Numerical analysis of metallic hollow sphere structures

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Summary:

The paper presents a computational study of adhesively bonded metallic hollow sphere structures fully embedded within an adhesive matrix. Their behaviour under compressive dynamic loading was evaluated by means of dynamic computational simulations, where the influence of topology (simple cubic, body centred cubic and face centred cubic arrangement) and gaseous pore filler was studied. The behaviour of analyzed structures was evaluated with use of the representative volume element accounting for the strain rate sensitivity. The computational results show a characteristic porous material response. The initial linear-elastic response is followed by a short transition zone, then followed by a stress plateau. At high strains, the inner surfaces of the spherical shell touch and the stress level increases rapidly. The topology considerably influences the deformation mechanism of the hollow sphere structures, where the simple cubic structure orientation exhibits the highest stiffness. From the computational results it can be observed that the influence of the internal pore pressure is negligible through the deformation of the metallic hollow sphere structures.

Keywords:

Metallic hollow sphere structures, Numerical analysis, Topology, Gaseous pore filler.

1 Introduction

The metallic hollow sphere structures combine the well-known advantages of cellular metals in terms of their high capacity of energy absorption, good damping behaviour, excellent heat insulation and high specific stiffness without major scattering of their material parameters [1, 2]. The combination of these properties is of interest in a wide field of potential applications, e.g. in automotive and aerospace industry [3].

A powder metallurgy based manufacturing process enables economic production of metallic hollow spheres of defined geometry, where the hollow spheres can be manufactured from every metal suitable for sintering, such as steel, aluminium or copper [2]. Different joining technologies such as sintering, soldering and adhering can be applied to assemble hollow spheres to interdependent structures [1]. Adhering provides the most economic way of joining and allows for further cost reduction and therefore the expansion of potential applications. Adhesively bonded MHSS can be applied as fillers for steel pipes, such as A-pillars or front side members in cars [4]. The results of preliminary experimental testing underline the high potential of this innovative lightweight material.

Initial investigations of MHSS were aimed at determining the quasi static properties of these advanced composites at small strains which are primarily required for structural applications [5-8]. A comprehensive experimental study of the impact behaviour of metallic cellular materials is given in [9]. Further analyses of epoxy syntactic foams with spherical inclusions confirm the necessity of accounting for the strain rate sensitivity of porous metals under impact conditions [10, 11].

The purpose of this research is to describe the behaviour of syntactic metallic hollow sphere structures subjected to dynamic loading. The response of hollow sphere structures considering three different arrangements (topologies) has been evaluated using the finite element code LS-DYNA and accounting for the material strain rate sensitivity. Additionally, the influence of the initial pore pressure on the global behaviour of metallic hollow sphere structures has been studied.

2 Computational model

In general, cellular structures exhibit a random topology. However, the MHSS have a certain degree of regular topology, as shown in Fig. 1. Analysis of the pseudo-random MHSS topology shows that a cubic symmetric arrangement of the hollow spheres can be presumed in order to decrease the model size.

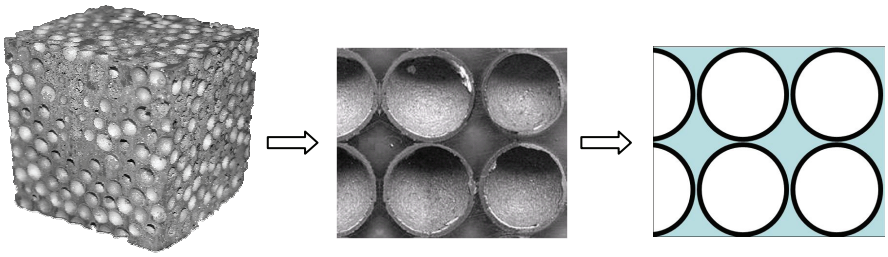
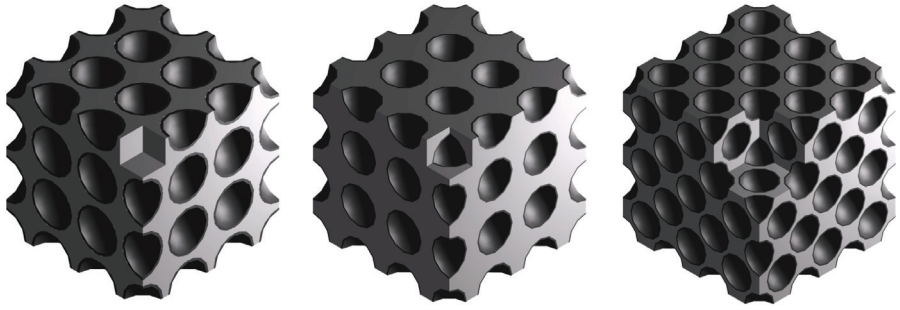


Fig. 1: Quasi-regular topology of hollow sphere structures

In this study three different cubic symmetries of hollow sphere structures are considered: (a) simple cubic, (b) body centred cubic and (c) face centred cubic arrangement (Fig. 2).



a) b) c)

Fig. 2: Topologies of MHSS: a) simple cubic; b) body centred cubic; c) face centred cubic

The characteristic dimensions of the metallic hollow sphere structures were determined from measurements of experimental samples. For the chosen syntactic geometry, the outer radius *R* of the spheres is equal to 1.0 mm and the minimum distance between two neighbouring spheres is a_{min} = 0.36 mm. The thickness *t* of the metallic shells was set to 0.05 mm.

Constitutive behaviour was described with an elastic-plastic material model with the von Mises yield condition. The material properties are listed in Table 1 [12].

Table 1: Material properties of the sintered steel spheres and epoxy resin L1100

	Young's modulus	Poisson's ratio	Yield stress	Density	Cowper-Symonds parameters	
	E	ν	σ_y	ρ	*C*	*p*
	MPa	-	MPa	g/dm^3	s^{-1}	-
Sintered steel	115000	0.3	255	6.95	40.4	5
Epoxy resin	2460	0.36	113	1.13	1050	3.7

Because the complete detailed modelling of cellular materials is usually not possible due to insufficient computer capabilities, the cellular materials are often modelled by considering a "representative volume element", which serves for detailed studies of mechanical behaviour of a minimum number of unit cells and its mathematical characterization [12, 13]. In this study the considered topologies allow the use of only one eighth of a unite cell with proper boundary conditions, significantly reducing the number of unknowns and the required computing time.

Reflective symmetry boundary conditions (Fig. 3) were defined along the symmetry planes to simulate the behaviour of the whole unit cell. The periodic boundary conditions (repetitive boundary conditions, Fig. 3) presume that the considered unit cell is positioned in the middle of a regular hollow sphere structure, where boundary effects are negligible [13].

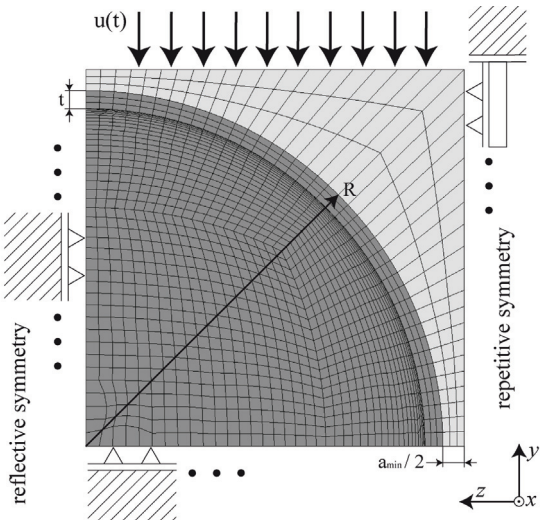


Fig. 3: Boundary conditions of the finite element models

Hexahedron fully integrated finite elements with quadratic shape functions were used in the discretisation of the models. The sphere surface elements were defined as one contact group to account for self-contact at very large deformations. The coefficient of friction was set to 0.1. The displacement controlled loading, corresponding to desired strain rate (up to $\dot{\varepsilon}$ = 1000 s^{-1}), was applied to the upper surface of the unit cell model.

The behaviour of metallic hollow sphere structures under uniaxial dynamic loading conditions was analysed by using the explicit finite element code MPP LS-DYNA [14, 15]. Adequate element types, mesh densities, and time step sizes have been determined by initial parametric analyses to establish sufficiently accurate computational results insensitive to space and time discretisation.

3 Computational results

The deformation mechanism of the metallic hollow sphere structure with simple cubic sphere arrangement subjected to uniaxial dynamic loading is shown in Fig. 4.

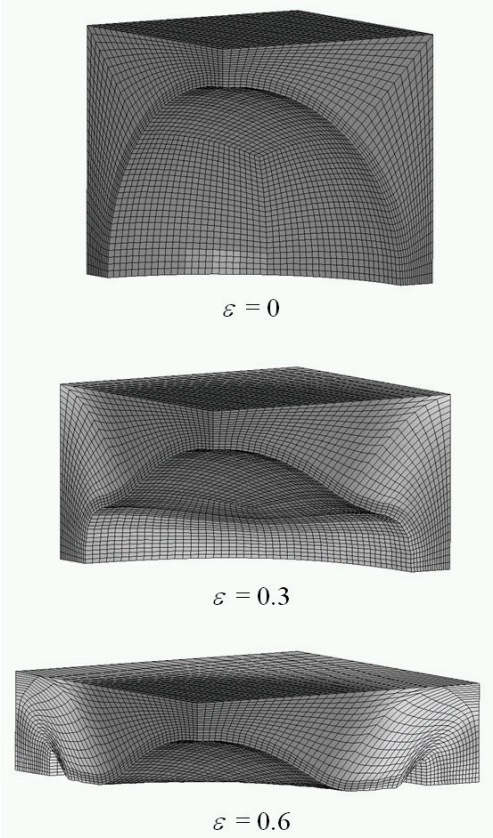


Fig. 4: Deformation mechanism of the metallic hollow sphere structure with simple cubic topology

Further computational results are shown in stress – strain diagrams. The macroscopic engineering stress of metallic hollow sphere structure unit cells in the loading direction is derived as a sum of reaction forces divided by the initial unit cell cross-section .The macroscopic engineering strain is calculated as displacement in the loading direction divided by the initial unit cell length.

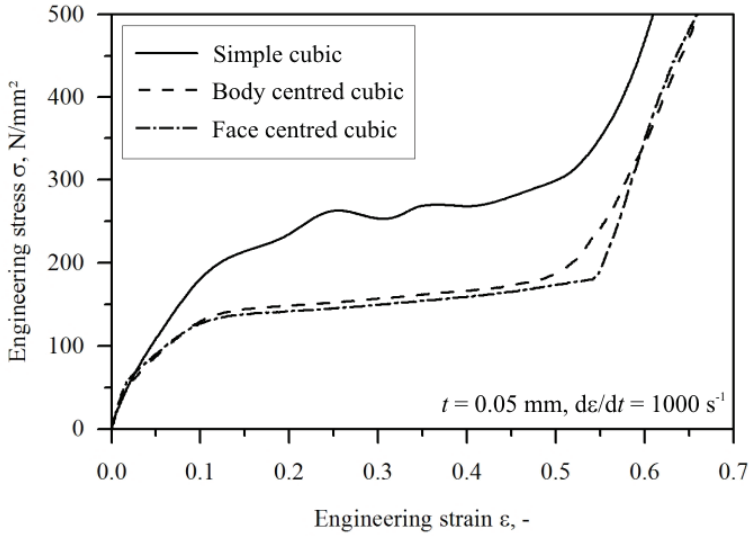


Fig. 5: Influence of the topologies on the macroscopic behaviour

Figure 5 shows the comparison of the stress-strain relations of metallic hollow sphere structures for the three different topologies. The initial linear-elastic behaviour is followed by the transition zone, then by the stress plateau, where the stress oscillations due to sphere walls buckling can be observed. When the inner surfaces of the spherical shell touch, the densification process starts and the stress rapidly increases. As expected, the simple cubic structure exhibits the highest stiffness due to the lowest porosity (porosity is defined as the ratio between the spherical void volume and full unit cell volume). In comparison, the porosity of the body centred cubic structure and face centred cubic structure is 1.31 and 1.43 times higher, respectively, which consequently results in smaller structural stiffness during the deformation process.

The influence of the initial pore pressure, caused by the gas trapped inside the hollow sphere structures is illustrated in Fig. 6. It is expected that during the deformation of the hollows spheres containing gases the internal pore pressure changes and consequently influencing the macroscopic behaviour of the metallic hollow sphere structure [13, 16]. However, as shown in figure, the influence of the internal pore pressure is negligible through the deformation. Furthermore, it must be considered that the hollow spheres exhibit certain porosity. Therefore, a high initial pore pressure cannot be expected.

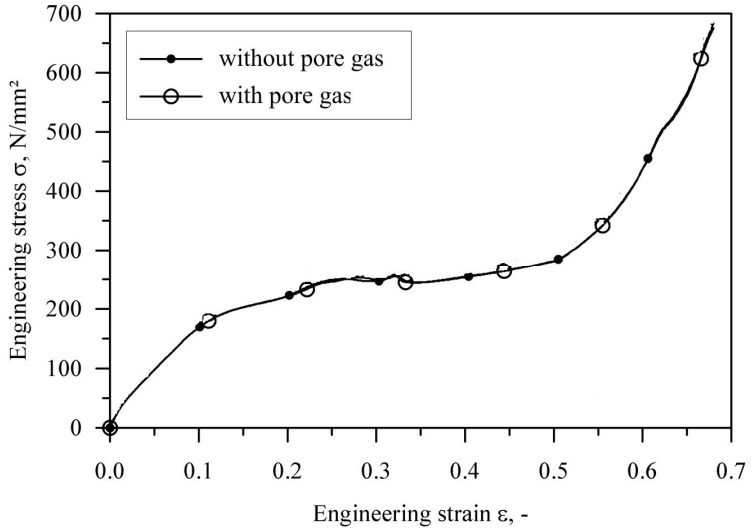


Fig. 6: Influence of the internal pore pressure on the macroscopic behaviour

4 Conclusions

The paper presents a computational study of adhesively bonded metallic hollow sphere structures fully embedded within an adhesive matrix. Their behaviour under compressive dynamic loading was evaluated by means of dynamic computational simulations, where the influence of topology (simple cubic, body centred cubic and face centred cubic arrangement) and gaseous pore filler was studied. The macroscopic stress-strain behaviour of the metallic hollow sphere structures exhibits typical porous material characteristics. The initial linear-elastic response is followed by a short transition zone, then followed by a stress plateau. At high strains, the inner surfaces of the spherical shell touch and the stress level increases rapidly. The computational simulations topology considerably influences the deformation mechanism, where the simple cubic structure orientation exhibits the highest stiffness due to its low porosity. Additionally the computational results have shown that the influence of the internal pore pressure is negligible through the deformation.

5 Literature

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