Numerical Study on the Elastic Properties of Perforated Hollow Spheres Structure in Body-Centered Cubic Pattern

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Abstract. This paper investigates the elastic properties of a new type of hollow spheres structure numerically. In the new structure, hollow spheres perforated regularly with several holes, which are to open the inner sphere volume and surface, are bonded in the body-centered cubic (BCC) pattern. A 5×5 cells finite element model under the uniaxial load is established by Abaqus for the simulation. By changing the wall thickness, hole diameter and the bonding radius in the finite element model, the Young’s modulus and Poisson’s ratio of the BCC packing perforated hollow spheres structure (PHSS) as functions of these geometrical properties are shown, and the influence of these parameters on the structural elastic properties is analyzed.

1. Introduction
As a high quality porous metal material, Metal Hollow Spheres Structure (MHSS), which is comprised of many identical metal hollow spheres stacked in a certain form, has gradually drawn the attention of more and more researchers [1]. In practical projects, there are three main kinds of connection methods for producing the hollow spheres materials [2]: (1) to fill the hollow spheres into the polymer matrix, such materials are commonly referred to as syntactic foams [3]; (2) to pile up and sinter metal hollow spheres by applying heat and pressure [4, 5]; (3) to bond the spheres using a liquid phase which forms a neck region between spheres [6-9]. The present work focuses on the hollow spheres structure belonging to that produced by the third method.

Recently, a new type of hollow spheres structure, i.e. where the spherical shell has been perforated, was investigated in a few references [10-12]. The basic idea of the perforation is to open the inner volume and surface area of the hollow sphere so that for example a gas, a liquid or any second phase can better flow through the structure or reinforce the hollow sphere. Related work showed that the heat transfer efficiency of the perforated hollow spheres structure (PHSS) is obviously higher than that of the classical HSS [10]. The basic mechanical properties, such as elastic modulus, Poisson’s ratio and initial yield stress, of PHSS under uniaxial load were also studied [11, 12]. However, related work about PHSS only focuses on the simple cubic arrangement, accordingly, the single hole arrangement, which is not sufficient to fully reflect the performance of this new type of hollow spheres structure.

In this paper, the perforated hollow spheres are arranged in the body-centered cubic (BCC) pattern. Finite element (FE) method is employed to investigate the elastic properties of the BCC packing PHSS. By changing the wall thickness, hole diameter of the hollow spheres and the bonding areas radius in the FE Model, the effects of these geometrical properties on the structural elastic properties are studied.
2. Geometric model of the BCC packing PHSS
The BCC packing PHSS is shown in Figure 1(a). The profile of the unit cell structure is shown in Figure 1(b). The perforated hollow spheres are arranged in the body-centered cubic pattern and connected with neck regions described as certain geometry presented in Figure 1(b). The holes are located between the bonding areas, and the largest holes can’t reach the bonding areas.

![Figure 1](image_url)

Figure 1. (a) The BCC packing PHSS; (b) Profile of the unit cell of the BCC packing PHSS.

In Figure 1(b), R refers to the external radius of hollow spheres, t refers to spheres wall thickness, r refers to the radius of the bonding region, d refers to the center thickness of the linking neck, D refers to the hole diameter.

In the case of cellular materials, physical properties are commonly described as a function of their relative density [1].

$$\rho_{rel} = \frac{\rho}{\rho_{so}}$$  \hspace{1cm} (1)

Where $\rho$ is the density of the cellular material and $\rho_{so}$ is the density of the solid material from which the cells are made. Since the mass of the solid material and the mass of the cellular material itself is identical, the right hand side of Eq. (1) can be divided by the mass to express the relative density in terms of volumes as below.

$$\rho_{rel} = \frac{V_{so}}{V_{UC}}$$  \hspace{1cm} (2)

Where, $V_{so}$ is the volume of the solid material and $V_{UC}$ is the volume of the unit cell or of the entire specimen.

3. Finite element models
In order to evaluate the elastic properties (Young’s modulus and Poisson’s ratio) of the BCC packing PHSS, a series of 5×5 cells finite element models with geometry variation are established by software Abaqus. In simulation, the model is placed between two rigid plates (Figure 2 (a)). The bottom one serves as the fixed boundary whereas the top one serves as the punch, so that only the displacement in the vertical direction (Y-axis) is allowed. The “hard contact” algorithm in Abaqus is adopted to describe the normal properties of the contacts between the rigid plates and the structure. The symmetric boundary conditions are used for the vertical side faces 1 and 2 to reduce the calculation time, and the free boundary conditions for other vertical side faces (Figure 2 (b)). Table 1 and Table 2 show the base material properties and geometric parameters of all the models. In all cases, the outer sphere radius R is 2mm and the center thickness of neck region d is 0.1mm if not otherwise mentioned.
Figure 2. (a) Construction of the finite element model; (b) corresponding boundary conditions.

Table 1. Base materials properties of the structures.

| Material     | Young’s modulus (Mpa) | Yield stress (Mpa) | Poisson’s ratio | Density (kg/cm$^3$) |
|--------------|------------------------|--------------------|-----------------|---------------------|
| Aluminum(Al) | 70000                  | 200                | 0.33            | 2.7                 |
| Steel        | 110000                 | 300                | 0.3             | 6.95                |

Table 2. Geometric parameters of the structures.

| Relative wall thickness ($t/R$) | Hole diameter fraction (D/2R) | Bonding radius fraction ($r/R$) | Relative density $\rho_{rel}$ (%) |
|---------------------------------|-------------------------------|---------------------------------|-----------------------------------|
| 0.025                           |                               |                                 | 4.733                             |
| 0.0375                          |                               |                                 | 6.31                              |
| 0.05                            | 0.4                           | 0.3                             | 7.963                             |
| 0.0625                          | 0.2                           | 0.3                             | 9.465                             |
| 0.075                           | 0.3                           |                                 | 10.892                            |
| 0.5                             | 0.4                           | 0.3                             | 7.963                             |
| 0.5                             | 0.2                           |                                 | 9.465                             |
| 0.5                             | 0.25                          |                                 | 10.892                            |
| 0.5                             | 0.3                           |                                 | 9.465                             |
| 0.5                             | 0.35                          |                                 | 9.465                             |
| 0.5                             | 0.4                           |                                 | 9.465                             |
| 0.5                             | 0.45                          |                                 | 9.465                             |

4. Result and discussion
In total 32 cases are processed on personal computer. The static approach (Abaqus Standard) is used to obtain the elastic response. For consistency, the nominal engineering strain is defined as the displacement of the top rigid plate divided by the initial height of the structure, the nominal stress is defined as the reaction force of the top rigid plate divided by the cross-sectional area of the structure, and the Poisson’s ratio is defined as the negative ratio of the transverse(X or Z-axis) strain and vertical
(Y-axis) strain. Considering the effect of free boundary conditions, the centered 2×2 cells of the whole model is extracted for the transverse strain calculation.

The results for the Young’s modulus are plotted as functions of the relative wall thickness, hole diameter fraction and bonding radius fraction in Figures 3(a), (b), and (c) respectively. It can be seen that the Young’s modulus increases with the wall thickness and bonding radius while decreases with the hole diameter. This is because the stiffness of the structure increases with the wall thickness and bonding radius, however, any perforation in an engineering structure constitutes a weakness, and the bigger the hole diameter the weaker the structure. In general, the Young’s modulus of the steel structure is about 45% larger than that of aluminum structure.

The Poisson’s ratio values as a second material property in the elastic range are also shown as functions of the relative wall thickness, hole diameter fraction and bonding radius fraction in Figures 4(a), (b), and (c) respectively. It can be found that the Poisson’s ratio increases with the hole diameter and bonding radius while decreases with the wall thickness. In general, the Poisson’s ratio of the steel structure is a little smaller than that of the aluminum structure, and the differences between the two are within 10%. Due to the elastic deformation mechanism inside the structure a negative Poisson’s ratio is obtained for the structures with the smallest hole diameter (Figure 4(b)). This is because the localization of the deformation yields a transverse contraction for compressive loading.

![Figure 3](image1.png)
**Figure 3.** Young’s modulus as a function of (a) relative wall thickness; (b) hole diameter fraction; and (c) bonding radius fraction, respectively.

![Figure 4](image2.png)
**Figure 4.** Poisson’s ratio as a function of (a) relative wall thickness; (b) hole diameter fraction; and (c) bonding radius fraction, respectively.

The results for the Young’s modulus and Poisson’s ratio are also plotted as functions of the relative density (Figures 5 and 6). It is clear that the trends of the results for the structures made of aluminum and steel are very similar. With the increase of the relative density the Young’s moduli with different geometrical effects increase (Figure 5). It is different that, the Poisson’s ratios under the wall thickness and hole diameter effects decrease with the relative density (Figure 6). It is worth to note that the
results for the Young’s modulus and Poisson’s ratio under the hole diameter effect vary rapidest, so the structure is most sensitive to the perforation (Figures 5 and 6).

![Graph showing Young's modulus of structures made of Al and Steel as functions of relative density.](image)

Figure 5. Young’s moduli of structures made of (a) Al and (b) Steel as functions of relative density.

![Graph showing Poisson's ratio of structures made of Al and Steel as functions of relative density.](image)

Figure 6. Poisson’s ratios of structures made of (a) Al, and (b) Steel as functions of relative density.

5. Conclusion
In the scope of this research, the elastic properties of the BCC packing PHSS as functions of the geometric parameters have been investigated numerically. A 5×5 cells finite element model under the uniaxial load was chosen for the simulation. By changing the wall thickness, hole diameter and the bonding radius in the FE Model, the influence of these parameters on the elastic properties was analyzed. The results reveal that (1) the Young’s modulus increases with the wall thickness and bonding radius while decreases with the hole diameter, accordingly, it increases with the relative density; (2) the Poisson’s ratio increases with the hole diameter and bonding radius while decrease with the wall thickness, the results under the wall thickness and hole diameter effects decrease with relative density while increase under the bonding radius effect; (3) the elastic properties of the PHSS are most sensitive to the perforation; (4) in general, the Young’s modulus of the steel structure is about 45% larger than that of aluminum structure, in contrast to this behavior, the Poisson’s ratio of the steel structure is about 10% smaller than that of the aluminum structure.

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