Performance evaluation of multi-cell sole structure under typical working conditions

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Abstract. The cellular structure has many advantages, which is widely used in in lots of industry fields. The application of cellular structure to the shoe sole can make it have fine buffer and power-assisted effect, but due to the lacking of structural performance evaluation, the sole cannot achieve the desired effects. Accordingly, this paper designs a multi-cell shoe sole, combines the traditional shoe sole with typical hexagonal honeycomb structure features, and the static and vibration characteristics of the traditional sole and multi-cell sole are evaluated by the finite element method, then the weight of the two soles are compared. The results show that the static deformations distributions of multi-cell sole structure are more uniform under the same condition, and the deformations of traditional sole show a trend of high in the middle and low on all sides. Besides, the fundamental frequencies of multi-cell sole and traditional sole structure are 312.62Hz and 381.11Hz, respectively, and the relative vibration deformations of multi-cell sole are also more reasonable, which reflects the multi-cell superiority of impact resistance performance. Furthermore, with the same material and size, the multi-cell sole weight is 83% of the traditional sole.

1. Introduction

As a light and multifunctional structure, the cellular structure has many advantages, which is widely used in the automobile, aerospace, aviation fields and so on. The application of cellular structure to the shoe sole can make it have fine buffer and power-assisted effect. China has become the largest shoe producer and exporter in the world. However, this high share ratio of products is mainly concentrated in the middle and low end shoe industry. In the advanced shoe market, especially the high-end sports shoes, there is still a big gap between domestic and foreign brands. The honeycomb technology, which is proposed by foreign sports shoes brand manufacturers, has been successfully applied to the vibration reduction technology of sports shoes. Domestic manufacturers also put forward similar power nest soles, similar in structure and shape to foreign brands, but the vibration, reliability and fatigue and other comprehensive performance indicators are lower than foreign products, caused weak product competition and low market occupation ratio. Due to technical blockade and other reasons, there are few references abroad for the performance evaluation the honeycomb structure sole.
By importing and absorbing foreign technology and referring to the sole structure, Chinese manufacturers make copies of the shoe sole structure, but the key technology and performance cannot be broken through. Accordingly, it is necessary to construct multi-cell sole structure on the basis of traditional sole scheme and analyze the sole structure performance under different working conditions, so as to provide technical guidance for the design of multi-cell sole scheme.

Currently, scholars mainly focused on multi-cell structure characteristics, performance evaluation and cell topological micro-structure design. The cellular structure originated from the honeycomb structure, was also known as honeycomb structure. Scholars have applied the cellular structure to different industries with quality characteristics. A square honeycomb structure was analyzed by Li et al., which was applied to anti-collision structure, and the collision process was presented by using the display finite element platform [1]. The longitudinal compressive properties of an aluminum alloy honeycomb were studied by Yamashita et al. with the numerical simulation and experimental methods [2]. The multi-cell structure was used in different fields, and the structure performance index was an important factor to evaluate its superiority.

Deformation mode evolution mechanism and dynamic response of hexagonal honeycomb structure under tilting loads were studied by Wang et al. [3]. Yamaguchi et al. carried out damping vibration analysis on an automotive door panels made of porous materials using finite element method, providing reference for vehicle vibration isolation design [4]. Wang et al. also analyzed mechanical properties of a kind of honeycomb structure under impact and vibration conditions [5]. He and Li proposed a new honeycomb structure, and the axial bearing capacity was studied [6]. The damage characteristics of a honeycomb sandwich composite plate were analyzed by Katunin et al., based on the nondestructive testing technology, which can provide key technology for composite plate damage identification and localization [7]. Yan et al. manufactured complex metal multi-cell structures with the application of laser melting technology, and analyzed the mechanical properties under different processing technologies [8]. In order to maximize the performance of the multicellular structure, it is necessary to optimize the cellular topological form and structure size parameters. The impact characteristics of a compressible square honeycomb structure were simulated and tested by Holloman et al., and the performance under different parameters was contrasted and analyzed [9]. Zeng et al. studied the elastic vibration test method of porous carbon nanocomposites [10]. Many scholars have optimized different honeycomb structures, and applied in different fields, just as honeycomb sandwich plates with satellite structure [11], Multi-scale modeling of honeycomb structures [12], and so on.

As mentioned above, scholars have studied cellular structure mechanical properties in different application fields, parameters optimization, cell design method, and so on, by using the methods of theoretical derivation, numerical simulation and model experiment. However, there were few studies on the application of multi-cell structure to shoe sole system, and the performance analysis of sneakers mainly focused on the study of sole shock absorption and anti-skid performance, as well as the stiffness and impact force monitoring [13, 14]. It was reported that foreign high-end sport shoe manufacturers have done deep research about multi-cell sole, but due to technical blockade and other reasons, there is little relevant literature in the public material. Therefore, this paper proposes a multi-cell sole structure scheme, based on the traditional sole scheme. Then the two sole structures statics performance and vibration characteristics under different conditions were solved by the finite element software ANSYS, to contrast the performance indexes of the two schemes. The results can provide guidance for the multi-cell sole structural design and performance evaluation.

2. Multi-cell sole structure scheme
Based on the existing traditional sole scheme and the traditional 42 yards shoe sole structure, at the same time, combined with the typical hexagonal honeycomb structure characteristics, the multi-cell sole structure innersole, insole and outsole are designed. The proposed general multi-cell sole structure scheme is shown in Figure 1, and the specific dimensions of each part are shown in Table 1~Table 3.
Figure 1. The overall structure model of multi-cell sole.

### Table 1. Outsole structure size.

| Position          | Thickness (mm) | Length (mm) | Width (mm) |
|-------------------|----------------|-------------|------------|
| Bottom            | 8              | 261         | 99         |
| Bottom groove     | 2.6            | 99          | 3          |

### Table 2. The bottom structure size of honeycomb layer (mm).

| Thickness | Length | Width | Hexagon depth | Hexagon length | Honeycomb spacing |
|-----------|--------|-------|---------------|---------------|------------------|
|           | 15     | 261   | 99            | 5             | 10               | 4.6              |

### Table 3. Insole structure size (mm).

| Thickness | Length | Width |
|-----------|--------|-------|
|           | 8      | 261   |
|           |        | 99    |

3. Structure and performance analysis of multi-cell shoe sole

3.1. Typical conditions

The load conditions of multi-cell shoe sole can be mainly divided into three conditions as follows: normal walking, uniform running and jumping. By referring to relevant literature and with the application of plantar pressure measurement system, the average loads of a 70kg adult man under the above three conditions can be obtained as follows:

1. 0.07MPa uniform load under the normal walking condition, with vertical downward direction.
2. 0.14MPa uniform load under the uniform running condition, also with the vertical downward direction.
3. 0.21MPa uniform load under the jumping condition, with the same direction.

3.2. Structural performance evaluation of sole under typical conditions

The traditional and multi-cell sole 3D models are imported into the finite element analysis software ANSYS Workbench, respectively. Then the material is defined as rubber, and the bonded contact algorithm is used to simulate the adhesive between the sole parts. Last the finite model is meshed with the Hex-dominant method, and a hexahedron dominance finite element mesh model is obtained, as shown in Figure 2.
The pressures are applied to the model according to the typical conditions in section 3.1, and the plane of the outsole contacting the ground is fixed. Then the static analysis is carried out, to contrast the static indexes of the two soles.

3.2.1. Statics performance index. The total deformation and equivalent stress distributions can be extracted through post-processing. The results of maximum load condition are compared, that is, the deformation and stress distributions of the two soles under the jumping condition are shown in Figure 2 and Figure 3.

As can be seen within results above, it can be observed that the deformation distribution of the multi-cell sole is more uniform, and the deformation value in most areas is about 0.54mm. The deformation of the traditional sole gradually increases from the center to the outside, causing the sole to appear high in the middle and low deformation around tendency, which affects the wearing comfort of the shoe. Furthermore, through counting the deformation data of sole nodes, the average deformation of multi-cell sole is about 0.25mm, and the value of traditional sole is about 0.12mm. It is generally known that the greater the deformation, the smaller the static stiffness of the sole, and the cushion property is better.
It is further indicated the superiority of multi-cell sole structure in the aspect of impacting resistance. Besides, the stress distribution of the multi-cell sole is also more uniform, the equivalent stress in most areas is about 0.1Mpa, which is beneficial to extend the sole life and avoid fatigue damage caused by uneven forces.

3.2.2. Inherent characteristics. In order to further evaluate the sole structure resisting dynamic excitation characteristics, in this paper, the natural frequencies of structures are used to characterize, and the first order natural frequencies and mode shapes of the two soles are contrasted. The first order mode shapes can be solved by modal analysis, as shown in Figure 5.

![Figure 5. First order mode shape of sole.](image)

From the above comparison, it can be known that the traditional sole first order natural frequency is 381.11Hz, and the value of multi-cell sole is 312.62Hz. Moreover, the relative vibration and deformations of the multi-cell sole nodes are more uniform than those of the traditional sole, which indicates that the multi-cell sole vibration response distributions are more reasonable under the same external excitations. Thus it can be seen, under the same external conditions, the multi-cell sole vibration characteristics make the sole deform more easily and easier to absorb vibration generated by external loads, so as to buffer the human foot impact.

3.2.3. Weight. Weight is a very important index of shoe performance. Hence, the volumes of the two soles are contrasted, which are measured by the 3D modelling software, as shown in Table 4.

| Name            | Innersole (cm³) | Insole (cm³) | Outsole (cm³) | Total volume (cm³) |
|-----------------|----------------|--------------|---------------|--------------------|
| Traditional sole| 157.49         | 295.30       | 147.94        | 600.73             |
| Multi-cell sole | 157.49         | 193.99       | 147.94        | 499.42             |

From the above results, we can see that the multi-cell sole total volume is about 83% of the traditional value. Thus it can be seen, for a pair of shoes with the same size, the multi-cell shoe sole structure is lighter than the traditional structure, which is more suitable for human body.

4. Conclusion

In view of the superiority of the cellular structure, a multi-cell shoe sole structure model suitable for all kinds of sports shoes is proposed, based on the traditional sole structure and typical hexagonal honeycomb structure characteristics. Then the statics, vibration and weight performance indexes of the multi-cell and traditional sole structure are contrasted. The following conclusions can be drawn through the comparative analysis. (1) Under the same condition, the deformation distribution of the multi-cell sole structure is more uniform. The traditional sole deformation tends to increase gradually from the
center to the outside, causing the sole middle to be high and around to be low, which affects the wearing comfort of the shoe. (2) The basic frequency of multi-cell sole structure is 312.62Hz, which is smaller than the traditional sole value (381.11Hz). Besides, the relative vibration deformation of multi-cell sole structure is more uniform, and the vibration characteristics make the sole easier to deform, so as to absorb external energy more easily and buffer the human foot impact. (3) Under the same material and size, the weight of multi-cell sole structure is about 83% of the traditional value, which illustrates that the multi-cell sole is lighter than traditional sole and more suitable for human. The results can provide reference for the multi-cell sole performance evaluation and relevant standards formulation for footwear industry.

Acknowledgments
This work was supported by the Natural Science Foundation of Fujian Province, China (Granted No.2017J01675), Science and Technology Plan (Guidance) of Fujian Province, China (Granted No.2017H0002), and Scientific Research Foundation of Fujian University of Technology (Granted No.GY-Z160048).

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