including features.

Sample name	Material	Fluting height (mm)	Fluting direction
SP	Steel	0	No
S2FL	Steel	2	Longitudinal
S3FL	Steel	3	Longitudinal
S4FL	Steel	4	Longitudinal
S2FT	Steel	2	Transverse
S3FT	Steel	3	Transverse
S4FT	Steel	4	Transverse
AP	Aluminum	0	No
A2FL	Aluminum	2	Longitudinal
A3FL	Aluminum	3	Longitudinal
A4FL	Aluminum	4	Longitudinal
A2FT	Aluminum	2	Transverse
A3FT	Aluminum	3	Transverse
A4FT	Aluminum	4	Transverse
TP	Titanium	0	No
T2FL	Titanium	2	Longitudinal
T3FL	Titanium	3	Longitudinal
T4FL	Titanium	4	Longitudinal
T2FT	Titanium	2	Transverse
T3FT	Titanium	3	Transverse
T4FT	Titanium	4	Transverse

2.2 Dimensions of toe cap

The toe caps were modeled according to the dimensions of the toe portion of an industrial boot last of size 41. Toe caps were 58 mm in length and 42.06 mm in height on the rear side, and the height gradually decreased on the front side. The maximum width was 50 mm, and the toe cap flutings were 2, 3, and 4 mm in height. Fig.2 shows the dimensions of the toe caps.

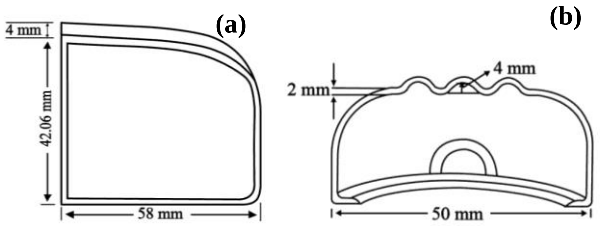

Fig.2 Dimensions of steel toe caps: (a) Side view, (b) Rear view.

2.3 Material selection

Steel, aluminum, and titanium metals were selected for the simulation to analyze the deformation. Steel has a high tensile strength, is highly resistant to wear, and is cost-effective. Similarly, aluminum has high malleability and ductility, which allows it to form various shapes; it is also cost-effective and lightweight. Likewise, titanium is extremely strong and lightweight. Moreover, titanium is expensive and exhibits excellent corrosion resistance. Table 2 presents the mechanical properties of the metals obtained from Ansys software.

2.4 Loading and Boundary conditions

All simulations were performed using Ansys software version 2022R1. A static structural analysis was performed to determine the deformation of the metal toe caps. First, the

"SolidWorks Parasolid" file was imported into the geometry, and the model was selected. The materials (steel, aluminum, and titanium) were assigned, and the model was converted into mash. Fixed support and force were then applied to the targeted surface. A force of 30 kPa was applied toward the y-axis so that the load would act on the surface longwise to evaluate the deformation. Although a previous study used a maximum 15 kPa force to observe the changes in the toe cap [16], this study applied a higher force than that study as the toe caps modeled in this study were for heavy load-bearing industrial footwear. Fig.3 shows the loading and boundary conditions used in the simulation.

Table 2 Mechanical properties of used metals.

Metals	Properties		
	Density (g/cm^2)	Young's modulus (Pa)	Poisson's ratio
Steel	7.85	2×10^{11}	0.3
Aluminum	2.77	7.1×10^{10}	0.33
Titanium	4.62	9.6×10^{10}	0.36

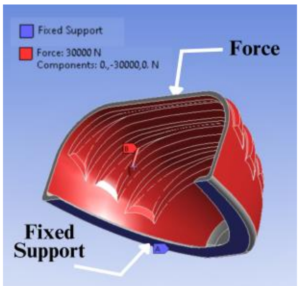

Fig.3 The loading and boundary conditions of the simulation.

2.5 Deformation analysis

The strength of the toe caps was determined through deformation analysis. Simulations were conducted for all developed steel, aluminum, and titanium samples. First, the effect of the fluting direction on toe cap deformation was determined. Second, the impact of the height of the flutings on the toe cap deformation was analyzed. Finally, the effect of the material on toe cap deformation was determined. Minor deformation of the toe cap was the determining factor for its strength.

3. Results and discussion

Simulations were performed for all 21 samples to determine their deformation values. Fig. 4-6 shows the deformation values of the samples at different locations on the toe caps. As the load was applied to the top surface of the toe caps, deformations were observed mainly on the top surface and slightly on the peripheral areas. In the case of the top surface, the rear portions were mostly deformed because they had no support to resist the load.

3.1 Effect of fluting direction on deformation

In the analysis of deformation under load, apparent differences were observed between the longitudinal and transverse flutings for steel, aluminum, and titanium, as shown in Fig.7. Deformations were observed initially, and the deformation increased over time for all three metals. The toe caps with no flutings exhibited the greatest deformation

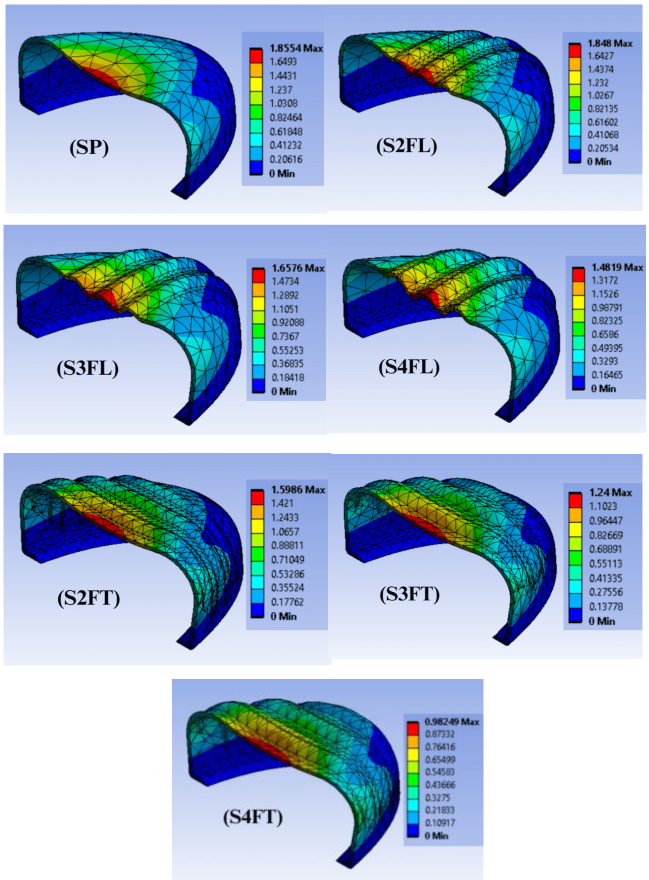

Fig.4 Simulation results of steel toe caps.

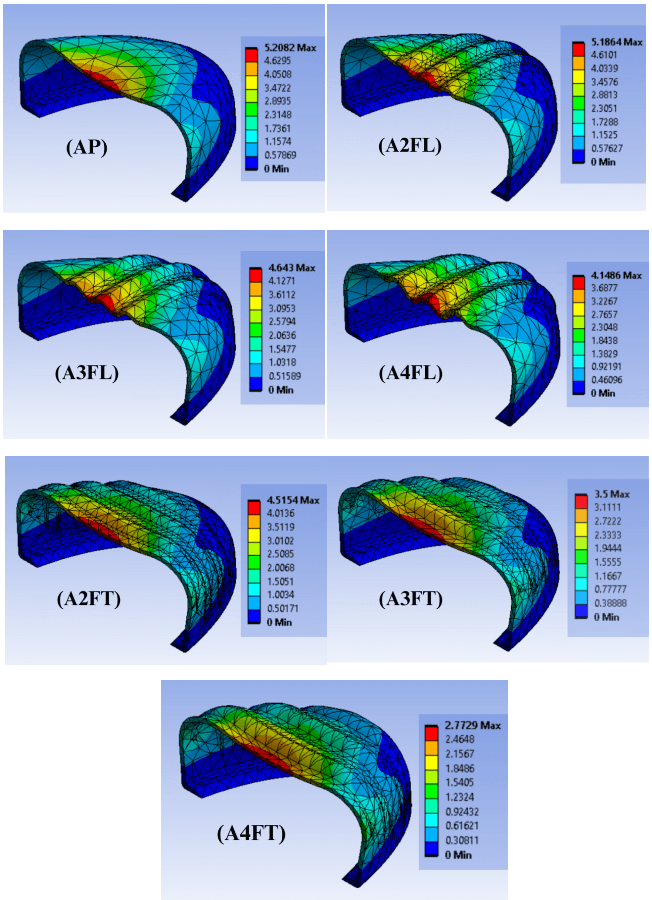

Fig.5 Simulation results of aluminum toe caps.

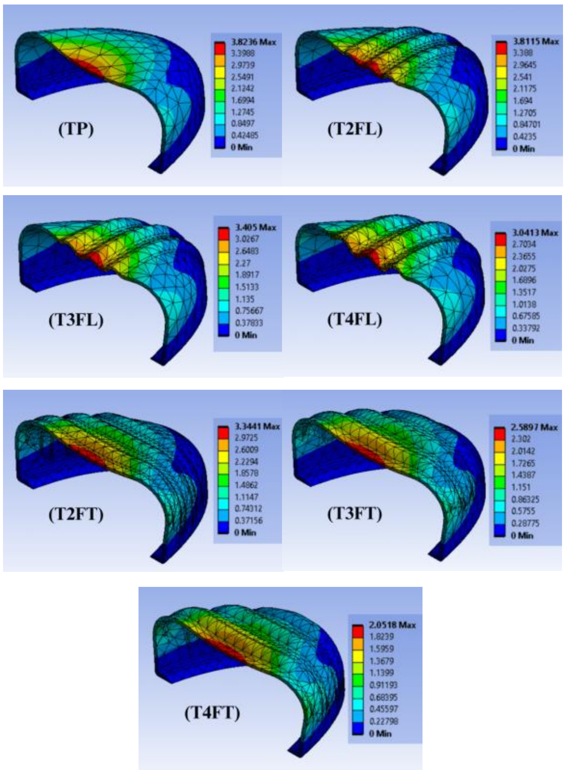

Fig.6 Simulation results of titanium toe caps.

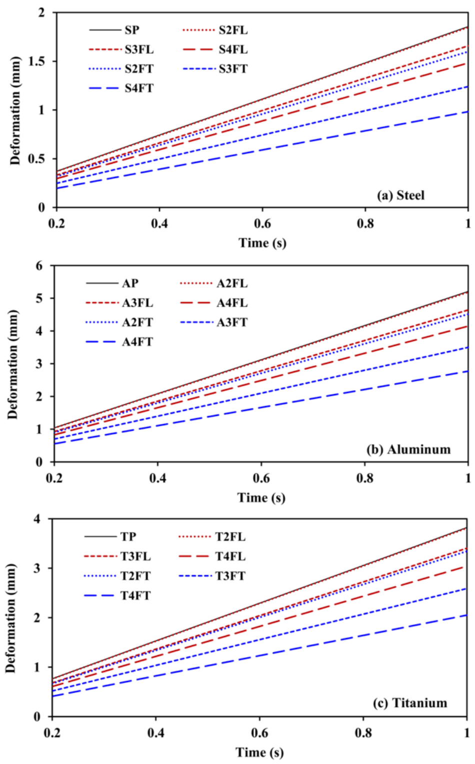

Fig.7 Deformation of toe caps over time: a) steel, b) aluminum, c) titanium.

for all three metals. Toe caps with 2 mm longitudinal flutings showed similar results to toe caps with no flutings. Longitudinal flutings of 3 mm (S3FL) and 4 mm (S4FL) showed less deformation than the plane surface, and the result was almost the same for steel, aluminum, and titanium. Better results were observed for transverse flutings of different heights, such as 2 mm (S2FT), 3 mm (S3FT), and 4 mm (S4FT). The transverse fluting of 4 mm showed the lowest deformation among all the different flutings in the steel, which was 0.98249 mm. A similar trend was observed for aluminum (2.7729 mm) and titanium (2.0518 mm). The deformation values of the longitudinal flutings for steel were 1.4819 mm, 4.1486 mm, and 3.0413 mm, respectively, when measured for 4 mm longitudinal flutings. Therefore, the transverse flutings with the maximum height showed the least deformation, representing the strongest one, and the plane surface showed the highest deformation for all three metals, indicating the least strength. The reason might be that the transverse flutings covered the edges on both sides for all three materials; however, the longitudinal flutings covered the edges only on the front. Therefore, covering both edges may have increased the strength of the transverse flutings.

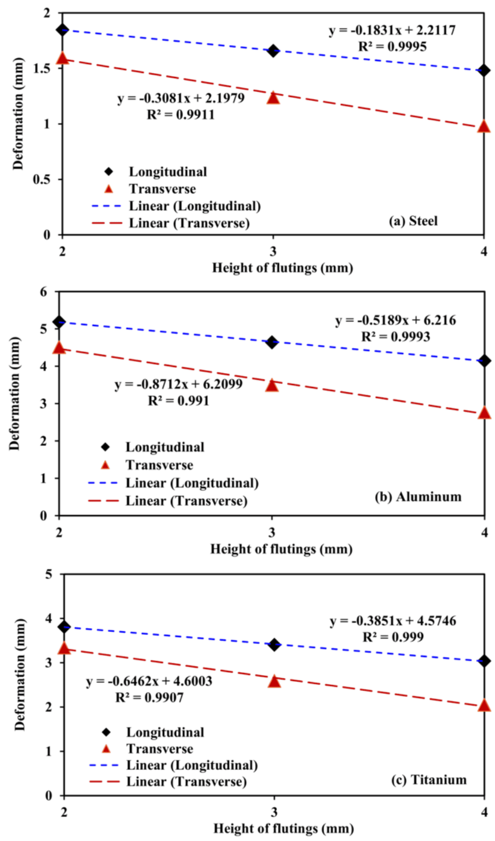

Fig.8 Relationship of deformation with fluting height: a) steel, b) aluminum, c) titanium.

3.2 Effect of fluting height on deformation

The height of the fluting has a significant influence on the deformation of the toe cap. The deformations of the toe cap were analyzed for three different heights (2 mm, 3 mm, and 4 mm) for steel, aluminum, and titanium in both the longitudinal and transverse directions. The deformation was inversely related to the fluting height increment. Moreover, the R^2 values were recorded as more than 0.99 in all cases, indicating a strong relationship between deformation and flutings height, as shown in Fig.8. The deformation decreased when the height increased, indicating that the strength increased with height. The same scenario was observed for aluminum and titanium.

3.3 Effect of toe cap materials on deformation

The study also analyzed the impact of material selection on toe cap strength. The toe caps with 4 mm fluting height in the transverse direction showed the maximum strength for steel, aluminum, and titanium metals. A comparison of the

S4FT, A4FT, and T4FT toe caps showed that the steel toe cap exhibited the least reformation among the metals, as shown in Fig.9. This variation in strength may be due to the Young's modulus of metals. The strength usually depends on the Young's modulus of the metals, and because of the higher value of Young's modulus, steel exhibits the most significant strength among steel, aluminum, and titanium [17]. From a material strength perspective, a steel toe cap (S4FT) can be considered the most suitable toe cap for safety footwear. However, from a weight perspective, aluminum is preferable according to its density. The cost is generally considered before production to make it available to the workers. Therefore, the least costly and strongest product can be made with steel, which is less expensive than titanium and aluminum [18, 19]. If cost is not the main factor, titanium is known for its strength and low-weight combination among the materials [20].

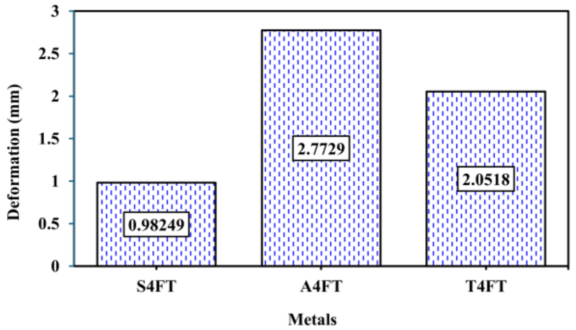

Fig.9 Deformation comparison of 4 mm transverse fluted metal toe caps

The study did not evaluate the strength of the material experimentally, which is a limitation of this study. However, further studies are required to compare the simulation and experimental results. Moreover, there is scope for further research related to the effect of the number of flutings on the strength of the toe cap of safety footwear.

4. Conclusion

This study determined the impact of various metals, fluting heights, and fluting directions on the strength of metal toe caps of safety footwear through finite element analysis. From the simulation, it was found that in the toe cap with transverse fluting, the deformation was less than that in the toe caps with longitudinal flutings. Furthermore, deformation decreased as the height of the flutings increased. In addition, the steel toe cap exhibited less deformation of the steel, aluminum, and titanium. The 4 mm transverse fluting exhibited the minimal deformation compared to all other flutings in steel, measuring 0.98249 mm, whereas aluminum recorded 2.7729 mm and titanium 2.0518 mm. Therefore, a steel toe cap with 4 mm transverse flutings was considered the strongest toe cap among the analyzed samples. Safety footwear manufacturers may find this study useful in designing and producing stronger toe caps for workers who lift heavy objects at their workplace.

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