International Conference on Mechanical, Industrial and Materials Engineering 2015 (ICMIME2015)
11-13 December, 2015, RUET, Rajshahi, Bangladesh.

Paper ID: MS-23

An Analysis on the Sustainability of Different Outsole Materials During Shoe Flexing Using FEA Method

Md. Ibnul Hasan*, Taufiq Rashid, Md. Samsul Arefin
Department of Leather Engineering, Khulna University of Engineering & Technology (KUET), Khulna-9203, Bangladesh
*Corresponding Author: Md. Ibnul Hasan (E-mail: ibnulhasanimu@gmail.com)

Abstract

An outsole is an essential bottom part of a shoe that comes in direct contact with ground according to shoe construction. Shoe outsole undergoes different types of stresses & strains while standing, walking, running etc. and these stresses & strains differ material to material. In this analysis, stress and strain of an outsole model using different materials has been analyzed to find out the most sustainable soling material among them. An average person weighting 700N was considered to run the analysis. The Finite Element Method (FEM) was used for generalizing the theory. And it was found that TPR was the most sustainable soling material among them with high displacement magnitude, high strain von Mises and low stress von Mises. PU & PVC showed poorer durability. HDPE was moderately better than PU & PVC but not good as TPR.

Keywords: Outsole materials, Sustainability, Material properties, FEA

1. Introduction

Footwear plays an important role in protecting the foot from the environment by reducing the risks associated with trauma and enables users to have pain free locomotion over a range of walking surfaces [1]. Footwear is considered one of the basic requirements of a complete costume. There are various types of footwear with different constructions worn by people to fulfill their requirements. The design of shoes has varied enormously through time and from culture to culture, with appearance originally being tied to function. Additionally, fashion has often dictated many design elements, such as whether shoes have very high heels or flat ones. Contemporary footwear varies widely in style, complexity and cost. All shoes have an outsole, which is the bottom part of a shoe according to shoe construction .The outsole is the layer in direct contact with the ground. Dress shoes often have leather or resin rubber outsoles; casual or work-oriented shoes have outsoles made of natural rubber or a synthetic material like polyurethane. The outsole may comprise a single piece, or may be an assembly of separate pieces, often of different materials. On some shoes, the heel of the sole has a rubber plate for durability and traction, while the front is leather for style. Specialized shoes will often have modifications on this design: athletic or so called cleated shoes like soccer, rugby, baseball and golf shoes have spikes embedded in the outsole to improve traction [2]. Outsoles can be made from a variety of materials, although most modern shoes have outsoles made from natural rubber, polyurethane, or polyvinyl chloride (PVC) compound. Outsole thickness and density and the type of materials used in manufacture and design also vary between brands. Changes in density and thickness have been shown to affect the stability and balance of the user. Shoes that are manufactured with a thicker and softer outsole have been associated with increases in dynamic instability and a reduction is postural balance [3]-[4]. Conversely shoes that have a thinner stiffer outsole improve both stability and balance parameters [5]-[7].Therefore, the design of outsoles directly affects the ground reaction force on foot. In order to design a functional outsole, biomechanics and other new technologies should be considered and the design process should be examined in the biomechanics laboratory over and over. The design process requires too much time and effort since the entire experimental and test work can only be done after the prototype is manufactured. Therefore, this study tried to introduce the Finite Element Method (FEM) into the shoe design process by building a three dimensional Finite Element outsole model with various loading conditions [8].Today, computational modeling, such as the finite element method, is a complementary tool to enhance our knowledge of foot biomechanics. Finite element analyses can predict the load distribution between the foot and supports, and provide information on the internal stress and strain states of the ankle-foot complex. The finite element analyses enable efficient parametric evaluations to be made for the outcomes of insole shape and material modifications, without needing to fabricate and test orthoses in a series of patient trials [9]. Several finite element models of the foot or footwear have been developed, based on certain assumptions. These assumptions include simplified geometry, limited relative joint movement and simplified material properties. Early models were based on a simplified or partial foot shape. Analyses were conducted under assumptions of linear material properties, infinitesimal deformation, and linear boundary conditions, without considering friction and slip. Recent models have improved in selected aspects by incorporating geometric, material, or boundary nonlinearity (e.g., large model deformation, nonlinear material properties, slip/friction contact conditions) [8],[10]-[12]. Previous finite element analyses have contributed to the understanding of biomechanics behavior and performance of foot supports and footwear, effect of insole, bodyweight distribution [8], [10], [12]-[14]. A more detailed model of the human foot and ankle—a model that incorporates realistic geometric and material properties of both bony and soft tissue components—is needed to enhance the reliability of the quantitative evaluations of different orthotic designs [15]-[16]. However, very few researches have been done on the sustainability of soling materials which plays a vital role in a shoe construction and also during wearing life. The objective of the present study is to establish a 3-dimensional (3-D) finite element model of different soling materials using actual geometry. The finite element model can be employed to predict the most sustainable soling material among different soling materials available.

2. Materials and Method

The sole in the finite element model only contains a solid sole without a heel attached with it. The soling materials are Poly urethane (PU), Thermoplastic rubber (TPR), High density polyethylene (HDPE) and Polyvinyl chloride (PVC).

Solid Geometry

For this analysis a 3D shoe sole (CAD model) was modeled using a CAD software. The isometric, top, front, right side view of the shoe soles has been shown in figure 2.1 to 2.2.

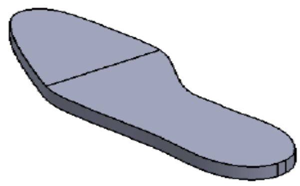

Fig 2.1: Isometric view of model

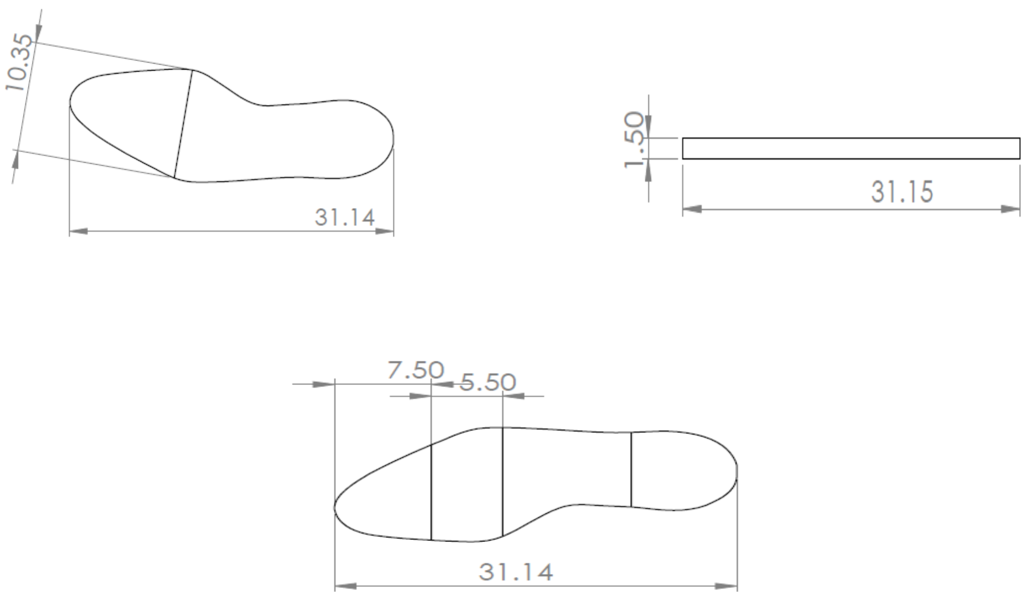

Fig 2.2: Top, Right side &Bottom view of the model

Assigned Material properties

Polyurethane is a family of polymers containing urethane chemical linkages formed by reacting materials containing hydroxyl chemical group with isocyanates. Good footwear should be comfortable, long-lasting and fit for purpose – not to mention affordable. Polyurethanes allow designers to meet all of these objectives. Light but highly abrasion-resistant polyurethanes are perfect for hardwearing shoe soles, with excellent long-term mechanical properties.

Table 2.1: Properties of Poly Urethane (PU)

Property	Value	Unit	Reference
Elastic Modulus in X	3.4x109	N/m2	[17]
Poisson's Ration in XY	0.49	N/A	[18]
Mass Density	1180	kg/m3	[19]
Tensile Strength in X	15x106	N/m2	[19]
Thermal co- efficient	57.6x10-6	1/°C	[20]

Thermoplastic rubber is one of the most common materials for making footwear outsoles. TPR is a form of synthetic rubber which is thermoplastic. There are a number of reasons for its popularity as a soling material, not the least of which is its ease of molding. Other advantages include: slip resistance of TPR sole which is superior to almost every other common soling material; flexing resistance is also very good, performing particularly well at very cold temperatures.

Table 2.2: Properties of Thermoplastic Rubber (TPR)

Property	Value	Unit	Reference
Elastic Modulus in X	0.12x109	N/m2	[21]
Poisson's Ration in XY	0.50	N/A	[18]
Mass Density	1060	kg/m3	[22]
Tensile Strength in X	14 x106	N/m2	[23]
Thermal co- efficient	130x10-6	1/°C	[24]

PVC is a thermoplastic material. Thermoplastic materials are those that can be melted again and again. These materials can be heated to a certain temperature and will harden again as they cool. Besides technical performance, environmental performance is also of fundamental importance in choosing the materials today. PVC is one of the materials that best satisfies both requirements.

Table 2.3: Properties of Poly Vinyl Chloride (PVC)

Property	Value	Unit	Reference
Elastic Modulus in X	3.4x109	N/m2	[20]
Poisson's Ration in XY	0.42	N/A	[18]
Mass Density	1330	kg/m3	[20]
Tensile Strength in X	24x106	N/m2	[25]
Thermal co- efficient	50.4x10-6	1/°C	[20]

HDPE is somewhat harder and more opaque and it can withstand rather higher temperatures. With a high strength-to-density ratio, HDPE is used in the production of plastic bottles, corrosion-resistant piping, geo membranes, and plastic lumber. HDPE is commonly recycled. HDPE is known for its large strength-to-density ratio. It is also harder and more opaque and can withstand somewhat higher temperatures (120 °C/ 248 °F for short periods, 110 °C /230 °F continuously).

Table 2.4: Properties of High Density Polyethylene (HDPE)

Property	Value	Unit	Reference
Elastic Modulus in X	8.136x108	N/m2	[17]
Poisson's Ration in XY	0.37	N/A	[17]
Mass Density	1382.88	kg/m3	[17]
Tensile Strength in X	26x106	N/m2	[26]
Thermal co- efficient	1.49x10-4	1/°C	[17]

Load and boundary conditions

The boundary condition is the application of a force and/or constraint. In Hyper Mesh, boundary conditions are stored within what are called load collectors. Here two forces have been applied on the sole models. One is on the upper surface of the fore part & the other is on the bottom surface of heel. The load is respectively 80% & 20% of the total body weight of an average person (700 N) [27]. And the bottom surface of the fore part was fixed.

Table 2.5: Setup parameters

Parameters	value	Units
Convergence Tolerance	10^{-6}	
Gravity	9.81	m/s^2
Temperature	20	°C
Voltage	0	V
Centrifugal	0	R.P.M
Max. no. of iterations	500	

Table 2.6: Mesh settings

Parameters	Values
Solid mesh's surface	1
Watertight solids	1
Final mesh size	0.001m
Elements	65615
Mesh operation	Solid mesh

3. Results and discussion

The commercial code Autodesk® Simulation Mechanical 2015 was used to solve the governing partial differential equations (PDEs) for simulating a three-dimensional static stress with linear material in the computational model. As the solution accuracy of any simulation is largely influenced by grid generation, a total number of 15398 elements were created in the computational domain. In the analysis different soling material was used to determine the most suitable soling material for shoe sole. The simulated results were compared both visually & graphically. The simulation was run until the convergence criterion of 0.000001 was satisfied.

Displacement of elements

For an average weighted person (700N) the displacement magnitude due to sole flexing is graphically represented below for four different types of soling material using the nodal values & found maximum displacement magnitude for TPR sole is very high & for PU sole it is minimum. The displacement magnitude of PU & PVC is almost same. The maximum displacement magnitudes of HDPE sole lies between TPR & PVC. So it is TPR>HDPE>PVC>PU.

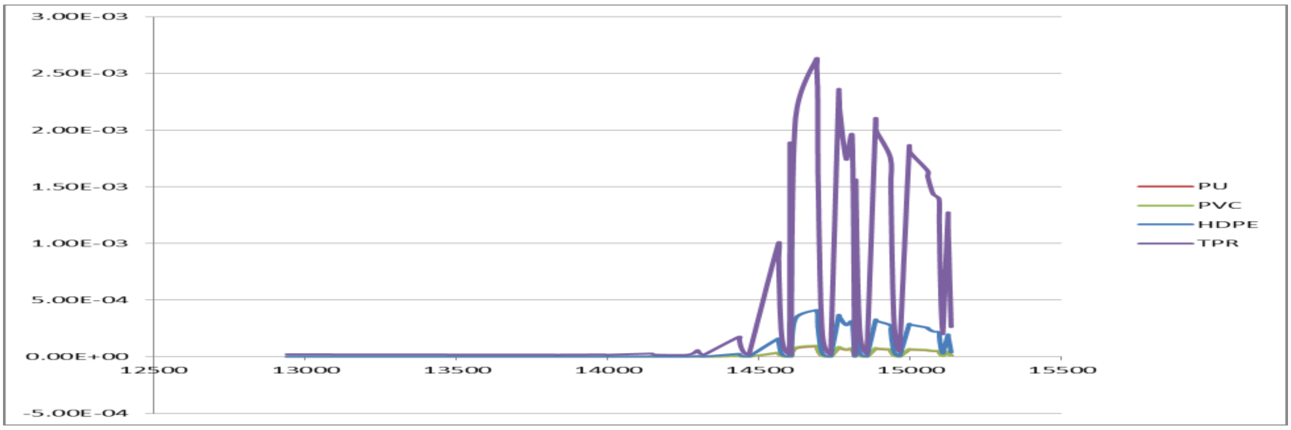

Fig 3.1: Displacement Comparison graph of the elements for different soling materials

Strain of the elements

Strain for TPR sole is very high & for PVC sole it is minimum. The Strain of PU & PVC is almost same. The Strain of HDPE sole lies between TPR & PU. So it is TPR>HDPE>PU > PVC.

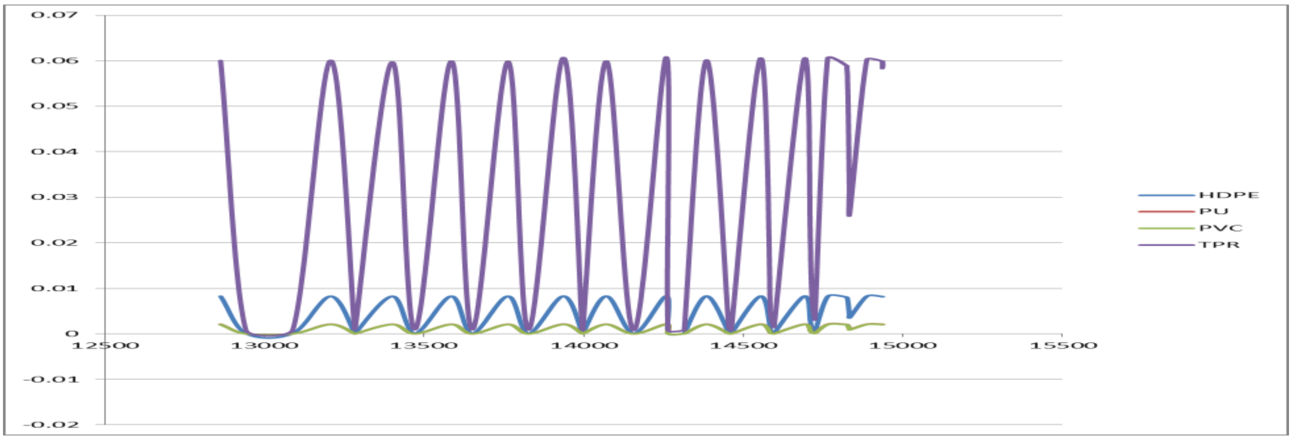

Fig 3.2: Strain Comparison graph of the elements for different soling materials

Stresses on the elements

Stresses for HDPE sole are very high & for PU sole it is minimum. The Stresses of HDPE & PVC are almost same. The Stresses of TPR & PU sole is also in a same range. Actually stresses vary a little due to change in soling materials. When compared, it is HDPE>PVC>TPR> PU.

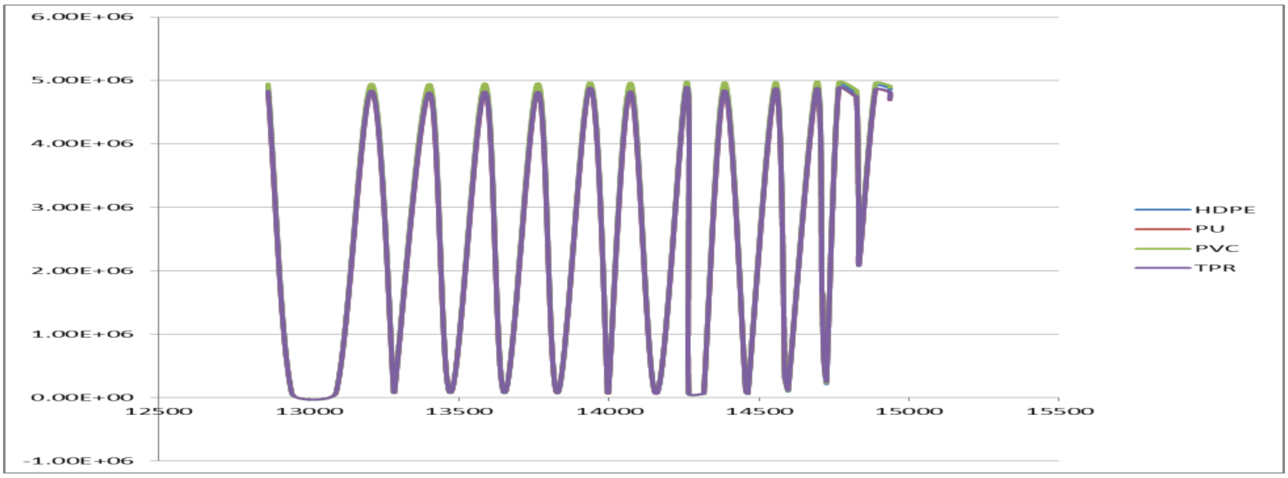

Fig 3.3: Stress Comparison graph on the elements for different soling materials

4. Conclusion

All shoes have a sole, which is the bottom of a shoe, in contact with the ground. Soles can be made from a variety of materials, although most modern shoes have soles made from natural rubber, polyurethane, or polyvinyl chloride (PVC) compounds. In this thesis, stress and strain of a sole model using different materials has been analyzed to find out the most sustainable soling material among them. This stress-strain analysis can be done in many ways but here numerical method was used to minimizing the cost. First of all stress- strain analysis was performed on the sole model by assigning Polyurethane (PU), Thermoplastic Rubber (TPR), Polyvinyl Chloride (PVC) and HDPE as soling material in the simulation software respectively. Then the nodal & element data was compared to find out the most suitable soling material. Both visual and graphical results were used to come to the conclusion. And it was found that TPR was the most sustainable soling material among them with high displacement magnitude (0.1248151 m), high strain von Mises (0.144444 m/m) and low stress von Mises (11633080 N/m^2). PU & PVC showed nearly same properties which is tough to distinguish. PU & PVC showed poorer durability with lower displacement magnitude & strain von Mises and high stress von Mises. HDPE was moderately better than PU & PVC but not good as TPR.

5. References

[1] T.G. McPoil, "Footwear", Physical Therapy, Vol.68 No.12 pp. 1857-1865, 1998.
[2] Vonhof, and J. Wilderness, "Fixing Your Feet: Prevention and Treatments for Athletes. Birmingham", Alabama: Wilderness Press, pp. 58–59, 2011.
[3] S. Robbins, G. Gouw, and J. McClaren, "Shoe sole thickness and hardness influence balance in older men", Journal of the American Geriatrics Society, Vol.40, No.11, pp. 1089-1094, 1992.
[4] K. Sekizawa, M.A. Sandrey, C.D. Ingersoll, and M.L. Cordova, "Effect of shoe sole thickness on joint position sense", Gait and Posture, Vol.13, No.3, pp. 221-8,2001.
[5] J.C. Menat, J.R. Steele, H.B. Menz, B.J. Munro, and S.R. Lord, "Effects of footwear features on balance and stepping in older people", Gerontology,Vol.54, No.1, pp. 18-23, 2008.
[6] S.D. Perry, Radtke, and C.R. Goodwin, "Influence of footwear midsole material hardness on dynamic balance control during unexpected gait termination", Gait and Posture, Vol.25, No.1, pp.94-8, 2007.
[7] S. Robins, E. Waked, G.J. Gouw, and J. McClaran, "Athletic footwear affects balance in men", British Journal Sports Medicine, Vol.28, No.2, pp. 117-122, 1994.
[8] T.Y. Shiang, "The nonlinear finite element analysis and plantar pressure measurement for various shoe soles in heel region", *Proc. Natl Sci Counc Repub China B* , Vol.21, No.4, pp. 168-74, 1997.
[9] J.T.M. Cheung, and M. Zhang, "A 3-dimensional finite element model of the human foot and ankle for insole design", Archives of Physical Medicine and Rehabilitation, Vol.86, No.2, pp. 353-358, 2005.
[10] W.P. Chen, C.W. Ju, and F.T. Tang, " Effects of total contact insoles on the plantar stress redistribution: a finite element analysis", *Clin Biomech* ,Vol.18, No.6, pp. S17-S24, 2003.
[11] A. Gefen, "Plantar soft tissue loading under the medial metatarsals in the standing diabetic foot", *Med Eng Phys*, Vol.25, No.6, pp. 491-499, 2003.
[12] S. Syngellakis, M.A. Arnold, and H. Rassoulian, "Assessment of the non-linear behaviour of plastic ankle foot orthoses by the finite element method", Proc Inst Mech Eng [H], Vol. 214, No.5, pp. 527-39, 2000.
[13] T.M. Chu, and N.P. Reddy, "Stress distribution in the ankle-foot orthoses used to correct pathological gait", J Rehabil Res Dev, Vol. 32, No.4, pp. 349-60, 1995.
[14] D. Lemmon, T.Y. Shiang, A. Hashmi, J.S. Ulbrecht, and P.R. Cavanagh, "The effect of insoles in therapeutic footwear: a finite-element approach", J Biomech,Vol.30, No.6, pp.615-20, 1997.
[15] D.L.A. Camacho, W.R. Ledoux, E.S. Rohr, B.J. Sangeorzan, and R.P. Ching, "A three-dimensional, anatomically detailed foot model: a foundation for a finite element simulation and means of quantifying foot-bone position", J Rehabil Res Dev, Vol.39, No.3, pp. 401-10, 2002.
[16] K.A. Kirby, "What future direction should podiatric biomechanics take?", Clin Podiatr Med Surg, Vol.18, No.4, pp. 719-23, 2001.
[17] Material Library (Autodesk Simulation Mechanical 2015)
[18]http://ocw.mit.edu/courses/materials-science-and-engineering/3-11-mechanics-of-materials-fall-1999/modules/props.pdf
[19]Margie Engel, Polyurethanes Conference 2000: Defining the Future Through Technology, CRC Press, London, UK
[20] http://www.engineeringtoolbox.com/
[21] http://www.efunda.com/
[22] http://www.plasticraw.com/products/plastic-compound-material/gse-41-additive-thermoplastic-elastomer
[23] http://cdn.intechopen.com/pdfs-wm/34065.pdf
[24] http://www.bpf.co.uk/plastipedia/polymers/thermoplastic_elastomers.aspx
[25] http://www.makeitfrom.com/material-properties/Plasticized-Flexible-Polyvinyl-Chloride-PVC-P/
[26] http://www.marleypipesystems.co.za/images/pdfdownloads/productbrochures/hdpe-physical-properties.pdf
[27] A. Rossi, William & Tennant, Ross. (2011), Professional Shoe Fitting, The pedorthic footwear association, Americus, Georgia, USA