DESIGN OF SHOE SOLES USING LATTICE STRUCTURES FABRICATED BY ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing (AM) has enabled great application potential in several major industries. The footwear industry can customize shoe soles fabricated by AM. In this paper, lattice structures are discussed. They are used to design functional shoe soles that can have controllable stiffness. Different topologies such as Diamond, Grid, X shape, and Vintiles are used to generate conformal lattice structures that can fit the curved surface of the shoe sole. Finite element analysis is conducted to investigate stress distribution in different designs. The fused deposition modeling process is used to fabricate the designed shoe soles. Finally, compression tests compare the stiffness of shoe soles with different lattice topologies. It is found that the plantar stress is highly influenced by the lattice topology. From preliminary calculations, it has been found that the shoe sole designed with the Diamond topology can reduce the maximum stress on the foot. The Vintiles lattice structure and the X shape lattice structure are stiffer than the Diamond lattice. The Grid lattice structure buckles in the experiment and is not suitable for the design.

Keywords: Additive Manufacturing, Simulation, Design methods, Lattice structure, Shoe sole

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1 INTRODUCTION

Additive manufacturing (AM) has a layer-by-layer fabrication strategy that is different from traditional subtractive manufacturing technologies. It not only reduces the material used, but it also reduces the difficulty in fabricating complex geometries. The broad design freedom permitted by AM leads to more and more innovative and efficient products in industries such as aerospace, biology, and healthcare (Bingheng Lu, 2015). Process planning of AM is not as time-consuming as traditional manufacturing, which is suitable for mass customization (Paoletti, 2017). Ko *et al*. (Ko *et al*., 2015) proposed a customized design method for additive manufacturing. It is mentioned that AM enables new opportunities for customization, through significant improvements in product performance, multi-functionality, and lower overall manufacturing costs.

The lattice structure in mesoscale is a type of architecture that has struts and nodes in a three-dimensional (3D) space. As shown in Figure 1, lattice structures can be divided into three categories based on their degree of order (Dong *et al*., 2017). The first type is the periodic lattice structure, which has a unit cell repeatedly distributed in the 3D space. The second type of lattice structure is the quasi-periodic lattice structure, which is also called conformal lattice structure (Wang and Rosen, 2002). It can maintain the integrity of the lattice structure on the boundary of the design space. It can keep the integrity of unit cells on a freeform surface. The last type is the randomized lattice structure. It has randomized unit cell shape and size in the 3D space. Therefore, its mechanical property is more difficult to control than the other two types of the lattice structure.

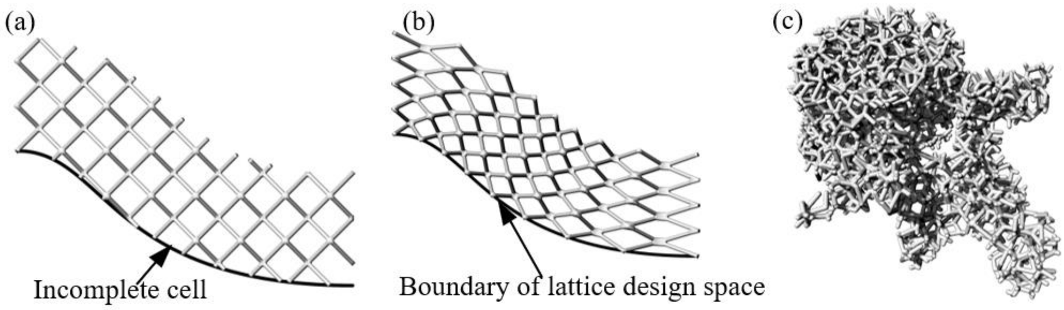

Figure 1. Three types of lattice structures, (a) period lattice structure, (b) conformal lattice structure, and (c) randomized lattice structure.

Due to the porous characteristic of lattice structures, it presents a new class of energy absorption materials that offer flexibility in tailoring the response to impulse loads over conventional materials (Schaedler and Carter, 2016). The lattice structures used for energy absorption can be categorized as single-use and multiuse applications. For single-use applications (Tancogne-Dejean *et al*., 2016, Maskery *et al*., 2017), the plastic deformation of the material can absorb energy, which is not recoverable. For multi-use applications (Brennan-Craddock *et al*., 2012), the lattice structure should be fabricated by a material that can recover from the deformation, such as elastomer-like materials. The excellent energy absorption property makes lattice structures suitable for shoe sole designs. Furthermore, the material distribution in the lattice structure can be trimmed to reduce and adequately distribute plantar pressure. The shoe sole made by lattice structures can also be customized by adjusting the relative density. The stiffness of the shoe sole can be more flexibly controlled.

AM has been used in the field of footwear to produce shoes (Birtchnell and Urry, 2013), shoe soles (Choi and Cheung, 2008, Carbon, 2018), and insoles (Davia-Aracil *et al*., 2018). Its layer-by-layer strategy permits the manufacture of complex, high-performance monolithic designs with varying performance zones within a single part. Therefore, shoe soles with different stiffness zones can be easily fabricated by AM. Davia-Aracil *et al*. (Davia-Aracil *et al*., 2018) reviewed certain computer-aided design (CAD) methodologies for the design and manufacture of insoles by means of additive manufacturing techniques. Different two-dimensional (2D) and three-dimensional (3D) patterns are used in the heel area to incorporate new functionalities. It is concluded that the footwear industry can benefit from the advantages of AM. It is also proved that AM is cost-effective and feasible on an industrial level.

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In this paper, the design method using lattice structures for AM fabricated shoe soles is proposed. Different types of lattice structures are used to infill the design space. The fused deposition modeling (FDM) process is used to fabricate lattice shoe soles. The mechanical performance of each type of lattice shoe sole is investigated both experimentally and numerically. In Section 2, the design procedures of lattice shoe sole will be explained. In Section 3, the result of finite element analysis (FEA) of the designed shoe sole is discussed. In Section 4, the designed shoe sole is fabricated by FDM and is physically tested to investigate the mechanical performance. Finally, conclusions are made, and future research is proposed in Section 5.

2 DESIGN PROCEDURES

2.1 Functional volume and functional surface

In the lattice structure design process, the functional volume (FV) and functional surface (FS) are geometries that have certain functional purposes (Tang *et al*., 2015). FS is defined as a surface that fulfills a certain functional requirement. FV is defined as the geometry volumes which are used to combine FSs and assist FSs in fulfilling their functional roles. Based on the definition, the shoe sole can be divided into three FVs as shown in Figure 2. FV1 is the top part of the shoe sole that connects the shoe and the sole. FV2 is the design space for lattice structure. FV3 is the bottom of the shoe sole. There are four FSs in the shoe sole design. FS1 is the surface touching the foot. The shape of FS1 should conform to the bottom of the foot, and it can be customized. FS2 and FS3 are functional surfaces connecting the lattice structure and the solid part. FS4 is the bottom surface of the shoe sole. Its function is to have enough friction and avoid abrasion.

In the design of the shoe sole with lattice structures, the FVs and FSs are predefined. The main objective is to select the topology that is suitable to infill the design space. As shown in the example in Figure 2, the FV2 is the design space of the lattice structure. FS2 and FS3 determine the top surface and the bottom surface of the lattice structure. The next step is to use FV2, FS2, and FS3 to design the conformal lattice structure inside the shoe sole.

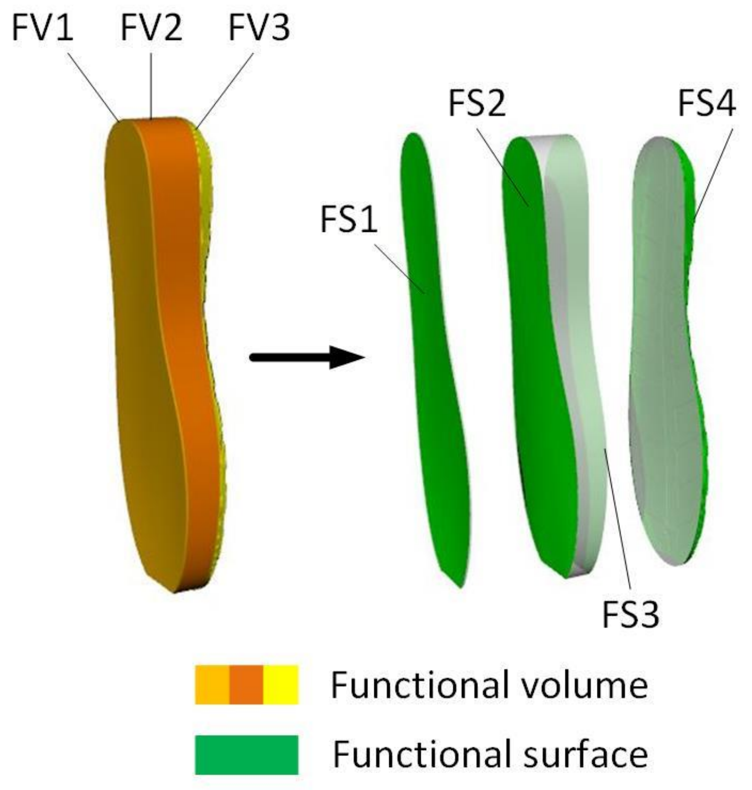

Figure 2. An example of FVs and FSs of a shoe sole.

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2.2 Conformal lattice design

The workflow of the lattice frame generation method for conformal lattice is shown in Figure 3. The concept of mapped shape is used in the generation (Whiteley *et al*., 1996). This technique extrudes 2D mesh into a general third dimension. Generally, the mapped shape is defined as a geometric body which contains two opposing faces (source and destination) and faces that directly connect the source and destination (along face). An example of the shoe sole using the mapped shape method is shown in Figure 3. The top surface and bottom surface of the design space are the source surface and destination surface. The side surface is the along surface. The lattice frame is generated between the source surface and destination surface. The shape of the lattice frame is conformal to the boundary surface. Therefore, there is no trimmed strut on the surface. As shown in Figure 1(a), if a uniform lattice frame is used to infill the shoe sole, the lattice strut on the boundary will be trimmed by the surface of the design space. The trimmed surface cannot keep the integrity of the surface on the boundary. Therefore, the conformal lattice structure is preferred in the shoe sole design.

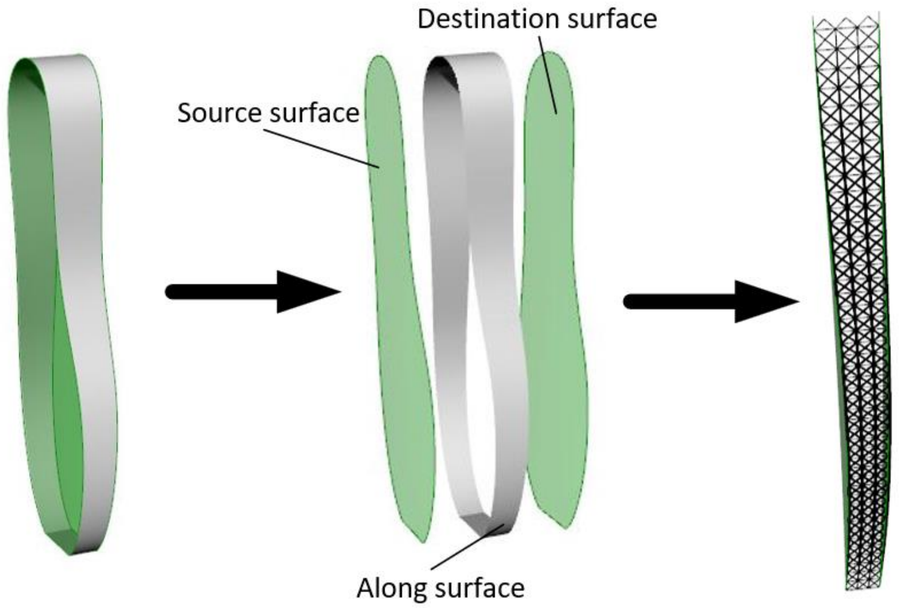

Figure 3. Conformal lattice frame generation.

The topology used in the wireframe should also be selected before the conformal lattice generation. In this research, four types of lattice topologies as shown in Figure 4 are used to generate infilled lattice structures. The strut thickness of the lattice structure with different topologies is tuned to keep the same weight. The value of the strut diameter is shown in Table 1. The geometry of the shoe sole with different types of lattice structures is shown in Figure 5. Because the property of the lattice structure is different with varying topologies, the stiffness of the sole and the plantar pressure are also different in these designs. Both numerical method and the experimental method are implemented to investigate the mechanical response of different lattice shoe soles. The details about the simulation and experiment will be discussed in the following sections.

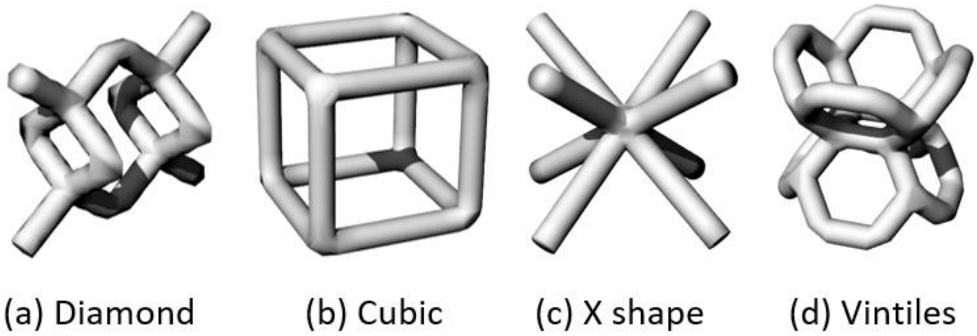

Figure 4. Selected topologies for the lattice structure.

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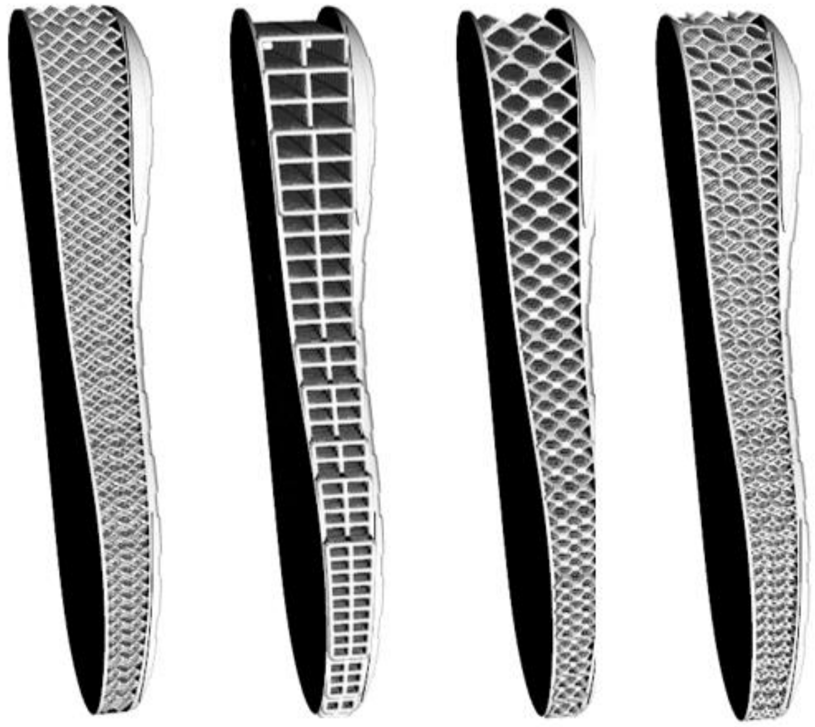

Figure 5. The shoe sole design with different topologies

Table 1. The strut diameter for different topologies

Topology	Diamond	Cubic	X shape	Vintiles
Strut Diameter (mm)	0.5	0.81	0.5	0.45

3 FINITE ELEMENT ANALYSIS

FEA is used to numerically investigate the mechanical response of the lattice shoe sole under the compression of the human foot. Firstly, simulation models are created for each design. The material property of the shoe sole is obtained experimentally. The material is Thermoplastic polyurethane (TPU) 95A (Ultimaker, 2018). The surface contact between the bottom of the foot and the top of the shoe sole is defined. The foot in the simulation model is considered as a bony structure to simplify the analysis. The elastic modulus of the foot is 7300MPa and the Poisson's ratio is 0.3. These values are obtained from the literature (Cheung and Zhang, 2006). Abaqus standard/explicit solver is used to solve the simulation model. Final, the simulation results are compared and discussed.

3.1 Simulation model generation

The lattice structure is saved as a wire-based model. Each lattice strut is defined as a curve from the start node to the end node. The Timoshenko beam element is used to mesh the lattice strut. Each lattice strut is meshed with five beam elements. The bottom surface of the foot is selected as the master surface. The top surface of the lattice structure is selected as the slave surface. The simulation models are shown in Figure 6. The displacement loads are added on the top of the foot. The bottom surface of the shoe sole is fixed. The interaction between the shoe sole and the foot is generated. The reaction forces on the foot are saved during the simulation process. The load-displacement curve of the simulation result can be obtained. The distribution of the plantar stress and the deformation of the shoe sole can also be displayed in the simulation result.

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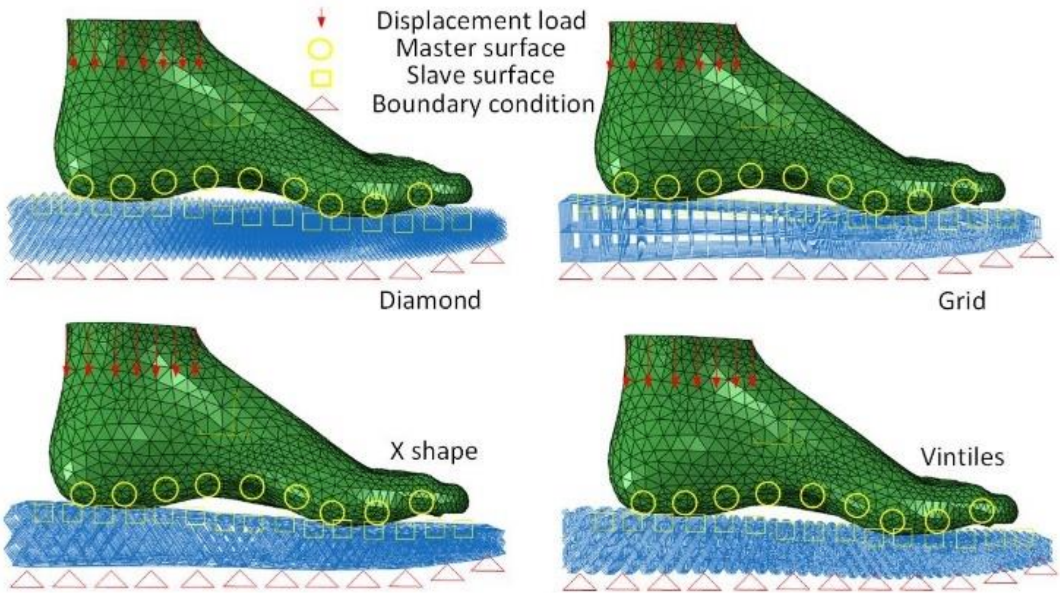

Figure 6. Simulation models

3.2 Result and discussion

The simulation result of the shoe sole is shown in Figure 7. When the reaction force is the same, it is found the deformation of the Diamond lattice structure is the greatest among all the designs. The Grid topology is the stiffest in all the structures. Because the homogenized material property of the lattice structure is anisotropic, each lattice topology has higher elastic modulus along some directions (Dong *et al*., 2018). The Grid topology is strong if the load is along the strut. It is stretching dominant before buckling happens. Therefore, the lattice structure with a Grid topology is the strongest among all the designs. The strut buckles if the load is over the compression load. Then the grid topology becomes bending dominant.

The other topologies (Diamond, X shape, Vintiles) are bending dominant from the beginning. The bending of the strut is the main deformation among all the lattice struts. Therefore, the bending dominant topology is more suitable for energy absorption. It is found that the stresses are more uniformly distributed in the Diamond lattice structure. It is softer than the other two bending dominant topologies. Thus, the contact surface between the foot and the Diamond lattice structure is greater than the other two topologies.

The load-displacement curves of the simulation result are shown in Figure 8. The maximum load is set to around 200N. It is found that the lattice structure with the Grid topology reaches 200N with the minimum displacement. It confirms that the Grid lattice structure has the highest stiffness among all the designs. The load-displacement curves of the X shape lattice structure and the Vintiles lattice structure are very similar. The stiffness of these two lattice structures is close. The lattice structure with the Diamond topology reaches 200N with the largest displacement. It is the softest one among the four lattice structures.

The plantar stress on the bottom surface of the foot is shown in Figure 9. It is found that the highest stress of the Diamond design is around 0.1 MPa, which is the lowest among all the results. The stress distribution is also more uniform than in the other topologies. However, the highest stress of the Grid design is around 0.19 MPa, which is higher than the other designs. The stress concentration is also obvious in the Grid design. The stress distribution of the Vintiles design and the X shape design are very close, which are around 0.12 MPa. The result of the stress distribution is consistent with the load-displacement curve. In a summary of all the simulation results, the lattice structures designed with the Diamond topology is most suitable since it has a smaller and more uniform stress distribution than the other designs.

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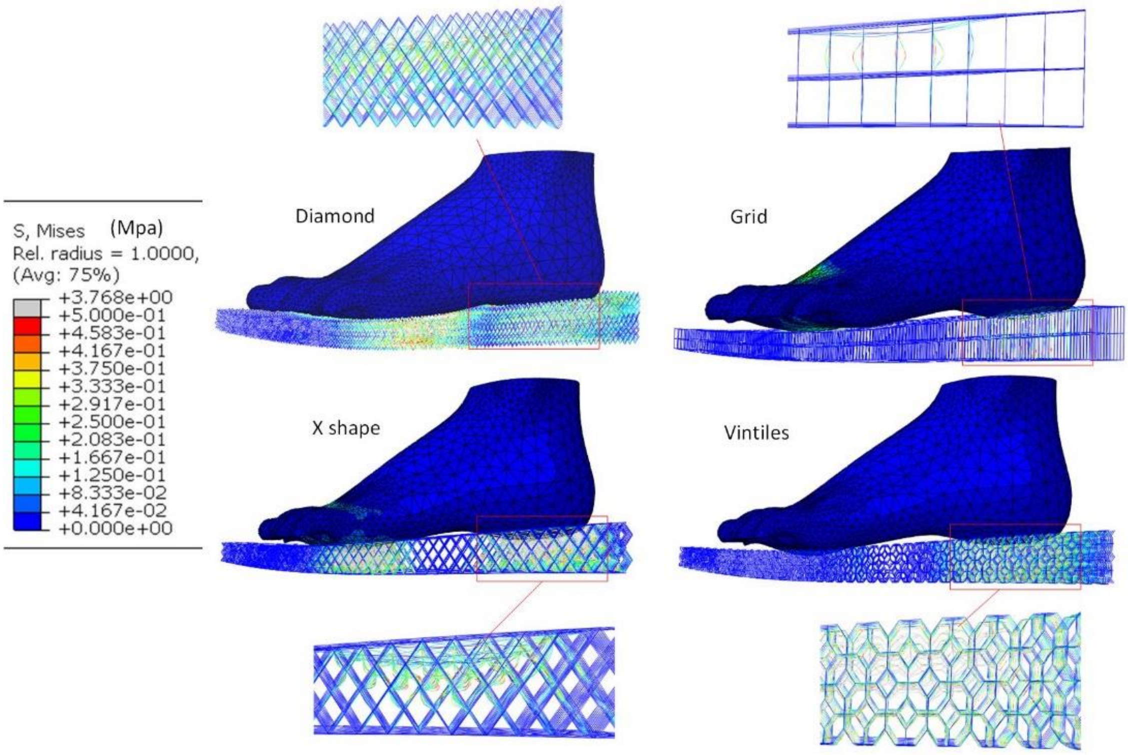

Figure 7. Stress distribution in the shoe sole.

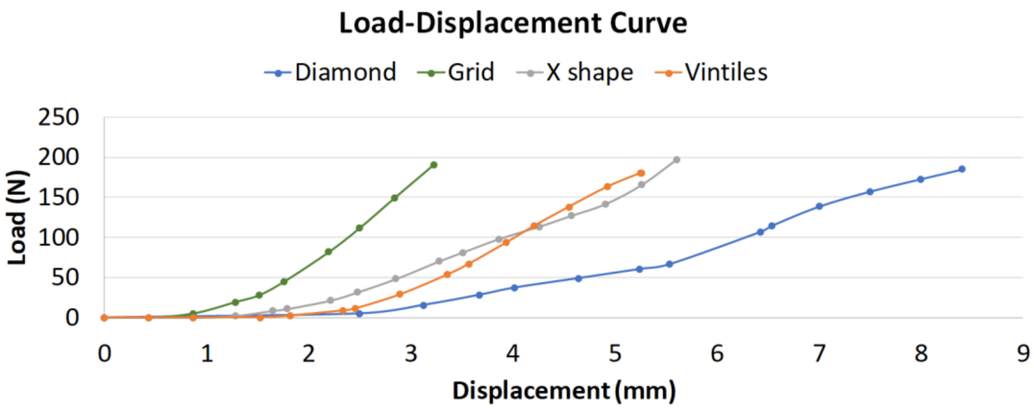

Figure 8. The load-displacement curves of the simulation result.

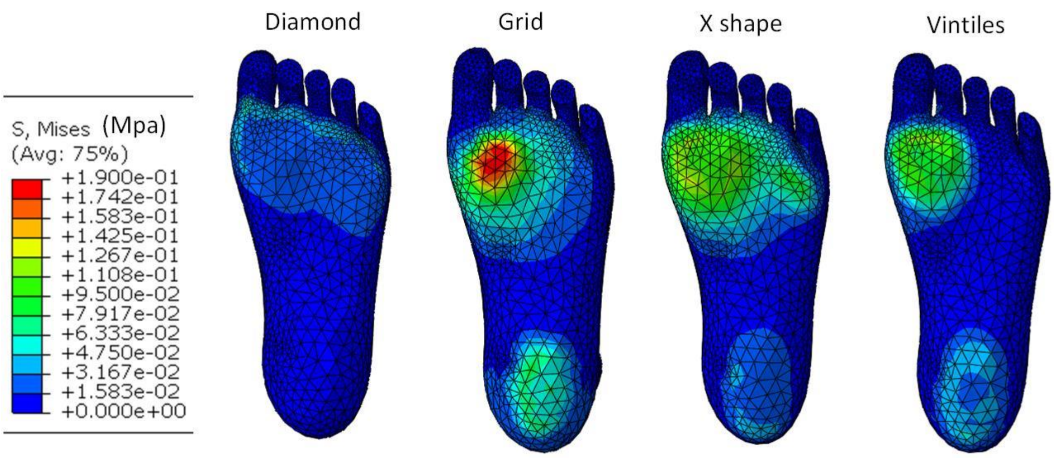

Figure 9. Plantar stress distribution on the bottom of the foot.

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4 EXPERIMENT

Except for numerical simulation, experiments are also conducted to investigate the differences among the mechanical responses of four lattice shoe soles. In this section, the experimental set-up and the experiment results will be discussed.

4.1 Experimental set-up

To conduct the experiment, a press-head is designed as shown in Figure 10(a). It is cut from a scanned human foot. The fabrication material of the press-head is Polylactic acid (PLA). Only the heel part of the foot remains. The compression test will focus on the heel of the shoe sole designed with a lattice structure. The Ultimaker 3 is used to fabricate this samples of the shoe sole using TPU 95A material as shown in Figure 10(b). This material is flexible, which is ideal for the shoe sole. If the material is not flexible, the strut of the lattice structure may break during the compression. Then, the energy absorption of the lattice structure is not repeatable. The experiment set-up is shown in Figure 10(c-f). The sample is put on the compression plate. The press-head is moved down to exert a compression load on the shoe sole. The rate of the movement is 10 mm/min. The experiment is done by the TestResourse 313 universal testing machine. In the design process, the volume of each sample is kept the same. The weight of each sample is measured before the test and is shown in Table 2.

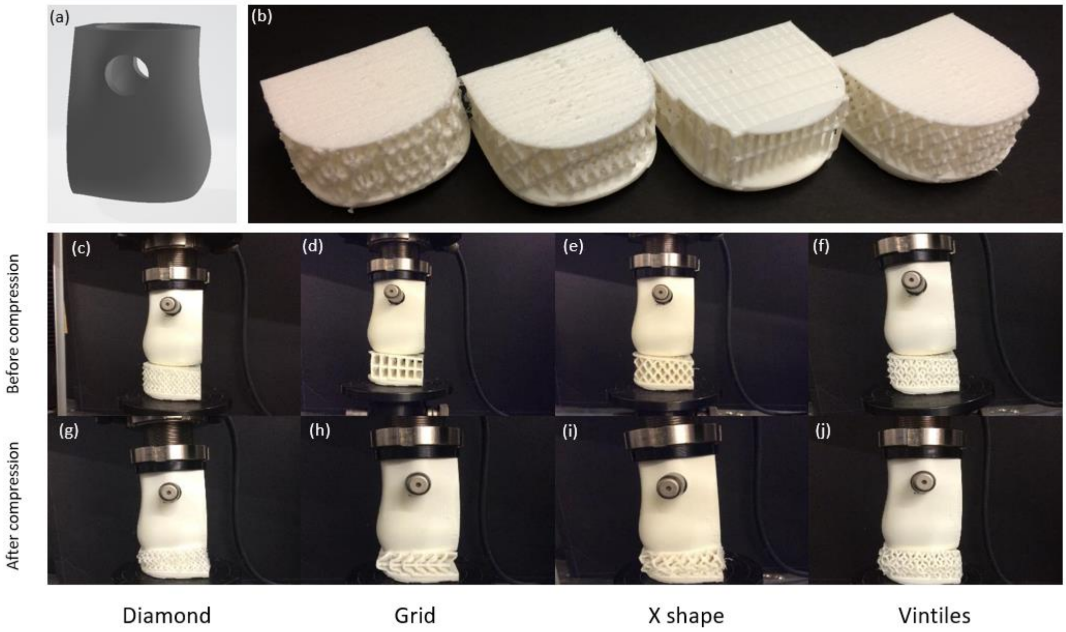

Figure 10. Experiment set-up, (a) the design of the press head, (b) fabricated samples, (c-f) start of the compression test, (g-j) end of the compression test.

Table 2. Weight of fabricated samples

Topology	Diamond	Cubic	X shape	Vintiles
Weight (g)	17.706	20.358	20.806	20.003

4.2 Experimental results and discussion

The deformation of the shoe sole is shown in Figure 10(g-j). It is found that the Grid topology is buckled during the compression test. The other topologies have large bending deformations during the compression test. The load-displacement curves are shown in Figure 11. It is found that, at the beginning of the compression test, the X shape, Grid, and Vintiles lattice structures have similar stiffness. Only the lattice structure with the Diamond topology is less stiff. However, when the load reaches 90N, the lattice structure with the Grid topology start to buckle. The load of the Grid topology is in a plateau region and is exceeded by the Diamond lattice structure. With the increase of the displacement, loads of the X shape lattice structure and the Vintiles lattice structure are very close. But

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when the displacement is over 10 mm, the load of the X shape lattice structure starts to increase dramatically. It means the densification of the X shape lattice comes earlier than the other topologies and the load first reaches 2000N. The second topology that starts the densification is the Vintiles. When the displacement reaches 20 mm, the load of the Grid lattice structure surpasses the load of the Diamond lattice structure. The Diamond topology is the last one to start densification.
It can be concluded from the experiment that the Grid topology is not suitable for the shoe sole application. The reason is that the struts will buckle under the compression load which may change dramatically. Even if there is no buckling, the simulation result shows that the plantar stress of the Grid lattice is the highest. It cannot avoid the stress concentration on the foot. By contrast, the Diamond lattice structure is the softest one among these four topologies. Both the simulation result and the experimental result show that the shoe sole with the diamond lattice structure has a larger displacement under the same load. It can increase the contact area between the foot and the shoe sole. The stresses on the foot are more uniformly distributed. The mechanical responses of the X shape lattice and the Vintiles lattice are quite similar. They are stiffer than the Diamond topology. But if the design requirement of the shoe sole is to absorb more energy and has more bouncing force, these two topologies may be more suitable than the Diamond topology. Therefore, the actual selection of the topology to design the shoe sole is determined by the function requirement.

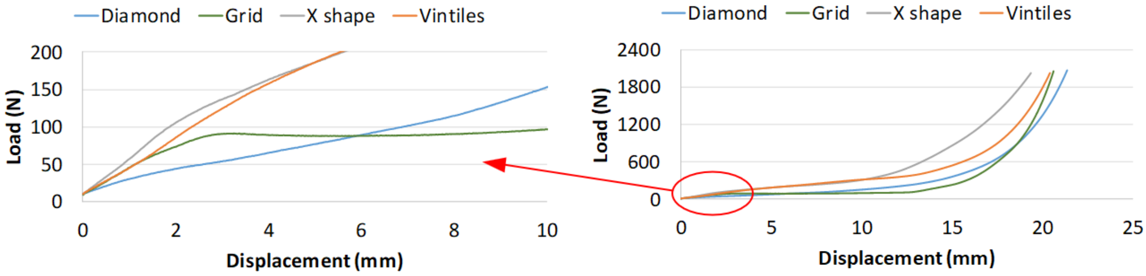

Figure 11. Load-displacement curves of the compression test.

5 CONCLUSIONS

In this paper, the lattice structure is used to design the shoe sole. Four topologies, Diamond, Grid, X shape, and Vintiles are used to generate the conformal lattice structure. The functional volumes and functional surfaces of the shoe sole are defined first. Then, the design space to generate the lattice structure are determined. The source surface, destination surface, and along surface are used to create the conformal wireframe of the lattice structure. To make the weight of each design the same, the diameter of the lattice structure for each topology is adjusted and the wireframe is thickened with the diameter.
The mechanical responses of the lattice structure with different topologies are investigated both numerically and experimentally. It is found from the simulation result that a shoe sole with Grid lattices is the stiffest among all the designs. The maximum stress on the foot is also the largest in all the structures. The mechanical responses of the Vintiles and X shape lattice structure are very similar. The diamond lattice structure is the weakest. The stress distribution of the foot on the Diamond shoe sole is more uniform than that on the other shoe soles. Then, compression experiments are conducted to validate the simulation result. It is found that the experimental result is consistent with the simulation result except that the Grid topology is overpredicted by the FEA. The reason is that the lattice strut buckles very soon under the compression load. The reaction force of Grid lattices is the lowest among all the structures when the displacement is over 6 mm. The mechanical response proves that the lattice structure with different a topology can influence the property of the shoe sole. Therefore, it is possible to control the property of the shoe sole with different lattice structures.
Future work will focus on changing the material distribution in the lattice structure so that the mechanical property of the shoe sole can be more accurately controlled. A design method needs to be proposed to infill optimized an heterogenous lattice structure in the shoe sole. The functions of the shoe sole can be for energy absorption, high elasticity, and for orthotic purpose. By adjusting the material property, a single- or multi-function shoe sole with lattice structure can be designed.

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REFERENCES

Bingheng Lu, D. L., and Xiaoyong Tian (2015), “Development Trends in Additive Manufacturing and 3D Printing”. *Engineering*, Vol. 1, pp. 85–89.

Birtchnell, T. and Urry, J. (2013), “3D, SF and the future”. *Futures*, Vol. 50, pp. 25–34.

Brennan-craddock, J., Brackett, D., Wildman, R. and Hague, R. (2012), “The design of impact absorbing structures for additive manufacture”, *Journal of Physics: Conference Series*, IOP Publishing, p. 012042.

Carbon. (2018), Available: https://www.carbon3d.com/stories/carbon-lattice-innovation-the-adidas-story.

Cheung, J.T.M. and Zhang, M. (2006, May) “Finite element modeling of the human foot and footwear”. In *ABAQUS users’ conference* (pp. 145–58).

Choi, S. and Cheung, H. (2008), “A versatile virtual prototyping system for rapid product development”, *Computers in Industry*, Vol. 59, pp. 477–488.

Davia-aracil, M., Hinojo-pérez, J. J., Jimeno-morenilla, A. and Mora-mora, H. (2018), “3D printing of functional anatomical insoles”. *Computers in Industry*, Vol. 95, pp. 38–53.

Dong, G., Tang, Y. and Zhao, Y. F. (2017), “A Survey of Modeling of Lattice Structures Fabricated by Additive Manufacturing”. *Journal of Mechanical Design*, Vol 139, pp. 100906–100906-13.

Dong, G., Tang, Y. and Zhao, Y. F. (2018), “A 149 Line Homogenization Code for Three-Dimensional Cellular Materials Written in matlab”, *Journal of Engineering Materials and Technology*, Vol. 141, pp. 011005-011005-11.

Ko, H., Moon, S. K. and Hwang, J. (2015), “Design for additive manufacturing in customized products”. *International Journal of Precision Engineering and Manufacturing*, Vol. 16, pp. 2369–2375.

Maskery, I., Aboulkhair, N. T., Aremu, A. O., Tuck, C. J. and Ashcroft, I. A. (2017), “Compressive failure modes and energy absorption in additively manufactured double gyroid lattices”. *Additive Manufacturing*, Vol. 16, pp. 24–29.

Paoletti, I. (2017), “Mass customization with additive manufacturing: new perspectives for multi performative building components in architecture”. *A sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016*, pp. 1150–1159.

Schaedler, T. A. and Carter, W. B. (2016), “Architected Cellular Materials”, *Annual Review of Materials Research*.

Tancogne-dejean, T., Spierings, A. B. and Mohr, D. (2016), “Additively-manufactured metallic micro-lattice materials for high specific energy absorption under static and dynamic loading”, *Acta Materialia*, Vol. 116, pp. 14–28.

Tang, Y., Kurtz, A. and Zhao, Y. F. (2015), “Bidirectional Evolutionary Structural Optimization (BESO) based design method for lattice structure to be fabricated by additive manufacturing”. *CAD Computer Aided Design*, Vol. 69, pp. 91–101.

Ultimaker. (2018), TPU 95A. Available: https://ultimaker.com/en/products/materials/tpu-95a.

Wang, H. and Rosen, D. W. (2002), “Parametric Modeling Method for Truss Structures”. pp. 759–767.

Whiteley, M., White, D., Benzley, S. and Blacker, T. (1996), “Two and three-quarter dimensional meshing facilitators”. *Engineering with Computers*, Vol. 12, pp. 144–154.

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