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Defect sensitivity of bulk PCMs composed of octet and Kagome trusses to mechanical behaviors subjected to compression

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Abstract

The Kagome truss has been attracting attention, because it has equivalent or even higher strength compared to the octet truss with the same material and density. In this work, another aspect, which seems to be important for its practical applications, that is, defect sensitivity of bulk PCMs (periodic cellular metals) composed of Kagome trusses to mechanical behaviors subjected to compression was compared with a counterpart composed of octet trusses. In order to investigate the mechanical characteristics of bulk PCMs composed of the two trusses, a hybrid approach was taken in this work. First, assuming perfectly uniform structure and deformation of WBK, the behavior of the bulk PCMs composed of infinite number of trusses was simulated by finite element analysis for a unit cell with periodic boundary conditions. From the results, the force-displacement response of a single strut composing the trusses in each bulk PCM was estimated. Then, the effects of geometric imperfections and the inhomogeneous material properties were evaluated by network analyses, in which the force-displacement responses were used to characterize mechanical behaviors of the networks. The imperfections were modeled to have Gaussian distributions, and the analysis results of the two bulk PCMs were compared to evaluate their defect sensitivities. For the geometric imperfections, the maximum strength of both bulk PCMs decreased gradually as the imperfection level increased. For material property imperfections, the maximum strength maintained nearly unchanged for the PCM composed of Kagome trusses. On the other hand, for that composed of octet trusses, it slightly dropped as the imperfection level increased. The octet truss PCM was found to be more sensitive to the property imperfections than the other.

Keywords: Cellular metal; PCM (Periodic Cellular Metal); Kagome truss; Octet truss; Imperfections; PBC (Periodic Boundary Condition); Network analysis

1. Introduction

Cellular metals are well-known for their high mechanical strength and stiffness with low weight advantage [1]. Because they have a high ratio of surface area to volume, they are used as a medium for heat exchangers or fluid storage as well [1, 2]. The metal foam was the first commercialized cellular metal, whose engineering applications have been, however, limited because of its high cost and relatively low mechanical strength due to the random patterns of its cell structure. On the other hand, a periodic cellular metal (PCM), as the name implies, a structure with uniform cells, enhances mechanical characteristics significantly. The PCM can be classified into three types, prismatic type, shell type, and truss type, according to the shape of the cell. Among them, the truss PCM composing an open cell structure is regarded to be multi-functional. Pyramidal [3, 4], octet [5-8], and Kagome [9] trusses are typical trusses proposed to date. The Kagome truss PCM is known to have equivalent or even higher strength compared to octet truss with the same material and density.

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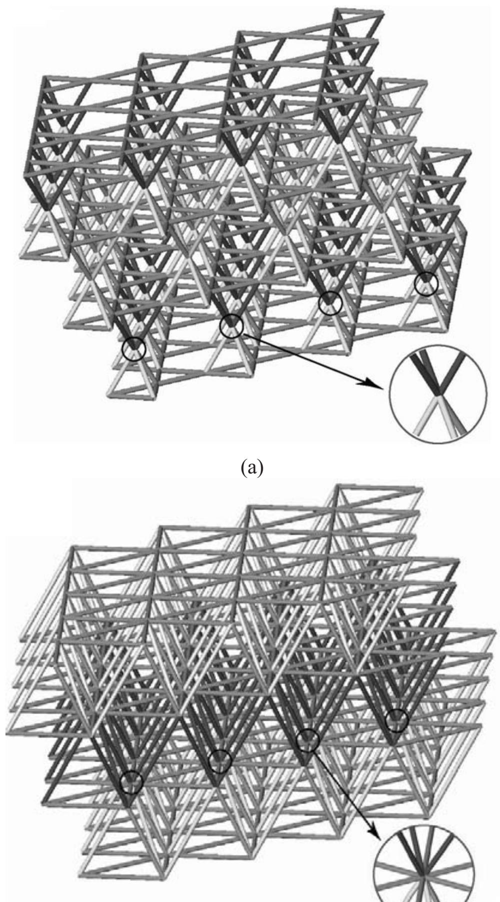
Since the Kagome truss was first introduced in 2003 [9], a few studies have been done on its mechanical performance [10, 11] and potential applications such as actuators [12]. However, no work has ever been reported on its practical fabrication process for mass-production. Recently, Kang and his colleagues [13, 14] have introduced the wire-woven bulk Kagome (hereafter called WBK) fabricated by 3-dimensional assembling of wires, which resembles the Kagome truss. WBK is assembled with helical metallic wires in six directions. The wire assembly is fixed by brazing at all the crossing points. Because WBK is assembled with continuous wires, it is more advantageous to fabricate and utilize in the form of a bulk material with multi-layered trusses. The mechanical behavior of this bulk PCM consisting of many fine cells is difficult to estimate by elementary structural mechanics because of the waviness of the wires and the brazed joints. Therefore, a numerical simulation technique such as the finite element method can be used. However, since a bulk WBK structure consists of many cells, it is time-consuming and tedious, or sometimes physically impossible, to apply a numerical technique such as a finite element method to the whole system.

Recently, works by Hyun et al. [15, 16] have shown that a hybrid approach, namely, a network analysis [17, 18] aided by simple finite element analysis on a unit cell is quite effective. To estimate the force-displacement response of a single strut composing the trusses in WBK, finite element analysis on a single unit cell under periodic boundary conditions was performed. Then, the force-displacement response was used to characterize non-linear properties of truss elements in the network analysis, which simulated the effect of imperfections existing in WBK on its mechanical behavior. It was proved that the network analysis gave reasonably good estimation of the stress-strain curve in comparison with the experimental measurement. Two types of feasible defects were considered to create a realistic model of WBK: geometric defects and material defects. The effects of the imperfections on the maximum strength under compression [15] and shear [16] were quantitatively estimated.

Do the results of the imperfection sensitivity study on the mechanical strengths apply only to WBK, a kind of Kagome truss? What about other types of truss structures like an octet truss? In fact, an octet truss consists of struts twice as long as those of a Kagome truss at a given relative density, which likely results in unstable behavior after its peak load. Furthermore, in an octet truss structure, twelve struts meet at a junction, while in a Kagome truss structure, six struts meet at a junction. Figs. 1(a) and 1(b) show the configurations of Kagome and octet truss structures, respectively, with enlarged views around the junctions in the two structures. A larger number of struts joined at a point might result in higher sensitivity to imperfections.

To address these issues, in this work, bulk PCMs (Periodic Cellular Metals) composed of two different types of truss, namely, Kagome and octet trusses with ideal configurations were considered to investigate their defect sensitivity to mechanical behaviors subjected to compression. The hybrid approach of Hyun



(a)

(b)

Fig. 1. Configurations of (a) Kagome and (b) octet truss structures.

et al. [15] was used. Two types of feasible defects were considered to create a realistic model of WBK. One was the geometric defect: the positions of the points joining the truss elements deviated from those of the corresponding ideal truss structure. The other was the material defect caused by various irregularities generated in the brazed joints or truss elements. By defining the two types of defects as mathematical expressions and stochastically distributing them through a network model of WBK, non-homogeneous characteristics of the defects existing in a realistic structure were simulated. Effects of difference in the truss geometry, i.e., Kagome truss versus octet truss, upon their defect sensitivity were evaluated.

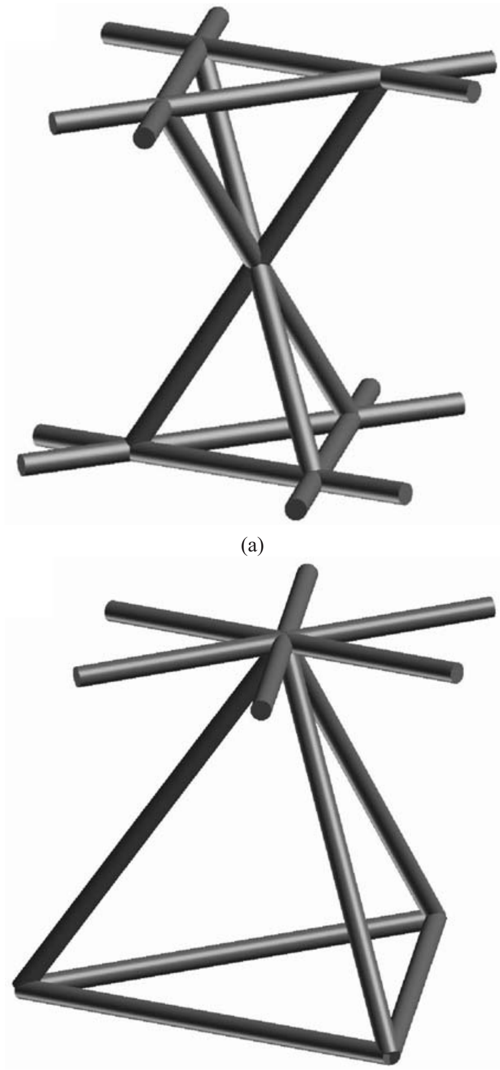
2. Force-displacement response of a single strut

To estimate force-displacement response of a single strut composing Kagome and octet trusses in the two bulk PCMs, finite element analysis on a unit cell under periodic boundary conditions was performed.

2.1 Periodic Boundary Conditions (PBC)

When a structure consisting of many uniform cells like WBK is to be analyzed, numerical analysis for the whole structural system can be severely inefficient or even impossible. An alternative is to use the periodicity of the structure expressed by periodic boundary conditions. Mills [19] successfully simulated large compressive deformations of open-cell foams by applying the 3-dimensional periodic boundary condition to a representative unit cell with multi point constraint (MPC) coded in a commercial software ABAQUS.

In a truss PCM, a constant unit cell is repeated in three-dimensional space to construct a bulk structure. Figs. 2(a) and 2(b) show the configurations of unit cells of Kagome and octet truss structures, respectively. If bulk samples of the two structures are composed of an infinite number of unit cells, the effect of the outer surfaces on the bulk material properties can be ignored and the mechanical behavior can be estimated by analyzing the inner material. Suppose that all the cells in the inner material deform uniformly under the external force acting on the bulk sample. The deformations of the cells should be compatible to each other. Namely, the deformed shape of a unit cell must be matched with that of the neighbors.



(a)

(b)

Fig. 2. Configurations of unit cells of (a) ideal Kagome and (b) octet truss structures.

To apply the periodic boundary condition on the unit cells of the two structures in the finite element analysis, the following scheme was used. Eq. (1) expresses the constraint equations of the unit cells as the periodic boundary conditions.

$$\begin{aligned} u_1\big|_j - u_1\big|_{j'} &= u_1(C_o) \\ u_2\big|_j - u_2\big|_{j'} &= u_2(C_o) \qquad (j, j' = 1,2,...,n) \ , \\ u_3\big|_j - u_3\big|_{j'} &= u_3(C_o) \end{aligned} \tag{1}$$

where u_1, u_2, u_3 and C_o denote the displacements in the x, y and z directions and the reference point, respectively. The subscript, j, denotes the nodes on the upper surface, while j' denotes the corresponding nodes on the lower surface. Every pair of nodes denoted by j and j' is displaced with a constant difference u_i (C_o) (i=1, 2, 3) in the x, y and z directions. This finite element analysis on a unit cell under the periodic boundary condition has been validated by checking the compatibility of the deformation [15].

The unit cells were modeled to be made of SUS 304 stainless steel. The diameter and length of the struts composing a Kagome unit cell were d=0.78mm and a=8.1mm, respectively. The struts composing the octet unit cell have the same diameter, d=0.78mm but twice length a=16.2mm. The unit cells were modeled by using a commercial graphics code, 3-D PATRAN 2005. The finite element analysis was performed by using ABAQUS version 6.5. The cross section of the struts was modeled by quadratic tetrahedron elements (C3D10 element of ABAQUS) to describe the detailed sectional shape. For the unit cell models of Kagome trusses, the number of elements and nodes was 45,529 and 74,424. For the unit cell models of octet trusses, the number of elements and nodes was 40,524 and 66,436, respectively. The material properties of the SUS 304 stainless steel struts were given according to those measured by the tensile test of Lee et al. [20, 21], as shown in Fig. 3. The elastic modulus was E=170 GPa, the yield stress was σ_y=184 MPa, and the Poisson's ratio was assumed to be ν=0.3. The J_2-incremental theory of plasticity was applied.

To apply the periodic boundary condition, a reference node point should be defined at an arbitrary position around each unit cell model. And then a displacement field, u_i (C_0), is applied on the reference point. For example, if a normal load in z-axis is to be applied, the displacement field should be given by u_1 (C_0)=u_2 (C_0)=0, u_3 (C_0)=u. In the actual simulation, a displacement corresponding to 23% compressive strain was applied according to Eq. (1).

2.2 Mechanical behavior of the uniform bulk PCMs and force-displacement response of a single strut

Fig. 4 shows stress-strain curves of the bulk PCMs composed of Kagome and octet trusses simulated by the unit cells under compression, as mentioned above. In the figure, the curve of a Kagome truss, which is expressed by open circles, shows a typical initial yielding, some hardening before a peak point at 2% strain, and then gradual decrease; whereas that of the octet truss, which is marked by blind circles, shows brittle-like behavior, namely, sudden rapid drop without any hardening.

To estimate the realistic force-displacement response of a single strut taking into account non-linear material properties and non-ideal boundary condition, the above results of the finite element analyses on the unit cells of the two truss structures were used. Namely, the load-displacement relations for the unit cell models under the periodic boundary condition, from which the stress-strain curves shown in Fig. 4 were obtained, were used to estimate the force-displacement response of a single strut in each PCM.

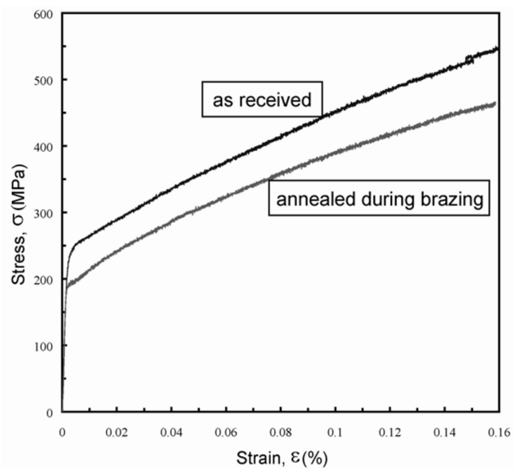


Fig. 3. Stress-strain curves of the as-received and annealed SUS304 during brazing.

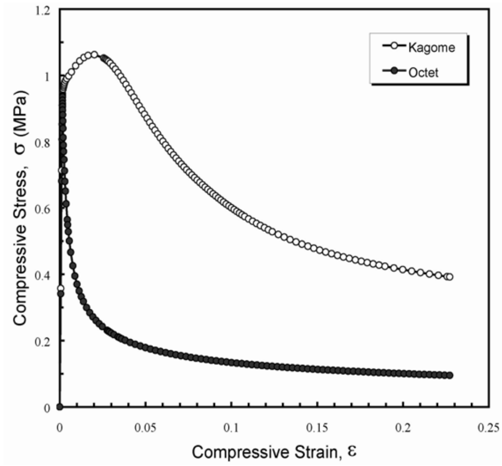


Fig. 4. Stress-strain curves of the bulk PCMs composed of Kagome and octet trusses simulated by the unit cells under compression.

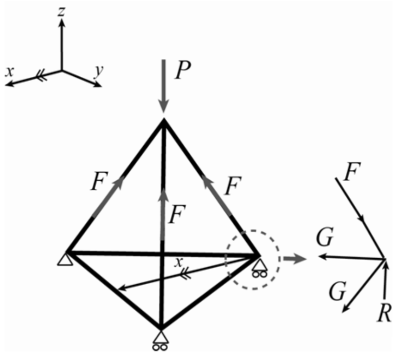


Fig. 5. A ball-jointed regular tetrahedron truss and boundary conditions.

For a ball-jointed regular tetrahedron truss shown Fig. 5, the force equilibrium leads to the relations,

$$F = \frac{P}{\sqrt{6}} \tag{2}$$

and $G = \frac{F}{3}$ among the externally applied compres sive load, P, and the forces subjected to a single strut in the unit cell, F and G. By applying Castigliano's second theorem, the whole displacement occurring in the tetrahedron due to P can be expressed as $\delta_P = \frac{5P}{9k} = \frac{20aP}{9\pi Ed^2}$, where k is the stiffness of the truss element can be expressed as $k = \frac{\pi Ed^2}{4a}$. Meanwhile, the displacement of a single strut can be expressed as $\delta_F = \frac{F}{k} = \frac{4aF}{\pi Ed^2}$. Because $P = \sqrt{6}F$, the two displacements, δ_F and δ_P, can be related to each other by

$$\delta_F = \frac{9\delta_p}{5\sqrt{6}}. \tag{3}$$

For the unit cells of the two trusses in Fig. 2(a), it was assumed that almost the same relations as Eqs. (2) and (3) were valid. (For Kagome truss, δ_P should be doubled because its unit cell has two serially connected tetrahedrons.) Fig. 6 shows the curves of force-displacement of the single struts, F-δ_F, composing the two truss structures. Here, the curve with open circles and that with blind circles represent F-δ_F responses for Kagome and octet trusses, respectively. Due to the linearity of Eqs. (2) and (3), the two curves were the same as the corresponding ones in Fig. 4 in their shapes.

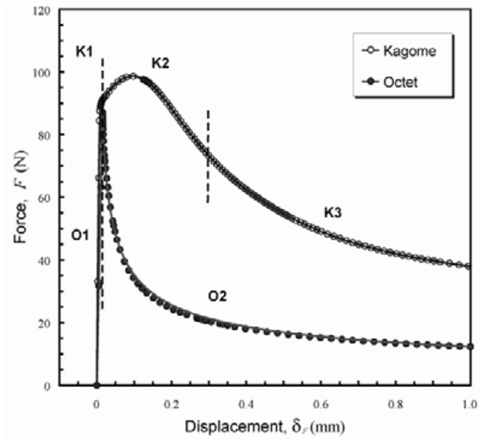


Fig. 6. Force vs. displacement curves for single truss in octet and Kagome lattices.

According to Euler's buckling theory, the elastic buckling load given by $P_{cr} = \pi^3 \frac{Ed^4}{64a^2}$ for the single strut of the octet truss is estimated as P_{cr}=116 N. On the other hand, the load corresponding to initial yielding for the same strut is estimated as P_{yield}=88 N, which is very close to the peak load, 87 N, presented in Fig. 6. Therefore, it can be concluded that the longer struts of the octet truss induced the brittle-like behavior, although the peak load still does not reach to the elastic buckling load.

3. The effect of imperfections

3.1 Random network analysis

To investigate the effect of the imperfections on the strength of bulk PCMs composed of Kagome and octet trusses under quasi-static compression, we used random network analysis for spring and truss systems, which has been applied in various numerical simulations on optimization, vibration, electrical, and thermal analysis [17, 18]. In this study, for random network analysis, we generated a reasonable sized truss system including random defects to achieve good statistics. We performed an analysis on the amorphous network structures under static compression.

For small deformations, the truss is deformed in linear elastic manner. For large deformations, the nonlinear behavior of each strut should be considered in the network simulations. To capture this nonlinearity of the truss networks, each truss was modeled based on the nonlinear response such as elasto-

Table 1. Fitting parameters of force vs. displacement curves for Kagome and octet trusses.

Truss Type	Region 1	Region 2	Region 3
	K1	K2	K3
Kagome	$0 \le \delta_F < 0.0074$ C_1=1.87531$\times 10^{-2}$ C_2=1.20114$\times 10^{4}$ C_3=0 C_4=0	$0.0074 \le \delta_F < 0.3$ C_1=8.67106$\times 10^{1}$ C_2=2.86904$\times 10^{2}$ C_3=-1.96406$\times 10^{3}$ C_4=2.85805$\times 10^{3}$	$0.3 \le \delta_F$ C_5=3.74505$\times 10^{-1}$ C_6=-5.52003$\times 10^{-1}$
	O1	O2	
Octet	$0 \le \delta_F < 0.0151$ C_1=1.90762$\times 10^{-1}$ C_2=5.68960$\times 10^{3}$ C_3=0 C_4=0	$0.0151 \le \delta_F$ C_5=1.21209$\times 10^{-1}$ C_6=-4.66910$\times 10^{-1}$	

plasticity. This nonlinear behavior of a single strut can be numerically obtained by finite element method (as described in Session 2.2). To get the response in a wide range of displacement, we interpolated and extrapolated the curves of force F vs. displacement δ_F shown in Fig. 6 using polynomials (Eq. (4)) and power curves (Eq. (5)) depending on the fitting domains.

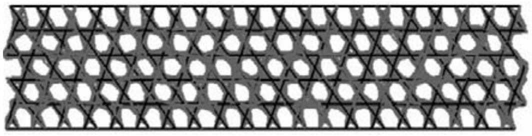
$$F(\delta_F) = C_1 + C_2\delta_F + C_3\delta_F{}^2 + C_4\delta_F{}^3, \quad (4)$$

$$F(\delta_F) = C_5\delta_F{}^{C_6}, \quad (5)$$

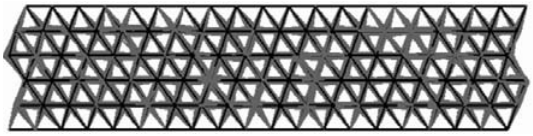
where C_i are the fitting coefficients. The fittings were performed in three separate regions (K1, K2, K3) for Kagome truss and two separated regions (O1, O2) for octet truss, as shown in the figure. The fitted curves can be used to model the nonlinear characteristics of the truss in the network analysis. The fitting parameters for each strut are presented in Table 1.

3.2 The definitions of imperfections: geometric and material property

To simulate the realistic truss models, two types of imperfections such as *geometric* imperfections and *material property* imperfections were considered in the present work as in the previous studies [15, 16]. Geometric imperfections refer to morphological defects generated by changing the alignment of the node positions from the perfect lattice sites of the octet and Kagome structures. Material imperfections are the property defects possibly induced by the imperfections of joints and truss shapes, and also some inhomogeneous material property of each truss.



(a)



(b)

Fig. 7. Side views of lattice models of (a) Kagome and (b) octet truss PCMs with geometric imperfection ($\Delta_g = 1.0mm$, grey area).

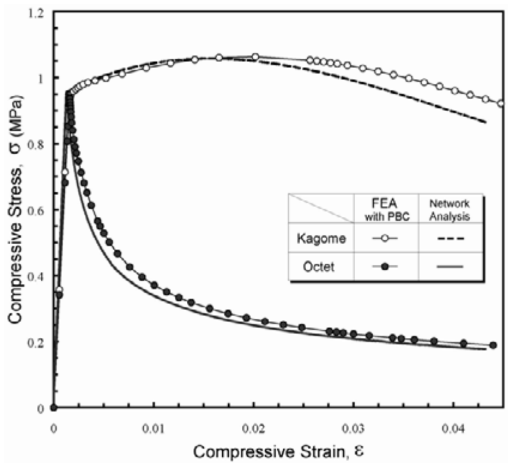


Fig. 8. Stress vs. strain curves estimated by perfect lattice models without any imperfections for Kagome and octet PCMs in comparison with those estimated by FEA for unit cell model under periodic boundary condition.

Fig. 7 shows typical shapes of the perfect lattice models of Kagome and octet truss PCMs for the network analysis. The models consisted of 10 unit cells both in planar directions (x-y) and 5 unit cells in the normal direction (z). For the octet trusses, the number of nodes was 9200, and the number of truss elements was 25700. For the Kagome trusses, the number of nodes and truss elements was 2400 and 12507, respectively. In the figure, we also present the trusses with geometrical imperfections (grey area), one type of defects, to be compared with the perfect lattice structure. Normal load was applied in the z-direction to simulate the compressive deformation. To avoid the boundary effect on the planar deformation under the normal deformation, the periodic boundary conditions were imposed in the x-y directions. We analyzed the perfect octet and Kagome lattice structures and later the lattice models with geometrical and material imperfections. The perfect lattice models were perfect in geometry with all equal-size truss elements and all nodes at precise lattice position and perfect in property being described by unique force-displacement response.

A wide range of compressive load (strain-0.045) was applied on the network models to obtain the compressive stress vs. strain curves, and the results are presented in Fig. 8. The simulation results are represented by the solid line for octet truss and the dashed line for Kagome truss structures. On the figure the curves estimated by FEA for the unit cell with the periodic boundary condition, as shown in Fig. 4, are also presented. The solid circles are for octet truss PCM and the open circles are for Kagome truss PCM. It is noticeable that, for both PCMs, the network analysis using the perfect lattice models gave nearly the same results (especially in the elastic regime and yield stresses) as those estimated by FEA for the unit cell with the periodic boundary condition. As mentioned above, the force-displacement curves used as the input of the network analysis were estimated by FEA for the unit cell and Eqs. (2) and (3). Therefore, the good agreement between the two results presented in Fig. 8 proves the flawlessness in the methodology and procedure of this hybrid approach. We later introduced geometric and material imperfections on the perfect lattice model to examine how the imperfections affected the strength of the two truss PCMs.

3.3 Geometric imperfections

When the truss structures are fabricated in the form of the two PCMs, for example, geometric defects can be included in the structures due to the joint mismatch and irregular shape of the trusses. To simulate these geometric imperfections, the positions ($\vec{x}$) of the nodes in the core parts were translated by the prescribed standard deviations $\vec{\Delta}_g$ of Gaussian distributions:

$$\vec{x} = \vec{x}_0 + \vec{\Delta}_g, \tag{6}$$

where $\vec{x}_0$ was the original position of the nodes for the perfect lattice model.

The geometric imperfections were added to the perfect lattice models of Kagome and octet trusses. In Fig. 9, the various stress-strain curves are presented

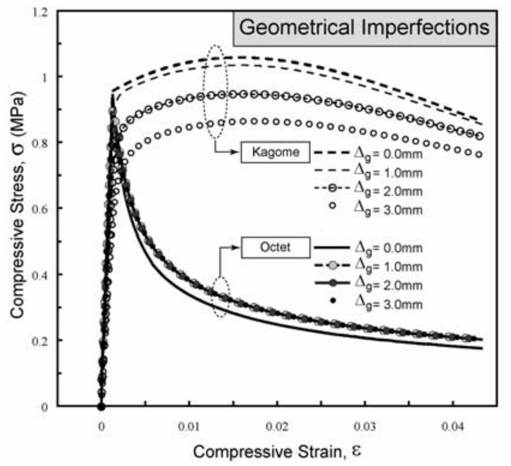


Fig. 9. Stress vs. strain curves for Kagome and octet PCMs with geometrical defects.

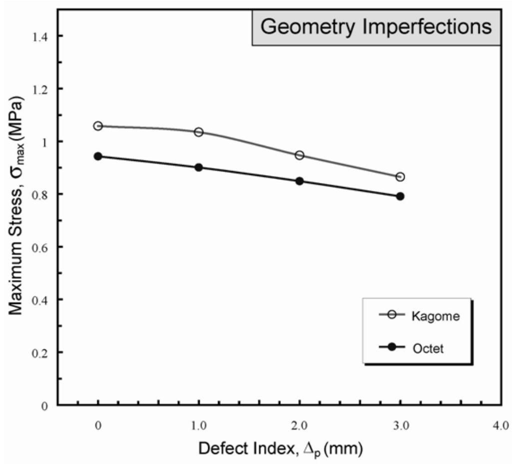


Fig. 10. Sensitivity curves of maximum stress for Kagome and octet PCMs on geometrical defects.

for a wide range of imperfection levels ($0<\Delta_g<3.0$mm). Note that the length of a single truss was 8.1mm and 16.2mm for the Kagome and octet PCMs, respectively. The yield stresses of both PCMs were about 0.95MPa for both truss types, but the post-yield responses were totally different. Kagome truss PCMs maintained high resistance over the entire simulation range after the yield. On the other hand, the octet truss PCMs showed abrupt decrease after the yield. The maximum stresses for Kagome truss PCMs were observed after the yielding regardless of the imperfection levels, whereas those for the octet PCMs were observed right at the yielding. This implies that the octet structures buckled immediately at the yielding.

In Fig. 10, we compared the maximum strength (σ_{max}) of two truss PCMs as a function of geometry imperfection levels. The maximum stresses linearly decreased as the imperfection level increased. The sensitivity (slope) of the maximum strength are nearly the same for both structures; the maximum stresses, however, occur at different positions, i.e., for Kagome in the post-yielding and for octet at the yielding.

3.4 Material property imperfections

The performance of the truss structures may be significantly affected by other types of imperfections, such as irregularly formed struts, non-uniform cross section, and also material defects. In this work, all of these imperfections were modeled by material property imperfections. To simulate material property imperfections occurring in the two PCMs, some random variations were added to the force vs. displacement curves shown in Fig. 6. Namely, the standard deviation ($\varDelta_p$) of Gaussian distributions was prescribed and added to the reference curves for the perfect lattice models:

$$F(\delta_F) = F_0(\delta_F)(1+\varDelta_p)\,, \tag{7}$$

where F_0 (δ_F) is the force acting on a strut in the perfect lattice model and it is a function of displacement. Fig. 11 shows variation of the force vs. displacement curves given by the deviation $\varDelta_p$ = 0.1. Note that, by adding the property random defects $\varDelta_p$, the force vs. displacement curves are scattered over the wide regions from the reference curves for the perfect models (dashed line for Kagome, solid line for octet).

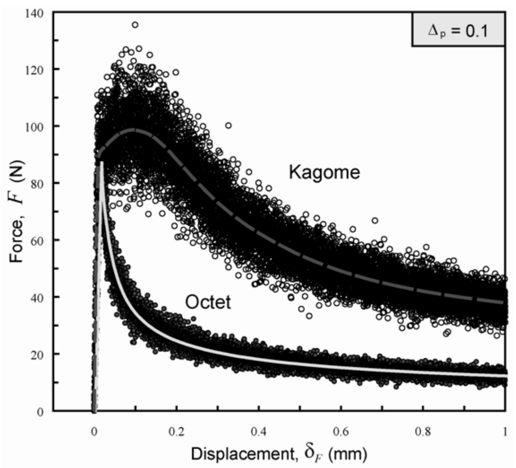


Fig. 11. Force vs. displacement curves can be transformed by material property imperfections in the form of Gaussian distributions.

By implementing the imperfection truss models, a random network analysis was done on the Kagome and octet truss PCMs. The imperfection levels ranging from $\varDelta_p$ = 0 to 0.7 were added to the perfect models, and the corresponding stress-strain curves are presented in Fig. 12. The slopes before the yielding (correspondingly Young's modulus) were almost unaffected by the property imperfections. The post peak responses were weakly dependent on the imperfection levels, as shown in Fig. 9. In Fig. 13, about defect sensitivity, the maximum stresses for Kagome truss PCM were nearly constant or even slightly increased with imperfection levels, while those for the octet truss PCM were more sensitive to the property imperfection levels ($\varDelta_p$).

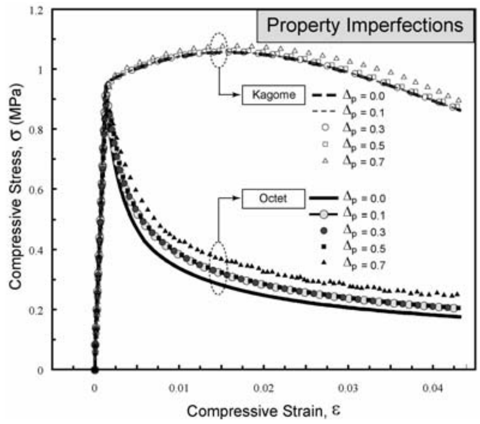


Fig. 12. Stress vs. strain curves for Kagome and octet PCMs with material property imperfections.

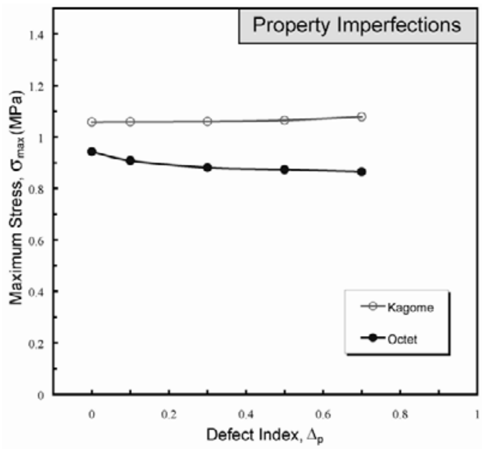


Fig. 13. Sensitivity curves of maximum stress for Kagome and octet PCMs on material property imperfections.

4. Concluding remarks

Octet truss structures have been considered one of the superior ultra-light structures following the suggestion by Fuller [22]. Later, the Kagome truss structures were identified as comparable ultra-light structures and suggested as a multifunctional material possessing superior buckling resistance to the octet truss structures [9]. However, few works have studied the defect sensitivities of the truss structures. In the authors' previous studies, two types of imperfections (geometric and property) in a wire-woven bulk Kagome were analyzed on their effect on strength under compressive and shear loads [15, 16].

In this work, by employing a hybrid numerical simulation method to statistical truss structures with imperfections, the mechanical strengths of two PCMs composed of octet and Kagome trusses under compression were examined. First, assuming perfectly uniform structure and deformation of WBK, the behavior of the bulk PCMs composed of an infinite number of trusses was simulated by finite element analysis for a unit cell with periodic boundary conditions. From the results, force-displacement response of a single strut composing the trusses in each bulk PCM was estimated. Then, the effects of geometric imperfections and the inhomogeneous material properties were evaluated by network analyses, in which the force-displacement responses were used to characterize mechanical behaviors of the networks. The imperfections were modeled to have Gaussian distributions, and the analysis results of the two bulk PCMs were compared with each other to evaluate their defect sensitivities.

A summary of the conclusions in the current study is following:

Without any imperfections, the stress-strain curve of Kagome truss PCM shows a typical initial yielding, some hardening before a peak point at 2% strain and then gradual decrease, while that of the octet truss shows brittle-like behavior, namely, sudden rapid drop without any hardening.

With the geometric imperfections, the maximum strength of both truss PCMs decreases gradually as the imperfection level increases.

With the material property imperfections, the maximum strength stays nearly unchanged for the Kagome truss PCMs. On the other hand, for octet truss PCMs, it slightly decreases as the imperfection level increases. The octet truss can be more sensitive to property imperfections than the Kagome truss structures.

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