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THE ELASTIC-PLASTIC PROPERTIES OF SYNTACTIC PERFORATED HOLLOW SPHERE STRUCTURES

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ABSTRACT

Hollow sphere structures are lightweight materials and belong to the group of cellular metals (such as metal foams). Metal foams exhibit a several interesting mechanical properties. This contribution investigates the elastic-plastic properties of a new type of hollow sphere structures. For this new type, the sphere shell is perforated by several holes in order to open the inner sphere volume for the matrix material. The effective elastic-plastic properties of syntactic (i.e. spheres embedded in a matrix) perforated sphere structures in a primitive cubic arrangement of unit cell models are numerically evaluated for a different filler fractions of the spheres. The results are compared to configurations without perforation and configurations where hollow spheres are only connected by so called "sintering necks", i.e. not completely embedded in a supporting matrix. In the scope of this study, three-dimensional finite element analysis is used in order to investigate unit cell models. The present investigation revealed that sintered arrangement of perforated hollow sphere structure is superior in terms of initial yield stress compared to the syntactic arrangement counterparts. The stronger structure possessed by sintered arrangement model is attributed to network of sphere morphology. The results also indicate a continuous cubic curve of 0.2% offset yield stress for syntactic and sintered arrangement models.

Key words: *Elastic-plastic; cellular material; finite element method; syntactic foam*

1.0 INTRODUCTION

Cellular metals are a new class of materials known for its low densities, excellent strength-to-weight ratio and demonstrate a variety of specific mechanical and physical properties. The combination of specific mechanical and physical properties in the cellular materials makes them different to dense metal. Cellular materials were applied in a number of applications using different base materials. High cost aluminium honeycomb was replaced by cheaper Aluminium Foam Sandwich (AFS) to build two cone-shaped adaptors for The European 'Ariane 5' rocket to support the payload [1]. A milling machine table and a robot arm made of hollow sphere composite (HSC) was also produced by Baumeister and colleagues [2]. The lightweight metallic composite investigated by Baumeister has an

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advantage of having higher speed and acceleration when applied to the robot arm. Lightweight structures are also help in more economical benefit for such application. Others investigated the usage of the highly promising cellular materials as shock absorbers [3], thermal conductors [4] , vibration dampers and acoustic behaviour of sphere structures [5, 6]. In a recent work, perforation holes were introduced onto Metallic Hollow Sphere Structures (MHSS). The motivation for the perforation of holes of circular cross section in the sphere shells is to make the inner sphere surface and volume usable [7].

Interconnected open sphere structures increase the permeability by gas, liquid or any second phase. Manufacturing techniques for Perforated Hollow Sphere Structures (PHSS) are still under development and an image of the early production stage of such perforated hollow sphere structures is shown in Figure 1. To date, the new type of hollow sphere structure has been investigated in a limited number of publications. Hosseini et al. worked on the thermal properties of perforated hollow sphere structures [7-9]. The effect of the size of the hole diameter and the geometry of the neck region on the effective thermal conductivity was examined in [7]. Furthermore, the influence of different base materials of the spheres was investigated in [8, 9]. Two different base material properties (i.e.: Aluminium and Steel) has been used as an input in their finite element analyses. In addition, the mechanical properties of this novel material have been investigated. Öchsner et al. conducted an investigation on the stiffness of basic PHSS [10], while Ferrano et al. worked on the large deformation behaviour of perforated hollow sphere structures [11]. Moreover, the initial yield surface was determined in [12] based on multi-axial stress states for perforated hollow sphere structures. The present numerical models can be grouped as syntactic perforated hollow sphere structures. Syntactic foams is a type of cellular material that was combined in a metal or composite matrix. All the above investigations on mechanical and thermal properties share a common characteristic of the spheres that connected by a neck region 'point contact'. Young's modulus and Poisson's ratio of syntactic PHSS were first addressed in [13]. In a recent study, syntactic configurations of PHSS under thermal load were investigated where the dominant influence of the matrix on the macroscopic conductivity was observed. This work is based on the previous work done on PHSS but investigates further both initial and 0.2% offset yield stresses of syntactic PHSS where the spheres completely embedded in an epoxy matrix.

Figure 1 Photograph of the perforated hollow sphere structures production. (Photo from the courtesy of Glatt GmbH, Dresden, Germany)

2.0 PERFORATED HOLLOW SPHERE STRUCTURE (PHSS)

Perforated hollow sphere structures are a special case of hollow sphere structures were interconnected structures are formed by connecting hollow spherical elements. In classic hollow sphere structures spheres are closed meaning the contained spherical pore is not accesible. In the case of perforated hollow sphere structures, the spherical shell is partially opened allowing access ot the interior space. In this work, holes are positioned in such a way that the largest possible perforation hole can be located between the linking elements in a primitive cubic arrangement. By following the same procedure introduced in literatures [13, 14], the spheres are arranged in a primitive cubic pattern and a unit cell is investigated under consideration of symmetry planes. In addition, two configurations are investigated where either the spheres are seperated and scattered in the matrix or where the spheres have first undergone a sintering process (thus, forming an interconnected network between the spheres). These two configurations are shown schematically in Figure 2.

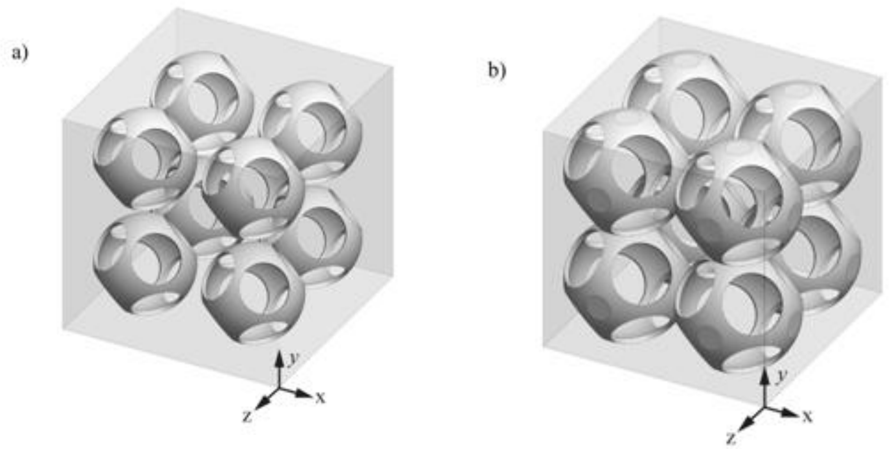

Figure 2 Schematic illustration of primitive cubic sphere arrangement of PHSS: a) arrangement with a bond gap syntactic PHSS; b) sintered syntactic PHSS

Referring to Figure 2, one can see that the solid volume consists of the perforated hollow sphere shells with (index 'sp') and the bond material (index 'ma'). V_{sp} and V_{ma} stand for the sphere's volume and the volume of the matrix respectively. The total volume of a unit cell (V_{uc}) can be calculated by:

$$V_{\mathrm{uc}} = V_{\mathrm{sp}} + V_{\mathrm{ma}} \qquad (1)$$

Accordingly, the average density (ρ_{avg}) of perforated hollow sphere structure can be calculated by using:

$$\rho_{\mathrm{avg}} = \frac{V_{\mathrm{sp}}}{V_{\mathrm{uc}}} \cdot \rho_{\mathrm{sp}} + \frac{V_{\mathrm{ma}}}{V_{\mathrm{uc}}} \cdot \rho_{\mathrm{ma}} = \frac{V_{sp}}{V_{uc}} \left(\rho_{sp} - \rho_{ma}\right) + \rho_{ma} \qquad (2)$$

where ρ_{sp} is the density of metallic sphere shell and ρ_{ma} is the density of matrix.

3.0 FINITE ELEMENT ANALYSIS

The accuracy of numerical study of cellular structures often suffers from the simplification of real structure that is quite inhomogeneous or stochastic. Although the numerical model can be generated based on micro computed tomography scans, such approach does not allow for quick predictions of macroscopic properties of a new structures and are still computationally expensive. An alternative approach which based on periodic structures are commonly taken from space groups in crystallography, i.e. primitive cubic (PC), face-centered cubic (FCC), body-centered cubic (BCC) or hexagonal (HEX) [15]. By taking the so-called unit cell approach, the size of this system can be significantly reduced from a larger or infinite amount of periodically arranged spheres to a single unit-cell. A unit cell then might be further reduced if symmetry boundary conditions can be applied [7, 16]. This work considers primitive cubic arrangement, which is the simplest case and can serve a first estimate for the elastic-plastic properties.

This investigation used the commercial finite element package MSC.Marc® (MSC Software Corporation, Santa Ana, CA, USA). The results were extracted by a respective subroutine in order to calculate the initial yield stress and 0.2% offset yield stress. In the scope of this work, the 0.2% offset yield stress is defined as 0.2 % the compressive stress at the plastic compressive strain of 0.2 %. This is to follow the international standard (ISO 13314) for metallic compression test for porous and cellular materials [17]. Preliminary investigations on the meshed model were performed and it was found that the used meshes are in the converged region. The entire models composed of metallic sphere and matrix consist of 6277 to 11688 nodes for both configurations with the largest perforation hole radius equal to 0.68 mm. Subsequent models were generated as shown in Figure 4 where the size of the hole opening was reduced to 75%, 50%, 25% and 0% (i.e. the sphere shell without perforation as limiting case for comparison) of the maximum radius.

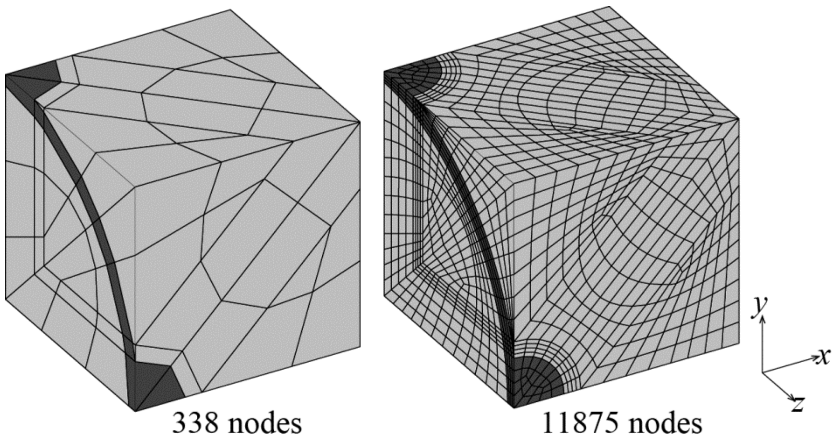

Figure 3 On left is the 1/8th of a unit cell in primitive cubic (PC) arrangement with a fewer number of nodes and on the right is the selected meshed model after refinement.

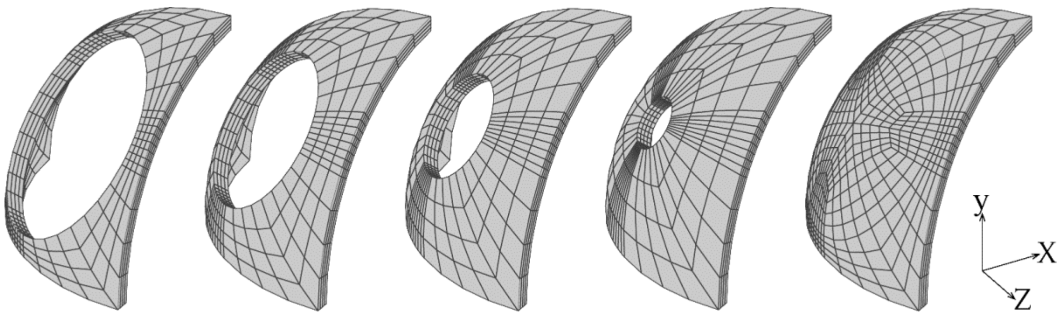

Figure 4 Metallic sphere shell with the variation of the perforation size.

The finite element models of syntactic perforated hollow sphere structure consist of two basic arrangements, where a perforated hole sphere structure (PHSS) is mixed with a matrix (i.e. epoxy resin), in the manufacturing process. For the first configuration, the spheres that are not directly contacting each other are arranged in a primitive cubic pattern where a minimum distance (matrix gap) of length 2*a* between the adjacent spheres occurs (due to symmetry, the length shown in Figure 5(a) is equal to 1*a*. Furthermore, this first configuration was adjusted by increasing this distance by a factor two. Hence, a similar arrangement was used, where the matrix gap now was increased to 2*a*. The second possible configuration consists of directly connected spheres due to sintering process, where flattened contact areas between the spheres will be created (see Figure 5b).

Due to the symmetry of the applied load and the geometry, reflective boundary conditions were applied at three perpendicular surfaces, i.e. along the symmetry planes of the singles sphere. The influence of neighbouring cells in PC pattern is considered by the so-called repetitive boundary conditions. Reflective boundary condition can be explained as every node located on the described surfaces is constrained not to move in the direction of the surfaces' normal vector and repetitive boundary condition means that every node located on a connected surface must experience the same displacement perpendicular to the surface [10]. The geometric dimensions used in Figures 5 and 6 are summarised in Table 1, while the material properties selected in this work are listed in Table 2.

Table 1. The considered geometric dimensions

Dimension	Value [mm]
r_i	1.25
r_l	1.35
r_o	1.47
d_l	1.36
b_s	0.30
t	0.10
a	0.12

Table 2. Base materials considered for the spheres and the matrix phase [12, 18]

Material	Young's modulus (GPa)	Initial yield stress (MPa)	Poisson's ratio (-)	Density (kg/m^3)
Steel (316 L)	136.00	300	0.30	6950
Epoxy	2.46	113	0.36	1130

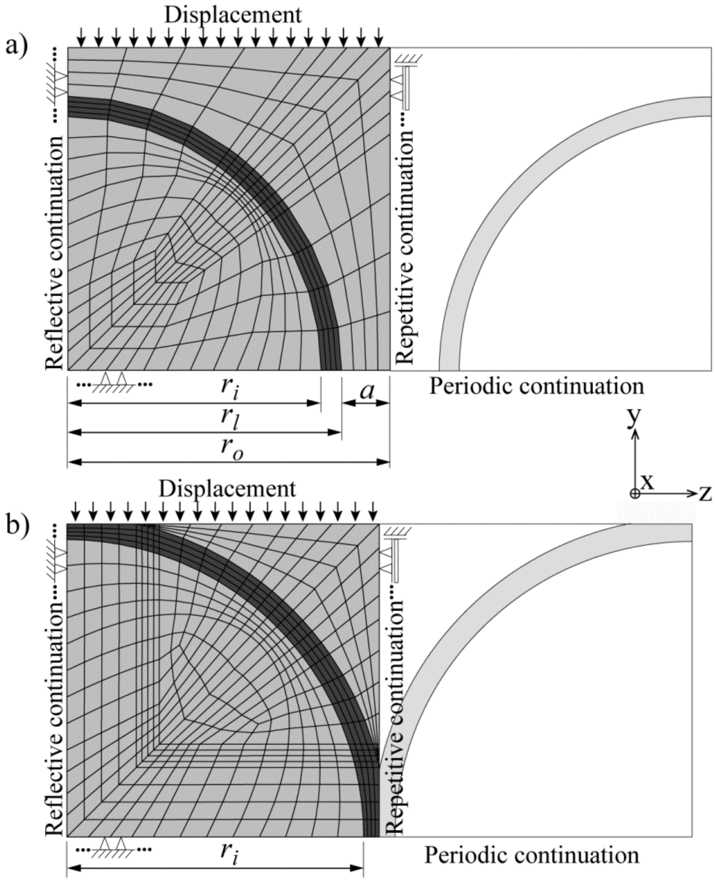

Figure 5- Finite element meshes and applied boundary conditions of a syntactic perforated primitive cubic unit cell: a) bonded arrangement; b) sintered arrangement

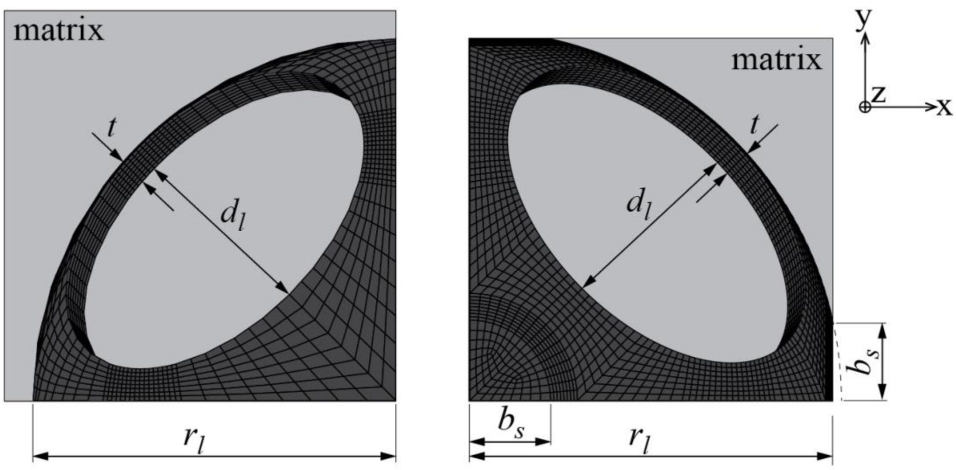

Figure 6 On the left is the finite element mesh of a PHSS with arrangement completely immersed in the matrix and on the right is the sintered arrangement.

4.0 RESULTS AND DISCUSSION

In the following, the results of the finite element analyses are presented. Figure 7 summarises the macroscopic initial yield stress for syntactic perforated hollow sphere structures for both bonded and sintered configurations. The arrangement with the biggest distance of the matrix exhibits the lowest average density among the other arrangements due to the density of the matrix itself that occupied the unit cell. In contrast, the sintered configurations of primitive cubic unit cell shows the highest average density since there are more metallic sphere shell in a unit cell. It also can be deduced from Figure 7 that sintered arrangement of PHSS has a higher initial yield stress. The network of metallic spheres for sintered arrangement clearly helps in having a stiffer structure as compared to syntactic arrangement for models with the same perforation size. In Figure 8, the diagram summarises 0.2% offset yield stress plotted against the average density. The result from the numerical simulation reveals a continuous curves of 0.2% offset yield stress among all configurations. Closed form expression for the fitting function y is given in terms of variable x which is equal to 10^{-3}·average density.

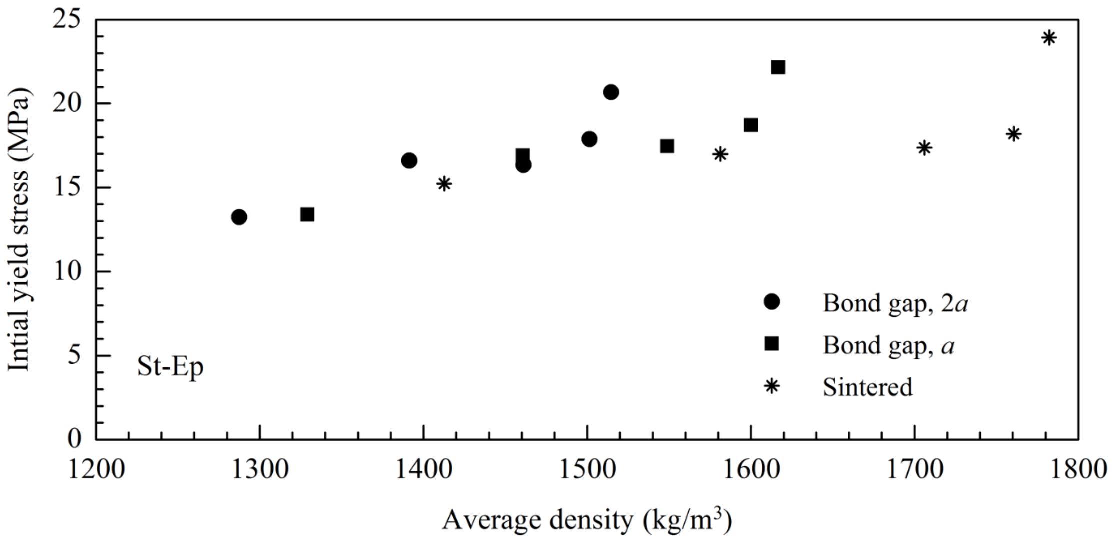

Figure 7 Initial yield stress versus average density using steel (316 L) as the material of the shell embedded in epoxy matrix (a = 0.12 mm)

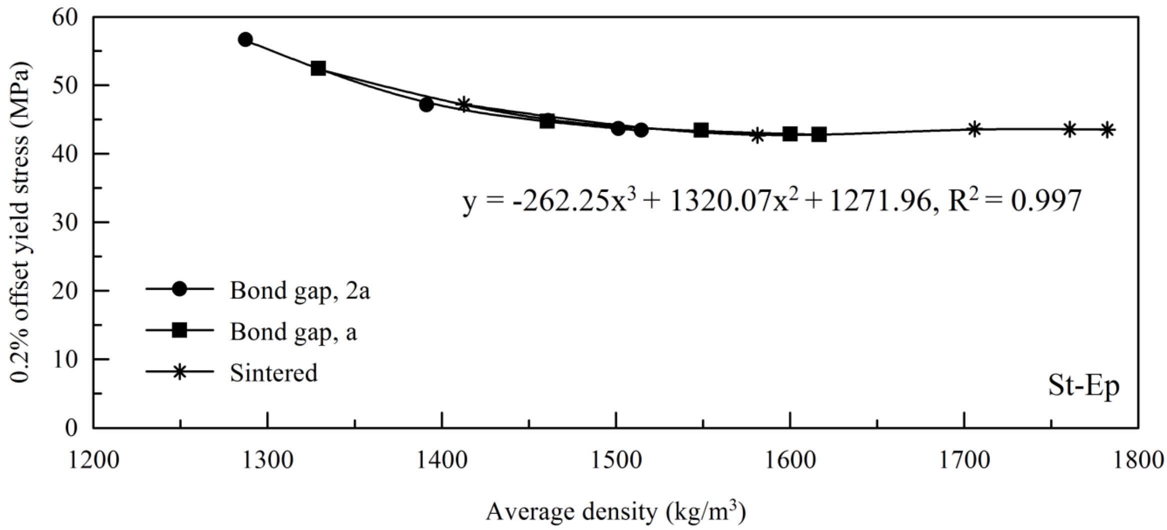

Figure 8 0.2% offset yield stress versus average density using steel (316 L) as the material of the shell embedded in epoxy matrix (*a* = 0.12 mm)

5.0 CONCLUSIONS

The elastic-plastic properties of syntactic perforated hollow sphere structure have been numerically simulated and analysed. In the scope of this work, the numerical model is based on primitive cubic unit cell arrangement. Result shows that sintered arrangement of PHSS has a higher initial yield stress compared to the arrangement with bond gap. This is attributed to a stronger structure of interconnected sphere morphology in the sintered structure. For the 0.2% offset yield stress, a continuous cubic curve was found as the unit cell contains more metallic material from bond gap as compared to the sintered arrangement.

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