Structural Health Monitoring in Lightweight Structures

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Abstract

In recent years guided ultrasonic waves have become increasingly popular in the non-destructive testing community. Excited and received using piezoelectric transducers they offer the advantage of a possible on-line monitoring during service life. It is a fast developing technology due to its sensitivity to small structural damages, its long range inspection capabilities and the low costs of the required equipment. Therefore, guided wave based structural health monitoring is an interesting methodology for several industries including civil engineering, aerospace engineering and wind energy.

In the present study we focus on lightweight materials such as sandwich panels with a cellular core layer. In order to successfully apply guided waves for damage detection purposes the interaction of the wave field with the micro- and macrostructure has to be fully understood. Therefore, parametric studies are conducted deploying the finite element method.

Another important aspect why numerical simulations are used is to reduce the experimental measurements that are both time-consuming and costly. In engineering the finite element method is the numerical tool of choice for wave propagation analysis in the time domain. Since a fine spatial as well as temporal discretization is needed an important research area is both seen in developing efficient numerical models (higher order finite elements) and in reducing the model size. One possibility would be to use higher order finite element approaches, such as the spectral element method, the p-version of the finite element method or isogeometric analysis, to increase the accuracy of the simulation. However, the present investigation is focused on a different approach. In the work at hand novel non-reflecting boundary conditions are used to reduce the computational domain. Thus, the number of degrees of freedom is significantly reduced. The proposed non-reflecting boundary conditions - based on dashpot elements - can be easily included in commercial software tools. Therefore, it is possible to simulate the wave propagation without writing your own special needs finite element software. Hence, data to study different damage detection and localization methodologies can be created in no time.

Kewords: Structural Health Monitoring, Non-reflecting Boundary Conditions, Lightweight Materials, Finite Element Method, Ultrasonic Guided Waves.

1. Introduction

Due to the increasing application of modern materials such as composites and sandwich panels, the demand for structural health monitoring (SHM) is equally increasing. Therefore, to deal with these heterogeneous materials further developments in on-line monitoring methodologies are needed. Cellular sandwich plates are novel among the group of lightweight materials. Typical examples of different core structures are illustrated Fig. 1. Honeycombs, metallic foam and hollow sphere core layers are depicted.

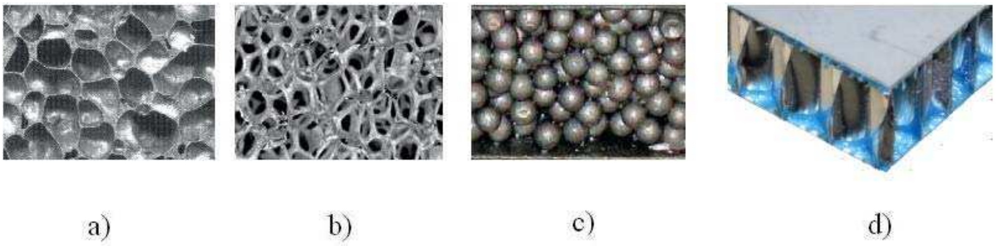

Figure 1: Cellular sandwich plates: a) open-cell foam; b) closed-cell foam; c) hollow spheres; d) honeycomb.

These structures exhibit high porosity and the material is divided into distinct cells. Due to their mechanical and physical properties, a wide range of potential applications in different industries is imaginable for these structures [1]. However, development of structural health monitoring techniques is a vital key to extend their application in different industries. The objective of this work is to investigate the capabilities of guided wave based structural health monitoring systems to detect various types of damages in cellular sandwich panels.

Among different non-destructive methods, the guided wave based structural health monitoring is the most prominent candidate. It is widely mentioned that it has the possibility for a qualitative inspection and can be used for an online structural health monitoring. Moreover, the low costs of the required equipment [2] is a highly beneficial point to be taken into account. However, despite several years of scientific research and its undeniable potential, only few industrial applications of SHM technologies can be found. One of the essential limiting factors for its utilization is the fact that the inspection of complex thick geometries, e.g. Cellular sandwich plates. is very demanding [2, 3]. This point is the main objective for the present study. Guided wave-based structural health monitoring in cellular structures is of steadily growing research interest and has been addressed in several studies [2, 4, 5, 6].

Different numerical and analytical approaches are used to investigate Lamb wave behavior in isotropic elastic structures using the actuator/sensor coupled system [7, 8, 9]. However, the propagation of guided waves in heterogeneous structures is much more complex and the analysis becomes quite difficult using analytical approaches. Therefore, numerical approaches are the only viable way to analysis the interaction of guided waves with non-homogenous composite structures such as cellular sandwich plates [8, 10]. The finite element method is known to be a versatile and efficient numerical tool for a vast variety of structural problems with complicated geometries [11, 12]. Among the classical numerical methods such as the boundary element method, the finite difference method and the finite volume method FEM offers several advantages and is widely used in engineering practice.

2. Finite Element Method Modeling

The decomposition of a domain with a complicated geometry into geometrically simple sub-domains, such that the governing differential equation can be solved approximately for these sub-domains is the basic idea of the finite element method. The complete system of equations with the appropriate boundary conditions can be obtained by assembling the single element contributions. Appropriate balance equations at the nodes which can then be used to define the elements and serve also as connection points between the elements are used for the assembly process. The governing differential equations will be transformed to the principal finite element method equations that is used to model wave motion [7, 8].

However, using the finite element method to model guided wave propagation in cellular sandwich plates requires enormous computational costs [13], as a very fine spatial as well as temporal discretization is needed to achieve reasonable results. To reduce the computational costs a novel non-reflecting boundary condition has been proposed in [14]. The model size can be reduced to smaller models which represent and capture the main features of the micro- and macro-structure of the propagating medium by using the proposed boundary, cf. Fig 2.

To reduce the computational costs further, geometrically simplified structures are used in some of the recent investigations [4, 26]. In this type of analysis, instead of a cellular mid-core, an orthotropic layer with homogenized properties approximated is deployed. This approach reaches to its limitations when computing guided waves with wavelengths smaller than the characteristic length scale of the cellular structure. One can explain the limitations of the homogenization based simplification by the fact that the wave interacts with the microstructure, in case the loading frequency is high enough and therefore, the wavelength of the propagating guided waves is in the range of the characteristic length scale of the cellular structure. But, the interaction of the guided waves with the cellular microstructure cannot be simulated using the simplified model with a compact homogenous core layer. One might still suggest the homogenization based simplification to simulate the guided wave propagation in heterogeneous composite structures with a random material distribution, such as particle reinforced composites. The guided wave propagation in particle reinforced composite plates has been studied and is compared to a homogenized RVE based simplified model in [7]. A good agreement (with an average of 5 % difference) between the guided wave propagation properties in the real structural model and the simplified model has been observed.

Therefore, a new kind of simplification approach based on geometrical parametric studies is suggested. In this new kind, instead of using material homogenization the main aim is to simplify the structural geometry. The proposed method has been used to simplify different cellular structures. The results of ultrasonic guided wave propagation are compared with the complex geometrical models.

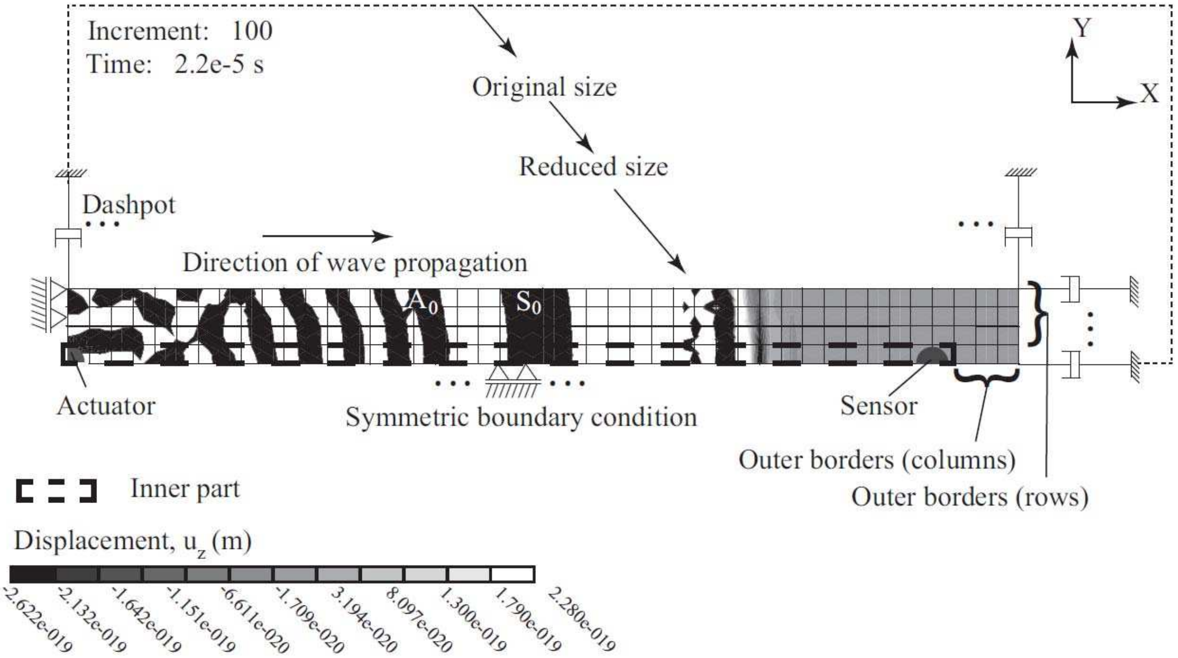

Figure 2: Reducing model size using non-reflecting boundary condition based on dashpot elements [14].

The approach is based on a fundamental knowledge of guided wave behavior in cellular sandwich panels which are investigated in parametric studies [5, 6, 15]. In addition, the gained knowledge is essential to design efficient structural health monitoring systems, i.e. choosing the appropriate loading signal for structural health monitoring applications as well as the determination of possible damages which can be detected by the propagating waves, depending on the wavelength, during the signal processing level [4].

In the parameter based simplifications, the main aim is to simplify the structural geometry. The guided wave propagation in a complicated cellular structure can be characterized based on structural geometrical properties. Alternatively, one can suggest a simplified structure with similar geometrical properties, in which the waves propagates in a similar way in comparison to the real structure. Summarizing the parametric studies in [5, 6, 15] one can realize that the relative density has the most effective impact on the wave propagation in a cellular structure. Similar results have been reported for particle reinforced structures in [6]. The second important factor to influence guided waves in cellular structures is the characteristic length scale (the core size).

Simplified models are suggested for different sandwich plates with cellular core layers including honeycomb, hollow sphere, open-cell and closed-cell foam structures. The relative difference (%) between the wave propagation properties in numerical and experimental results has been calculated as the central frequency of the loading signal changes (logarithmic values are used to compare the energy transmission results). No trend (neither increasing nor decreasing) in changes of the relative difference dependent on the increasing of central frequency of loading signal has been observed. Therefore, the arithmetic mean and absolute maximum for the relative difference values are used to indicate similarity of results obtained from simplified and fully resolved models. The wave propagation properties, including the group velocity, the wavelength and the energy transmission are compared in the simplified and detailed models and a good agreement has been observed (with an average difference of less than 6.60 % and total average of 4.81 %). In addition, the wave propagation properties in hollow sphere sandwich plates obtained from an experimental test are compared with a simplified model and again a good agreement has been observed (with an average difference of less than 7.25 % and total average of 6.48 %).

Within this section a new geometrical simplification approach based on parametric study is suggested. In this approach the main aim is to introduce a simplified model with a similar characteristic length scale as the cellular structure which causes interactions of the guided waves with microstructure of the simplified model in a similar way as encountered in the real cellular structure. Therefore, the results of the parametric studies are used in which the guided wave propagation phenomena is characterized based on geometrical properties of the cellular structures. Finally, it must be mentioned that in order to judge the proposed simplification for real stochastic and cellular structures more experimental data of the guided wave propagation in real cellular structures is required. Then more parametric studies concerning the geometrical properties can be conducted in the future to highlight the feasibility of the proposed simplification approach.

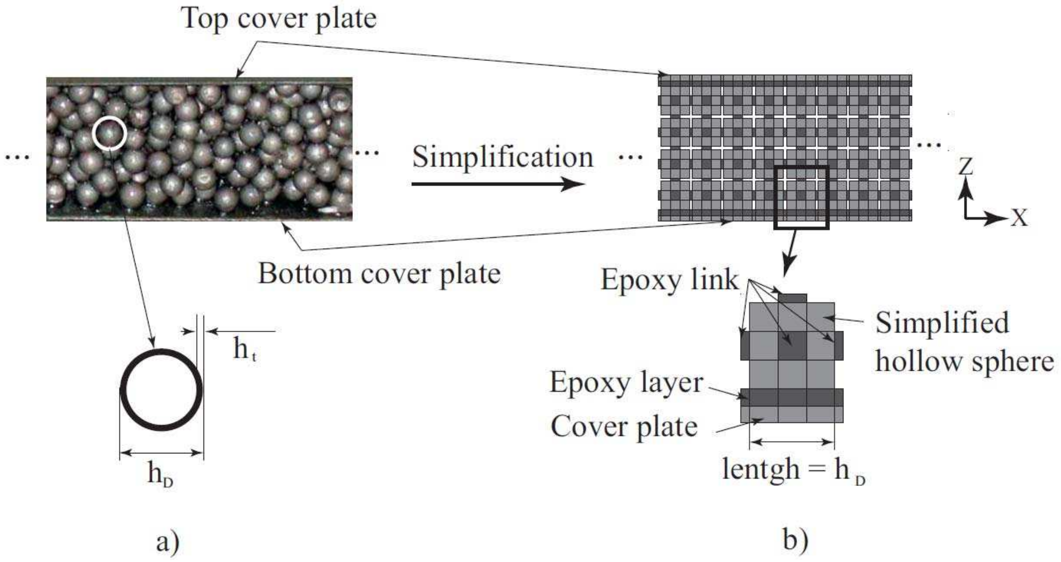

Figure 3: Simplification a Hollow sphere sandwich plate. The cover plate thickness is equal to 0.60 mm, the average hollow sphere wall thickness is equal to 0.15 mm and the average hollow sphere outer diameter is equal to 3.00 mm.

3. Structural Health Monitoring

Guided waves propagate with different modes in the structure. Each mode can be either symmetric (S mode) or anti-symmetric (A mode). These modes can be converted to each other facing damages in the structure. This mode conversion can be used for damage detection. In the following an application of the proposed simplification approach for structural health monitoring in a metallic hollow sphere structure is presented.

In the first step an appropriate frequency range for structural health monitoring is estimated using simplified model. An artificial gap region is introduced in the vicinity of the bottom surface, see Fig. 4, and the wave propagation at the bottom surface of the plate is measured, see Fig. 5. If the connection between the hollow sphere core and the cover plates is disturbed the waves reflect and convert at this position. A complete inspection of the sandwich plate has been provided with a single actuator attached to one side of the sandwich plate.

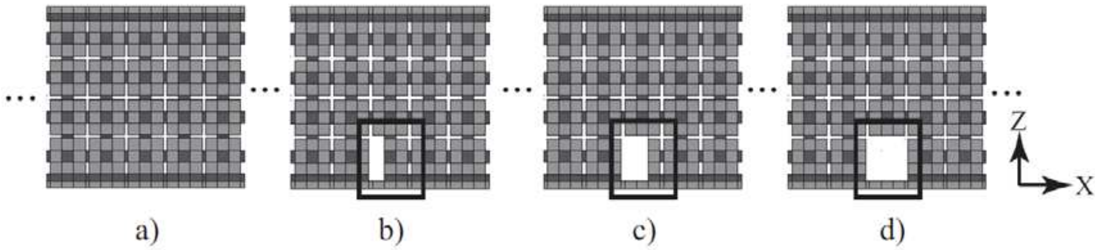

Figure 4: Introducing a gap on the bottom surface of a metallic hollow sphere structure: a) healthy structure; damage structures with gap size of b) 1 mm; c) 2 mm and d) 3 mm.

The wave propagation on the bottom surface of an undamaged numerical simplified metallic hollow sphere structure is shown in Fig. 5 a) and compared with the wave propagation on the bottom surface of damaged ones in Fig. 5 b), c) and d) with gaps in direction of the wave propagation (*x*) with length of 1, 2 and 3 mm, respectively. In the gap region some parts of hollow sphere and epoxy are removed. The maximum gap length of 3 mm corresponds to the removal of a single hollow sphere, gap height (*z* direction) and width (*y* direction) remain constant equal to 3 mm (diameter of a single hollow sphere), see Fig. 4.

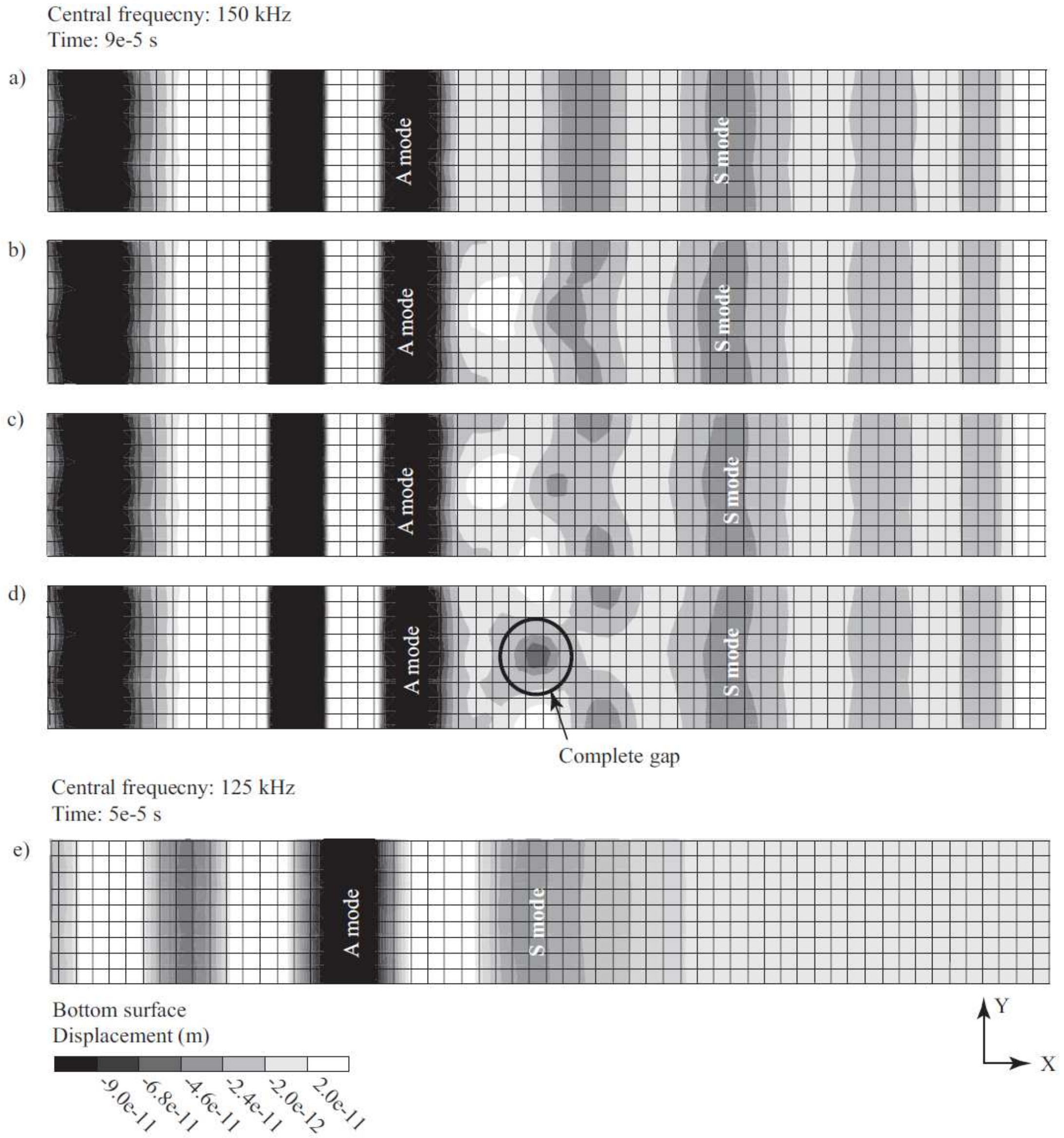

Figure 5: the simulation of guided wave propagation with the central frequency of 150 kHz shown on the bottom surface of a metallic hollow sphere structure using simplified model. The structure is a) undamaged; damaged and gap length is b) 1 mm; c) 2 mm and d) 3 mm, see Fig. 4. In part e) Guided wave propagation with the central frequency of 125 kHz on the bottom surface of damaged metallic hollow sphere structure (with gap length of 3 mm) is shown.

The GWs are excited with a central frequency of 150 kHz, and a wavelength of 3 mm to the bottom surface for the S mode. The best result of damage detection is achieved in Fig. 5 d) as the length of defect region tends to the wavelength of the propagated S Mode on the bottom surface. Furthermore, Fig. 5 e) shows the GW propagation with a central frequency of 125 kHz on the bottom surface of the defected metallic hollow sphere structure (with 3 mm gap). It is indicated that GWs with a lower central frequency and therefore a bigger wavelength, which is 8 mm for the S mode, are not able to locate the gap in the structure effectively.

This estimation is used to conduct experimental investigations. The surface of the hollow sphere structure (1 m × 320 × mm × 20 mm) made of steel is scanned by Laser Vibrometer System. The GWs are generated by a PZT actuator with a central frequency of 150 kHz (as suggested in simulations) to detect damages in size of hollow sphere. Both sides of the plate are scanned to show the capability of the GWs to travel through the plate. Fig. 6 shows there regions (highlighted with white circles) where an arrival S mode converts to A mode (which has a higher out-of-plane displacement). In addition, CT images are used to show the inner structure in region B (where the white color shows metallic parts). A continued black area in several frames shows a gap size of a single hollow sphere in the structure. Similar images are obtained for regions A and C.

As a summery, the simulation (using the proposed simplified model) and the experimental investigations show that the propagated GWs interact with continued debondings 3 mm (approximately equal to wavelength of the propagating S mode with a central frequency of 150 kHz). Weaker interactions are observed for smaller gaps. However, further studies must be conducted to find the minimum debonding size which can be detected using GWs in such a structure.

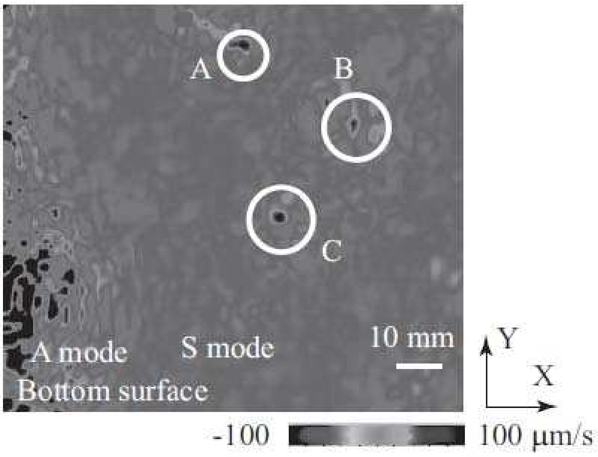

Figure 6: Experimental inspection guided wave propagation with central frequency of 150 kHz on the bottom surface of metallic hollow sphere structure (after 0.09 ms from exaction) using the laser vibrometry.

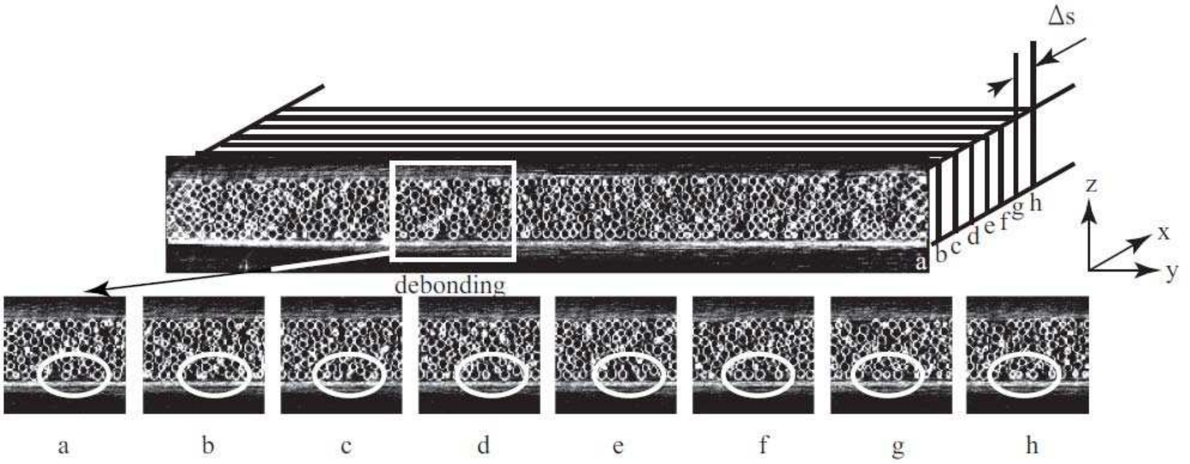

Figure 7: Inner structure of metallic hollow sphere structure (region"B" shown in Fig. 6) presented with CT images, Δs = 0.6 mm.

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