A Geometric Parameter Study of Re-Entrant Honeycomb Obstruction Block

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Abstract. As a kind of protective equipment, obstruction block is playing an important role in traffic accidents. In this work, a novel re-entrant honeycomb obstruction block (RHOB) with negative Poisson’s ratio was proposed. The energy-absorbing performances under static compression were examined and the influences of re-entrant angle $\alpha$, material thickness $t$ and aspect ratio $\gamma$ on deformation behaviours of RHOB were investigated with finite element method (FEM). It is demonstrated that RHOB has distinguished bearing capacities and energy-absorbing properties compared to traditional honeycomb obstruction block (THOB). Besides, with the reduction of re-entrant angle $\alpha$, the negative Poisson’s ratio of RHOB is decreased. Also, RHOB has notable bi-directional stabilities with a proper range of aspect ratio $\gamma$. And the increasing material thickness $t$ enhances stiffness of RHOB. These findings highlight that a well-constructed re-entrant honeycomb obstruction block has extraordinary mechanical properties and can be widely applied in practical engineering.

1. Introduction
Negative Poisson’s ratio structures have characteristics such as light weight, superior stiffness, specific strength, high energy absorption capability and so on [1]. These properties make these systems applicable in many industries, particular in the biomedical industries [2-3] and metamaterials [4-6]. A double-arrow-shaped energy absorption box with negative Poisson’s ratio was designed in 2015 [7]. Geometric parameters studies of 2D auxetic unit cell were conducted to observe their effects on blast resistance performances [8]. The impact resistance and deformation characteristics of different auxetic structures under blast load were studied through FEM [9-10]. A number of metamaterials with perforated architectures possessing the ability to exhibit 2D auxetic responses with negative Poisson’s ratios were manufactured [11]. An innovative three-dimensional hierarchical design strategy was systematically summarized and a novel class of mechanical metamaterials based on topology analysis was proposed [12], which offered a useful method for design, fabrication and analysis of 3D metamaterials with auxetic behaviour.

Above studies have done many explorations on the deformation behaviours, energy-absorbing performances and impact resistances of negative Poisson’s ratio structures. To improve the protective abilities of obstruction block, designing new obstruction blocks with negative Poisson’s ratio is highly expected. On the basis of above theories, a centrosymmetric RHOB is designed in this work. What’s more, the effects of geometric parameters such as re-entrant angle, material thickness, aspect ratio of RHOB on its static mechanical properties and energy absorption performances were studied through the finite element simulation.
2. Finite Element Model

2.1. Geometric Model
Two different types of unit cells were investigated in this work. THOB is the most typical guardrail blocks (see Figure 2), while RHOB with re-entrant and centrosymmetric shape (see Figure 1) is a kind of novel guardrail block. And the unite cell displayed in Figure 1 is described with 8 parameters, where $L$ is the length of RHOB, $H$ is the height of RHOB, $\alpha$ is the angle between the tilted ligament and the bottom ligament, $t$ is the material thickness of ligament, $R$ is the radius of big arc, $r$ is the radius of small arc and $h_1$ ($h_2$) is the height of left (right) re-entrant node. A semi-rigid guardrail with double-wave is investigated in this study, whose configuration details are listed in Table 2. Because the study focuses on the mechanical behaviors of obstruction blocks, the effect of the remote guardrail can be ignored. As a result, two-span guardrail is established and the length of each span is $4 \text{m}$. The schematic drawing of the guardrail is shown in Figure 4.

| $L$ (mm) | $H$ (mm) | $\alpha$ (°) | $h_1$ (mm) | $h_2$ (mm) | $R$ (mm) | $r$ (mm) | $t$ (mm) |
|----------|----------|-------------|------------|------------|----------|----------|----------|
| 120      | 178      | 60          | 119        | 59         | 70       | 5        | 4        |

Table 2. Configuration details for guardrail (mm).

| Beam plate | Column | Obstruction block | Hight $^a$ | Depth $^b$ | Space $^c$ |
|------------|--------|-------------------|-----------|-----------|-----------|
| $310\times85\times3^d$ | $\Phi114\times4$ | $196\times178\times200\times4^e$ | 600       | 1400      | 4000      |

$^a$ Distances between geometric center of beam slab and the ground.
$^b$ Embedding depth of the column.
$^c$ Spaces between columns.
$^d$ Length×width×thickness.
$^e$ Length×height×depth×thickness.

Figure 4. Schematic drawing of the guardrail.
2.2. Material Parameters and Mechanical Model

In this paper, Ansys is used for finite element simulation. In order to better simulate the real working conditions, the material adopts structural steel, whose properties are defined as follow: the elastic modulus is 200 GPa, the Poisson's ratio is 0.3, the density is 7850 kg/m³, the yield strength is 200 MPa and the ultimate strength is 460 MPa. Fixing the bottom surfaces of the soil body and applying a load at the geometric midpoint of the right span fence (see Figure 3). To simplify the model, the bolt connection is ignored and contact relationship between the guardrail blocks and the beam plates and the columns is bonded. Default mesh method is used in mesh generation. The relevance is coarse, the maximum element growth ratio is 1.2 and the number of elements is 26381.

2.3. Numerical Analysis of RHOB

According to the geometric relationship, the mathematic expression of the recessed depth \( x_0 \) is equation (1).

\[
x_0 = (H - h_1) \tan \alpha
\]

Assuming that \( h_1 \) is a constant, parametric \( h_2 \) is changed continuously. RHOB have the following geometric relationships as equations (2).

\[
\begin{align*}
\theta &= \tan^{-1} \frac{H-h_1}{x_0} \\
\beta &= \tan^{-1} \frac{H-h_2}{x_0}
\end{align*}
\]

Owing to static equilibrium condition and the triangle rule of force, we can get a relationship as in equations (3).

\[
\begin{align*}
F_{N_{1Y}} &= F_{N_{1X}} \tan \theta \\
F_{N_{2Y}} &= F_{N_{2X}} \tan \beta
\end{align*}
\]

Combining Equations (2) and (3), the interplay between the vertical force components and geometric parameters can be obtained:

\[
\Delta F_y = F_{N_{2Y}} - F_{N_{1Y}} = F_{N_{1X}} (\tan \beta - \tan \theta) = F_{N_{1X}} \left( \frac{H-h_2}{x_0} - \frac{H-h_1}{x_0} \right) = F_{N_{1X}} \frac{\Delta h}{x_0}
\]

The uneven bending moment is obtained:

\[
M = \Delta F_y L = F_{N_{1X}} \frac{l \Delta h}{x_0} = \frac{F_{N_{1X}} l \Delta h}{(H-h_2) \tan \alpha}
\]

It’s shown that RHOB is asymmetric. Therefore, asymmetric forces lead a bending moment \( M \), which makes RHOB rotating under compression. Obviously, the bending moment \( M \) is closely linked with the geometric parameters of RHOB. So, a further study is carried out to discussing the influence of geometric parameters on static mechanical and energy-absorbing properties of RHOB. The re-entrant angle \( \alpha \), material thickness \( t \) and aspect ratio \( \gamma \) were studied respectively. Geometrical parameters studied in this work are listed in Table 3. There are nine groups of parametric study for re-entrant angle \( \alpha \) and material thickness \( t \) and seven groups of parametric study for obstruction block length \( L \).

| Table 3. List of dimensions studied in this work \(^a\) |
|----------------------------------|
| **Parameter** | 1\(^\circ\) | 2\(^\circ\) | 3\(^\circ\) | 4\(^\circ\) | 5\(^\circ\) | 6\(^\circ\) | 7\(^\circ\) | 8\(^\circ\) | 9\(^\circ\) |
| \( \alpha (^\circ) \) | 60 | 61 | 62 | 63 | 64 | 65 | 70 | 75 | 80 |
| \( t (\text{mm}) \) | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 |
| \( L (\text{mm}) \) | 90 | 100 | 110 | 120 | 130 | 140 | 150 |

\(^a\) Control variable is used in this table.
3. Results and Analysis

3.1. Influences of Re-entrant Angle $\alpha$ on Mechanical Properties of RHOB
As evident from Figure 6, the deformation behaviour of RHOB is quite different with THOB’s. The representative THOB (see Figure 6 (b)) does not show any material densification effects and it tends to expand from the centre towards the sides. However, the material densification effect of representative RHOB is apparent (see Figure 6 (a)) and it tends to recess towards geometric centre. In addition, RHOB also exhibits rotating deformation behaviour under compression, which contributes to better energy-absorbing properties. As one may observe from Figure 7 and Figure 8, mechanical responses of RHOB are characterised with a total drop both in maximum stress curve and maximum displacement curve when angles $\alpha$ varies from 60° to 80°. Under equivalent loadings, the maximum stress of RHOB is reduced by 7%, and the maximum displacement of RHOB is reduced by 13.8%. The results indicate that smaller angle $\alpha$ leads to decreasing negative Poisson's ratio of the RHOB, so that the auxetic effects become more prominent. Especially, mechanical properties of RHOB are significantly improved when angle $\alpha = 63^\circ$.

Figure 6. Deformation behaviours of two kinds of obstruction blocks under forces of 1000N. a) Deformation of RHOB; b) Deformation of THOB.

Figure 7. Effects of re-entrant angle $\alpha$ on maximum stress $\sigma_{max}$ of RHOB.

Figure 8. Effects of re-entrant angle $\alpha$ on maximum displacement $y_{max}$ of RHOB.

3.2. Influences of Material Thickness $t$ on Mechanical Properties of RHOB
As one may observe from Figure 9 and Figure 10, there are three main stages: $t$ is less than 2.7mm, $t$ is not less than 2mm and no more than 2.7mm and $t$ is greater than 3.5mm. At the first stage, it’s obvious that maximum stress curve and maximum displacement curve are both declining. At the second stage, the maximum stress curve and maximum displacement curve of RHOB represents an abnormal pulsed growth. Meanwhile, the maximum displacement reaches a peak of 4.86 mm when $t$ is 2.9 mm, and the maximum stress reaches a peak of 256.1 MPa when $t$ is 3 mm. At the third stage, the maximum stress and displacement decreases very slowly with the growth of material thickness, which indicated that material thickness has a small effect on mechanical properties of RHOB at this
stage. It’s indicated that material thickness has a great impact on the deformation behaviour and mechanical properties of RHOB. At primary stage, the increasing material thickness causes a rise in structure rigidity, which significantly improving the local stabilities of RHOB. But, it’s has more complicated relationship in the next two stages, which needs a further study to explore the essences.

3.3. Influences of Aspect Ratio $\gamma$ on Mechanical Properties of RHOB
In this work, the aspect ratio of RHOB is defined as $\lambda = L/H$, where $L$ is RHOB’s length and $H$ is the height of RHOB. Figure 11 and Figure 12 gives information about the maximum stress and the maximum displacement when $\gamma$ varies from 0.52 to 0.8. Firstly, two curves are symmetrical about $\gamma = 0.67$. Interestingly, the maximum stress curve of RHOB looks like the letter "W", while the maximum displacement curve looks like the letter “U”. It is noticeable that the two curves fall at the primary stage and climb up at the final stage. At the mediate stage, the maximum displacement curve almost keeps constant, while the maximum stress curve has a little fluctuation. It can be concluded that RHOB has double limits of aspect ratio. On one hand, there is a minimum $\gamma$, which ensures the overall stability in the $x$ axis direction. On the other hand, there is a maximum $\gamma$, which promises the locally stability in the $y$ axis direction.

4. Conclusion
In this work, a kind of centrosymmetric re-entrant honeycomb obstruction block was designed. The relationship between different geometric parameters and mechanical and energy-absorbing properties of RHOB were studied using finite element simulations. The conclusions are as follows:
(1) Compared to THOB, RHOB has re-entrant and rotational deformation behaviors, which enhances the bearing capacities and energy absorption properties. It shows that the bearing capacities of RHOB is 3 times greater than THOB’s, while the maximum deformation of RHOB is 2.5 times greater than THOB’s.

(2) With the reduction of the angle $\alpha$, the negative Poisson's ratio of RHOB is decreased. When angle $\alpha$ is $63^\circ$, RHOB is characteristic with the largest displacement and the smallest stress.

(3) The aspect ratio of RHOB has double limits. Only aspect ratio between 0.57 and 0.78 can the bi-directional stability of RHOB be ensured.

(4) The material thickness has a significant influence on RHOB. With material thickness increased, the stiffness of RHOB enhances. Noticed that an abnormal mechanical behavior appears when material thickness is $3mm$, which needs a further study to explain its essential reasons.

5. References
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