The high strain compression of micro- and nano-sized random irregular honeycombs

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Abstract

This paper investigates the effects of cell wall thickness, initial stress/strain, and cell regularity on the high strain compressive responses of micro- and nano-sized low density random irregular honeycombs.   The strain gradient effects at the micrometer scale, and the surface elasticity and initial stress effects at the nanometer scale are incorporated into the dominant deformation mechanisms in finite element simulations. It is found that the dimensionless compressive stress strain relation strongly depends on the thickness of the cell walls at the micron scale, and at the nano-meter scale, this relation is not only size-dependent, but are also tunable and controllable over a large range. It is also found that under high strain compression, the Poisson's ratios of micro- and nano-sized low density random irregular honeycombs strongly depend on the cell regularity, but are almost independent of the cell wall thickness and the amplitudes of the initial stress or strain.

Keywords: Size effects; Irregular honeycombs; High strain compression; Strain gradient effects; Surface elasticity; Initial stress.

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1. Introduction

With the advance of manufacturing techniques, micro- and nano-sized honeycombs can be easily produced [1, 2] and they have already been widely used in different engineering and biomedical applications, e.g., the actuator material of nano-sensors [3]. Understanding the linear and nonlinear deformation behaviors of micro- and nano-sized random irregular honeycombs is essential, not only for the precise design of such materials but also for their correct applications in different areas.

This paper will focus on the numerical simulation of the high strain compression behaviors of low-density micro- and nano-sized random irregular honeycombs. The high strain compression behaviors of low density macro-sized honeycombs are well documented, examples include [4, 5]. The available results, however, may not apply to their micro- and nano-sized counterparts because of the effects of the surface elasticity [6-9] and the initial stress or strain [6, 10, 11] at the nanometer scale, and the strain gradient effect at the micrometer scale [6, 12-19]. Experimental tests [3, 7, 20-23] have shown that the initial surface stress in cellular porous materials can be controlled to vary over a large range by adjusting the amplitude of an applied electric potential. For example, Biener et al. [20] have experimentally demonstrated that by adjusting the chemical energy, the adsorbate-induced initial surface stress of nanoporous Au material could be controlled to reach 17-26 *N/m* from the original 1.13 *N/m*. The above results [3, 7, 20-23] suggest that for a nano-sized honeycomb made of a solid material with Young's modulus $E_S \approx 100 GPa$ and Poisson's ratio $v_S = 0.3$, the cell wall length could be controlled either to increase or to reduce about 10% if the thickness of the cell walls is about 1.5*nm*. Biener et al. [20] and Weissmuller et al. [3, 22] have also experimentally demonstrated the large elastic recoverable deformation of nano-porous materials by adjusting the amplitude of the initial surface stress. It has been found that there exists a linear correlation between the surface stress and surface charge in anion adsorption on Au (111) [23]. Moreover, not only the mechanical properties but also the geometrical properties of nano-sized cellular materials can be controlled

to vary over large ranges [24, 25]. Thus, nano-structured cellular materials can be used as functional materials in many different areas.

The objective of this paper is to investigate the effects of the cell wall thickness, initial stress or strain and cell regularity on the high strain compression behaviors of micro- and nano-sized random irregular honeycombs. We will use a commercial finite element software (ANSYS) to perform the large deformation simulations, and explore how the cell wall thickness, initial stress or strain, and cell regularity affect the high strain compression behaviors of micro- and nano-sized random irregular honeycombs.

2. Geometrical model and treatment of finite element simulations

2.1 Geometrical model

The periodic random irregular Voronoi honeycomb models were constructed using a program developed by Zhu et al. [5].   The definition for the degree of cell regularity α is given in [5] and its value can be controlled to vary from 0.0 to 0.7.   It is noted that for a produced Voronoi honeycomb, it is very easy to measure the degree of cell regularity using the definition given in [5], and the measured result is unique.   According to the definition, the degree of regularity of a perfect regular hexagonal honeycomb is 1.   Figure 1 shows a representative volume element (RVE) of periodic random irregular micro- or nano-sized Voronoi honeycomb with 100 complete cells and a degree of regularity $\alpha = 0.7$.

In the periodical models, all the cell walls are assumed to be flat, and have the same initial uniform thickness h_0 and a unit initial width (i.e. $b_0 = 1$) which is assumed to be much larger than h_0.   When the effects of the initial surface stresses/strains are absent, the initial relative density of a random irregular micro- or nano-sized honeycomb is given as [5, 24]

$$\rho_0 = (h_0 \sum_{i=1}^{M} l_{0i}) / L_0^2 \tag{1}$$

where l_{0i} are the cell wall initial lengths and L_0 is the initial side length of the periodic unit honeycomb RVE model and M is the total number of cell walls.

2.2 Size-dependent rigidities of micro- or nano-sized cell walls

For the in-plane deformation of low density honeycombs, the main deformation mechanisms are cell wall bending, transverse shear, and axial stretching (or compression) [4-6, 24], and plane strain bending of the cell walls is the dominant deformation mechanism [6, 24]. As strain gradient [13-24] could significantly affect the bending and transverse shear rigidities when the cell wall thickness is between submicron and microns [12-19], the bending, transverse shear and axial stretching/compression rigidities are thus size-dependent, and given as [6, 24-26]

$$D_b = \frac{E_S h^3}{12(1-v_S^2)}[1+6(1-v_S)(l_m/h)^2] \quad , \tag{2}$$

$$D_s = \frac{hE_s}{2.4(1+v_S)} \cdot \frac{[1+6(1-v_s)(l_m/h)^2]^2}{1+2.5(1+v_s)^2(l_m/h)^2} \tag{3}$$

$$D_c = E_S h \tag{4}$$

where E_S and v_S are the Young's modulus and Poisson's ratio of the solid material, h is the cell wall thickness and l_m is the length scale parameter for strain gradient effect, which is usually between submicron and microns can be experimentally measured [6, 18, 19]. In Eqs (2) and (3), the cell wall width is assumed to be unity ($b=1$) and much larger than the thickness h. It is easy to check that when the plate thickness h is much larger than l_m (i.e. l_m/h tends to 0), the bending and transverse shear rigidities given in Eqs (2) and (3) reduce to those of conventional mechanics. The axial stretching/compression stiffness is always the same as the conventional result because the strain gradient effect is always absent when a cell wall undergoes uniaxial tension or compression.

When the cell wall thickness is at the nanometer scale, as the surface to volume ratio is large, both the surface elasticity and the initial stress or strain can greatly affect the bending, transverse shear and axial stretching/compression rigidities [6-11, 24-26]. For simplicity, both the surface

and the bulk materials of the cell walls are assumed to be isotropic and to have the same Poisson's ratio v_S. When an initial surface stress τ_0 is present, the amplitudes of the initial stresses in the bulk material in the length and the width directions of the cell walls are equal [6, 10, 11, 24-26] and given as $\sigma_0^L = \sigma_0^W = -2\tau_0 / h$, where h is the current thickness of the cell walls. When the size of the cell walls is at the nano-meter scale, the yield strength σ_y could reach $0.1E_S$ or even a larger value [20, 22, 27]. For recoverable elastic deformation, the initial von Mises stress should not exceed the yield strength σ_y of the cell wall material, thus $\sigma_e = \left|\sigma_0^L\right| = \left|\sigma_0^W\right| = \left|\dfrac{2\tau_0}{h}\right| \le \sigma_y = 0.1E_S$. The initial elastic residual strains in the length and width directions of the cell walls are the same, and given by [24-26]

$$\varepsilon_0^L = \varepsilon_0^W = \frac{\sigma_0^L}{E_S}(1 - v_S) \tag{5}$$

The initial elastic residual strain in the thickness direction of the cell walls is derived as

$$\varepsilon_0^t = \frac{\Delta h}{h_0} \approx \frac{4v_S \tau_0}{E_S h} = -\frac{2v_S}{E_S}\sigma_0^L \tag{6}$$

The effects of surface elasticity and the initial stress or strain on the bending, transverse shear and axial stretching/compression rigidities of a nano-sized cell wall have been obtained in [11], [6] and [8], respectively, and given as

$$D_b = \frac{E_S b h^3}{12(1 - v_S^2)}[1 + 6\frac{l_n}{h} + \frac{v_S(1 + v_S)}{1 - v_S}\varepsilon_0^L] \tag{7}$$

$$D_s = \frac{G_s b h}{1.2} \cdot \frac{[1 + \dfrac{6l_n}{h} + v_s \dfrac{1 + v_s}{1 - v_s}\varepsilon_0^L]^2}{1 + \dfrac{10l_n}{h} + 30(l_n / h)^2} \tag{8}$$

$$D_c = E_s b h(1 + 2l_n / h) \tag{9}$$

In Eqs (7)-(9), $l_n = S / E_S$ is the intrinsic length of the material at the nano-meter scale and S is the surface elasticity modulus. The material nano-scale intrinsic length l_n is typically in the range from 0.01 to 1 nm [6, 8]. The current dimensions of the nano-sized cell walls are related

to their initial dimensions by following equations [24-26]

$$b = b_0(1 + \varepsilon_0^W) = 1 + \varepsilon_0^L \tag{10}$$

$$h = h_0(1 + \varepsilon_0^t) = h_0(1 - \frac{2v_S}{E_S}\sigma_0^L) \tag{11}$$

$$l = l_0(1 + \varepsilon_0^L) \tag{12}$$

Obviously, the bending, axial stretching/compression and transverse shear rigidities of the nano-sized cell walls can all be controlled to vary over large ranges [6, 11, 26].

2.3. Treatment of the equivalent deformation rigidities of micro- or nano-sized cell walls in finite element simulations

In finite element simulation, the cell walls of the honeycomb shown in Fig. 1(a) are usually partitioned into a large number of 2D beam elements.   Three parameters are required to enter to the computer in order to specify the mechanical properties of the beam elements.   These are the Young's modulus and Poisson's ratio of the solid material (from which the beam is made) and the cross-sectional dimension (i.e. the diameter if the cross-section is a circle, or the thickness if it is a rectangle).   The commercial finite element software ANSYS [28] was used to simulate the in-plane high strain compression behaviors of micro- and nano-sized irregular honeycombs. Each of the cell walls was partitioned into a number of BEAM3 elements.   This type of beam element has two nodes and takes account of the bending, stretching and transverse shear deformation mechanisms.   For a micro- or nano-sized random irregular honeycomb with a given initial relative density ρ_0, the initial cell wall thickness h_0 can be obtained from Eq. (1). In the available commercial finite element software, there is no any type of element which can directly incorporate the size-dependent effects into the deformation of solid structures in simulations.   We thus use equivalent cell wall thickness h_e, equivalent Young's modulus E_e and Poisson's ratio v_e for the beam elements in the finite element simulations [24].   These equivalent values are obtained from the following three simultaneous equations:

$$\frac{E_e h_e^3}{12} = D_b \tag{13}$$

$$\frac{G_e h_e}{1.2} = \frac{E_e h_e}{2.4(1 + v_e)} = D_s \qquad (14)$$

$$E_e h_e = D_c \qquad (15)$$

where D_b, D_s and D_c are given in Eqs (2)-(4) for micro-sized honeycombs, and in Eqs (7)-(9) for nano-sized honeycombs. As D_b, D_s and D_c are size-dependent and may also be tunable, the effects of the strain gradient, or the surface elasticity and initial stress/strain on the mechanical properties of the micro- or nano-sized random irregular honeycombs can be incorporated into the finite element simulations by using the equivalent values of h_e, E_e and v_e obtained from Eqs (13)-(15). For low density honeycombs, although the compressive strain is large, the amplitude of the strains in the cell walls is small [5]. The solid material of the honeycombs is assumed to be linear elastic, and to have a Young's modulus $E_S = 2 \times 10^5 MPa$ and a Poisson's ratio $v_S = 0.4$ in the simulations of this paper.

When the size effects are absent, the compression stress strain relation of a low density honeycomb is a function of the relative density ρ_0 and the degree of cell regularity α, and is independent of the actual cell wall thickness h [4, 5]. For a random irregular honeycomb model with a given relative density $\rho_0 = 0.01$, the actual cell wall thickness can be obtained from Eq. (1), which is slightly different for each individual model (this is because each random model has a slightly different total length of the cell walls). For each model, we use the same Young's modulus E_S and Poisson's ratio v_S for the solid material, but a slightly different cell wall thickness h that is obtained from Eq. (1) when constructing the geometrical model. The strain gradient effects or the surface effects are incorporated into the simulations by choosing different values of l_m / h or l_n / h in Equations (2-4) or (7-9). The correct equivalent values of h_e, E_e and v_e for each of the individual models can be obtained from Equations (13-15) and (2-4) or (7-9). The correct use of the equivalent values of h_e, E_e and v_e have been validated in [24].

2.4. Boundary conditions in finite element simulations

The constructed random irregular Voronoi honeycomb models are periodic, as shown in Fig. 1 (a), thus periodic boundary conditions [6, 30, 31] can easily be imposed in the finite element simulations, as can be seen in Fig. 1(b). The periodic boundary conditions are given by

$$u_i - u_j = u_i' - u_j', \quad \theta_i = \theta_i' \tag{16}$$

where u_i, u_j, u_i' and u_j' are the displacements in the x or y directions of the corresponding nodes on the opposite boundaries, θ_i and θ_i' are the rotational displacement (about the z axis) of the corresponding nodes on the opposite boundaries. The high strain compression of low density honeycombs is a geometrical nonlinearity problem. The solutions for the large compressive strains are obtained by a number of incremental loading steps, and in each incremental step, the convergent solution is obtained by the iterative method.

3. Results

The high strain compressive responses of random irregular micro- and nano-sized honeycombs are obtained by finite element simulations from periodic models with a fixed relative density 0.01 and a fixed number of 100 complete cells. The range of the degree of cell regularity is varied from 0.0 to 0.7. The compressive stress strain relations presented in this paper are the mean results obtained from 10--20 different random irregular honeycomb models with the same degree of regularity and the same set of other parameters (e.g. the same values of l_n / h and initial strain). The high strain compression of irregular honeycombs is a geometrically non-linear problem and the convergent solution is achieved by iteration in each loading step. It is a problem to find the global minimum for a function of multi-variables. The larger the irregular model, the larger the number of variables (i.e. the degrees of freedom), and the longer time it would take to compress the model to a certain strain, and the more difficult to obtain a convergent

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solution.   Therefore, the number of complete cells in each model is set to 100 for the simulations in this paper.

It has been found that although the obtained compressive stress strain relations could be quite different for the different individual random irregular honeycomb models, the standard deviations are small [5].   When the amplitude of the compressive strain is smaller than 40%, there is almost no cell wall contact.   Thus, cell wall contact has not been considered in this paper. As cell wall buckling is the dominant deformation mechanism in the high strain compression of low density honeycombs [5], for both micro- and nano-sized random irregular honeycombs, the in-plane compressive stress is normalized by the Young's modulus of the solid material and by the cube of the initial honeycomb relative density, and given as

$$\bar{\sigma} = \frac{\sigma}{E_S \rho_0^3} \tag{17}$$

where σ is the compressive stress, E_S is the Young's modulus of the solid material, and ρ_0 is the relative density of the random irregular honeycomb when the effects of the initial stress or strain are absent.

3.1. Micro-sized honeycombs

At the micro-meter scale, the strain gradient effect plays an important role in the mechanical behaviors [6, 12, 19].   The bending, transverse shear and axial stretching or compression rigidities of the micro-sized cell walls are size-dependent, and are given by Eqs (2) – (4). The equivalent solid Young's modulus E_e, Poisson's ratio v_e and beam thickness h_e can be determined from Equations (13) – (15).   The values of l_m/h are set to 0.0, 0.2, 0.5, and 1.0.

3.1.1. Size effects on the compressive stress strain relation

Figure 2 presents the size-dependent effects on the mean dimensionless compressive stress and strain relation of micro-sized periodic random irregular honeycombs with relative density $\rho_0 =$ 0.01 and different degrees of cell regularity. As can be seen, with the increase of the compressive strain from 0% to 60%, the dimensionless compressive stress increases monotonously, no matter what degree of cell regularity. For micro-sized random irregular honeycombs with the same degree of regularity, to compress them to the same compressive strain, the thinner the cell walls, the larger the dimensionless compressive stress is required. When the thickness of the cell walls is much larger than the material intrinsic length l_m (i.e. $l_m / h = 0$), the strain gradient effects are absent, and the results reduce to those of the conventional macro-sized counterparts in Ref. [5].

Figure 2(a) shows that for irregular honeycomb with $l_m / h = 0$ and $\alpha = 0.0$, when it is compressed up to 60%, the mean dimensionless stress is about 0.15, which is consistent with the value 0.13 of Zhu et al. [5] because the cell walls are assumed to undergo plane strain bending in this paper and the obtained stiffness is thus $1 / (1 - v_s^2) = 1.16$ times that of the plane stress case in Ref. [5]. This suggests that the results obtained in this paper are reasonable. The error bars shown in Figures 2 (a), (b), (c) and (d) represent the standard deviations of the data. It can be found that the thinner the cell wall thickness (i.e. the larger the value of l_m / h), the larger the standard deviations. For honeycombs with the same cell wall thickness, the larger the compressive strain or stress, the larger the standard deviation. This may happen because compressing an irregular honeycomb to a large strain leads to a large fluctuation in the convergent solutions. The results in Figures 2(a)-(d) indicate that the strain gradient effects have

a significant influence on the compressive stress strain relation of micro-sized random irregular honeycombs with different degrees of regularity.

3.1.2. Effects of cell regularity on the compressive stress strain relation

Fig. 3 presents the effects of cell regularity on the mean dimensionless compressive stress and strain relations of low density micro-sized periodic random irregular honeycombs with fixed values $\rho_0 = 0.01$ and $l_m / h = 0.5$. As can be seen, when the compressive strain is small, the larger the degree of the cell regularity, the smaller the tangent modulus. In contrast, when the compressive strain is larger than 10%, the larger the degree of the cell regularity of a micro-sized random irregular honeycomb, the larger mean dimensionless compressive stress, and the smaller the standard deviation. These results are consistent with their macro-sized counterparts [5, 24].

3.1.3. Size effects on the relation between the Poisson's ratio and compressive strain

As can be seen from Figures 4 (a), (b), (c) and (d), for micro-sized irregular honeycombs with different degrees of regularity, the in-plane Poisson's ratio reduces sharply with the increase of the compressive strain, whether the size-dependent effect is present or absent. This finding is consistent with the research result [5] for macro-sized irregular honeycombs. Figures 4 (a)-(d) indicate that the effects of the cell wall thickness (i.e. the value of l_m / h) on the relation between the in-plane Poisson's ratio and the compressive strain of micro-sized irregular honeycombs are negligible. It can also be observed that when the compressive strain of the micro-sized irregular honeycombs approached 60%, the value of the in-plane Poisson's ratio becomes negative, which

is the same as the finding for macro-sized irregular honeycombs [5]. This happens because the mean cell wall junction rotation is approximately proportional to the amplitude of the honeycomb compressive strain [5].

3.1.4. Effects of cell regularity on the relation between the Poisson's ratio and compressive strain

When the strain gradient effect is present, the effects of cell regularity on the relation between the in-plane Poisson's ratio and the compressive strain of micro-sized periodic random irregular honeycombs with $\rho_0 = 0.01$ are shown in Figure 5. The greater the degree of cell regularity, the larger the in-plane Poisson's ratio, which is consistent with the finding for the macro-sized irregular honeycombs [5]. With the increase of the compressive strain, the in-plane Poisson's ratio of micro-sized irregular honeycombs reduces and becomes negative when the compressive strain approached 60%, and the strain gradient effect does not influence this trend.

3.2. Nano-sized honeycombs

At the nano-meter scale, the surface elasticity and initial stress or strain can affect the mechanical behaviors of nano-sized materials [6-11, 20-26]. Thus, the bending, transverse shear and axial stretching or compression rigidities are all size-dependent, and are given by Equations (7) -- (9). The equivalent solid Young's modulus E_e, Poisson's ratio v_e and beam thickness h_e can be determined from Equations (13) – (15). The values of l_n/h are set to 0.0, 0.2, 0.5, and 1.0. The amplitudes of the initial strain ε_0^L are set to -0.06, 0, and 0.06 because the amplitude of the recoverable initial elastic strain in the cell wall length direction could be controlled to vary over

a range from -0.1 to 0.1 by application of an electric potential [6, 10, 11, 22-27].

3.2.1. Size effects on the compressive stress strain relation

Figures 6 (a), (b), (c) and (d) show the effects of surface elasticity on the relation between the dimensionless compressive stress and strain of low density nano-sized periodic random irregular honeycombs with fixed relative density $\rho_0 = 0.01$ and different degrees of cell regularity from 0.0 to 0.7. As can be seen, the dimensionless stress increases monotonously with the increase of the honeycomb compressive strain from 0% to 60%. When the surface modulus is positive, the thinner the cell wall thickness (i.e. larger value of l_n / h), the larger are the dimensionless compressive stress and the tangent modulus. If the surface modulus is negative, the effects of the cell wall thickness on the dimensionless compressive stress and the tangent modulus are inverted. When the cell wall thickness is much larger than the material intrinsic length l_n, i.e. $l_n / h = 0$, the size-dependent effects vanish, and the relations between the dimensionless stress and the compressive strain of nano-sized irregular honeycombs reduce to those of their macro-sized counterparts [5], as has been demonstrated from the results at the micro-meter scale. It can be seen from Figures 6 (a)-(d) that when the surface modulus is positive, the thinner the cell walls (i.e. larger value of l_n / h) and the larger the compressive strain, the larger the standard deviation of the dimensionless compressive stress. In general, the size-dependent behaviors of nano-sized irregular honeycombs are very similar to their micro-sized counterparts.

Figure 7 illustrates the effects of initial stress or strain on the relation between the dimensionless stress and compressive strain of low density nano-sized irregular honeycomb with relative

density $\rho_0 = 0.01$ and degree of cell regularity $\alpha = 0.2$. For the same amplitude of compressive strain, when the initial strain in the length direction of the cell walls is adjusted to vary between -6% and 6%, the dimensionless compressive stress of the nano-sized irregular honeycombs can be controlled to either reduce about 45% or increase about 70%. Therefore, the initial stress or strain can significantly affect the compressive stress and strain relation of nano-sized honeycombs.

3.2.2. Effects of cell regularity on the compressive stress strain relation

In addition to the size-dependent and initial stress or strain effects, cell regularity may also affect the compressive stress and strain response of nano-sized periodic random irregular honeycombs. When the surface elasticity effect is present, the effects of cell regularity on the relation between the dimensionless compressive stress and strain of nano-sized irregular honeycombs with $l_n / h = 0.5$ and different degrees of regularity are shown in Figure 8. The greater the degree of cell regularity, the smaller is the tangent modulus when the compressive strain is small, and the larger is the dimensionless compressive stress when the compressive strain is larger than 10%. This trend is consistent with the results for macro-sized honeycombs [5] and micro-sized counterparts, as discussed above.

3.2.3. Size effects on the relation between the Poisson's ratio and compressive strain

The cell wall thickness (i.e. the value of l_n / h) has negligible effects on the relation between the in-plane Poisson's ratio and the compressive strain of low density nano-sized random irregular

honeycombs, as can be seen in Figures 9 (a), (b), (c), and (d). Whether the size-dependent effects are present or absent, the in-plane Poisson's ratio decreases monotonously with the increase of the compressive strain and becomes negative when the compressive strain approaches 60%. This is attributed to the rotation of the cell wall junctions, which increases monotonously with the honeycomb in-plane compressive strain. It can also be seen from Figures 9 (a)-(d) that the standard deviation of the mean in-plane Poisson's ratio of nano-sized honeycombs increases with the compressive strain. The compressive responses of nano-sized honeycombs are consistent with those of their macro- [5] and micro-sized counterparts.

When the size-dependent effects are absent ($l_n / h = 0$), the effects of the initial stress or strain on the relation between the in-plane Poisson's ratio and honeycomb compressive strain for low density nano-sized random irregular honeycombs with the relative density $\rho_0 = 0.01$ and degree of cell regularity $\alpha = 0.2$ are shown in Figure 10. When the initial strain in the axial direction of the cell walls is controlled to vary from -0.06 to 0.06, the value of Poisson's ratio remains almost unchanged. The in-plane Poisson's ratio reduces with the increase of the compressive strain and becomes negative when the honeycomb compressive strain is large, confirming that the rotation of the cell wall junctions is an important deformation mechanism in the high strain in-plane compression of honeycombs.

3.2.4. Effects of cell regularity on the relation between the Poisson's ratio and compressive strain

The effects of cell regularity on the in-plane Poisson's ratio of nano-sized honeycombs are shown

in Figure 11.   As discussed in the above sections, the Poisson's ratio reduces monotonously with the increase of the honeycomb compressive strain because of the increasing amplitude of the rotation of cell wall junctions.   It can be seen that for the same amplitude of honeycomb compressive strain, the larger the degree of cell regularity, the larger the value of the Poisson's ratio. The results in Fig. 11 are consistent with those of the micro- and macro-sized honeycombs.

4.   Conclusion

The effects of cell wall thickness, initial stress or strain, and degree of cell regularity on the in-plane high strain compression behaviors of low density micro- and nano-sized random irregular honeycombs have been explored in this paper.   It is found that the thinner the cell walls, the relatively stiffer the micro- and nano-sized honeycombs.   The Poisson's ratio of the low density micro- and nano-sized honeycombs, however, is almost independent of the cell wall thickness and initial stress or strain.   Under large compressive strains, the greater the degree of cell regularity, the stiffer the micro- and nano-sized honeycombs.   At the nanometer scale, the compressive stiffness of irregular honeycombs can be controlled to either to reduce or to increase over a large range by adjusting the initial cell wall stress or strain via application of an electric potential.

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[28] ANSYS finite element software.

Figures

(a)   (b)
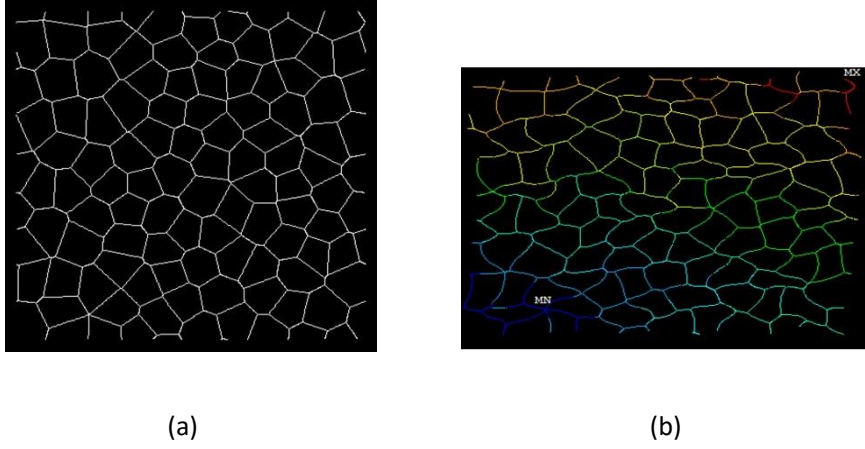
Figure 1. (a) A periodic Voronoi honeycomb with 100 complete cells and degree of regularity $\alpha = 0.7$; (b) The deformed honeycomb with periodic boundary conditions.

(a)

(b)

(c)

(d)
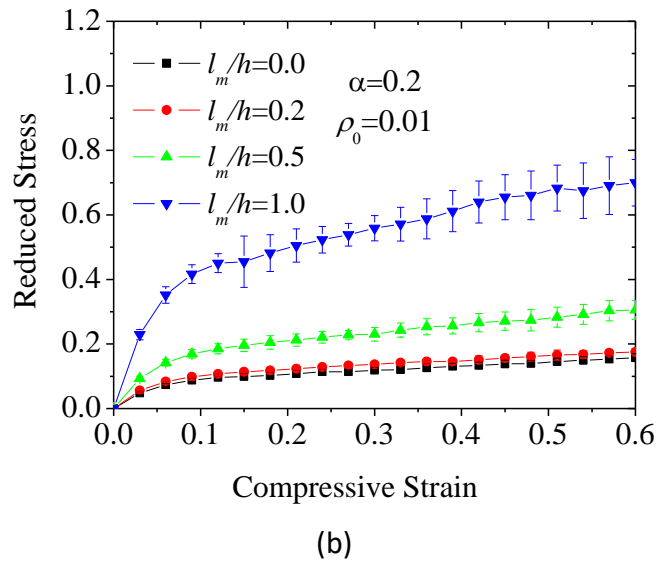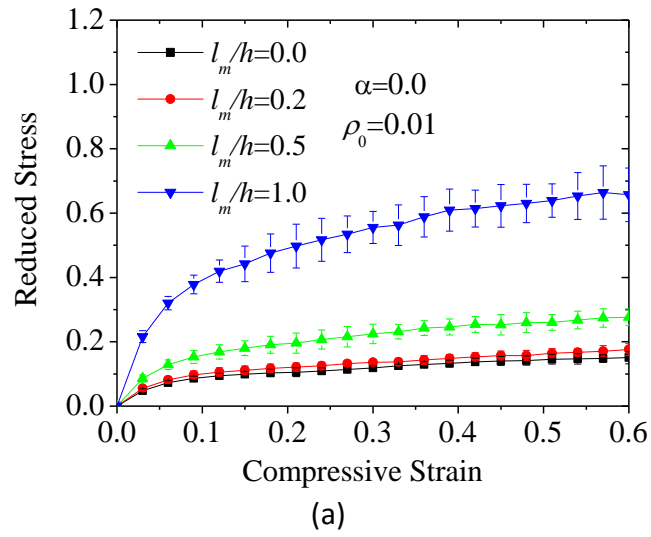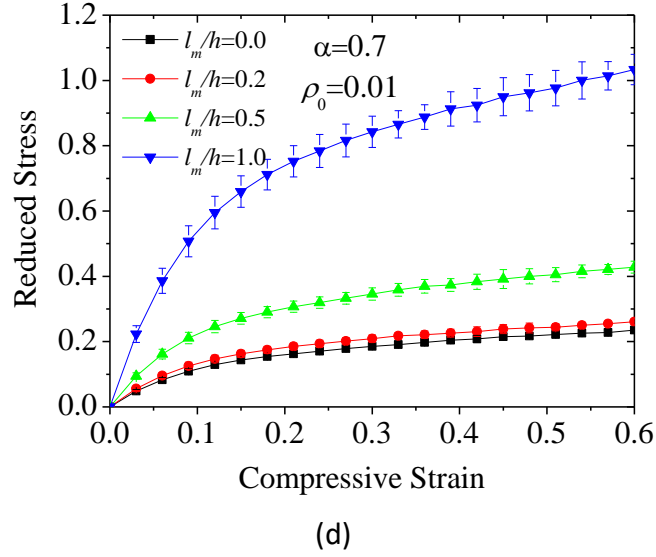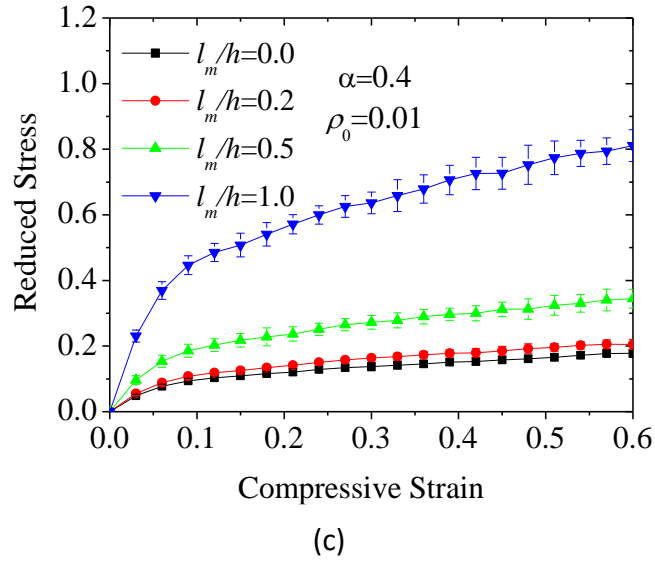
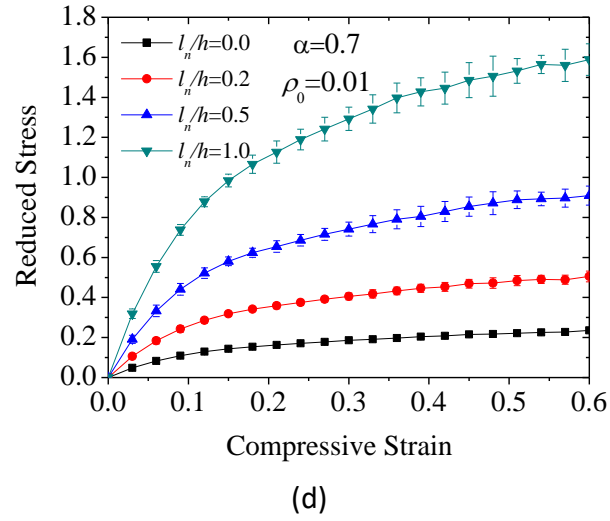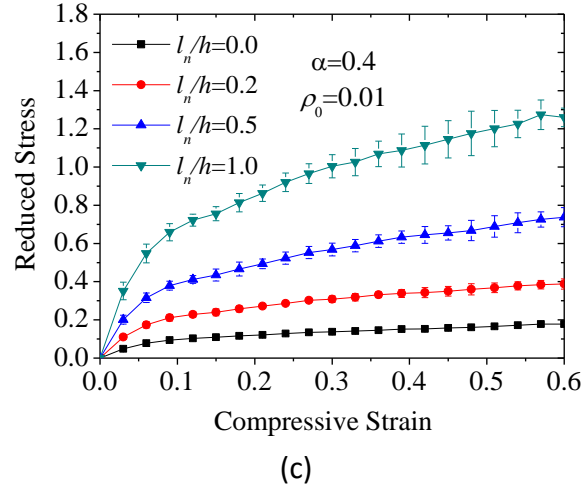Figure 2. Size-dependent effects on the mean dimensionless compressive stress and strain relation of low density micro-sized periodic random irregular honeycombs with relative density $\rho_0 = 0.01$ and different degrees of regularity: (a) $\alpha = 0.0$, (b) $\alpha = 0.2$, (c) $\alpha = 0.4$, and (d) $\alpha = 0.7$.
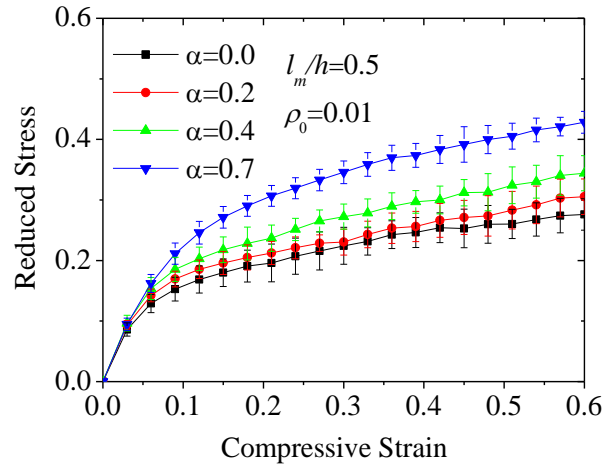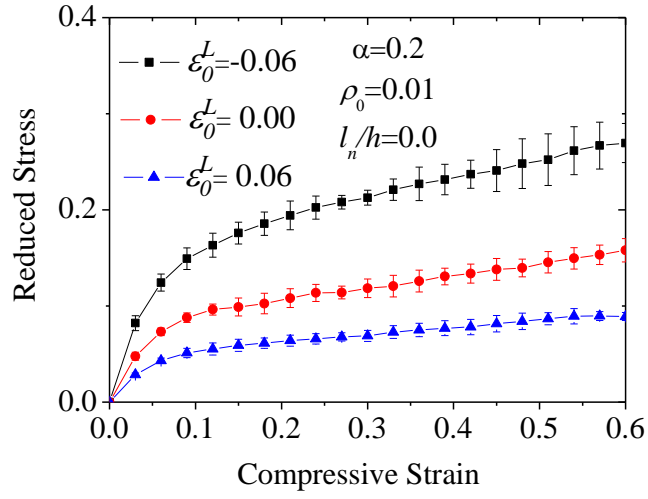
Figure 3. Effect of cell regularity on the dimensionless compressive stress and strain relation for micro-sized periodic random irregular honeycombs with $\rho_0 = 0.01$ and $l_m / h = 0.5$.

(a)

(b)

(c)

(d)
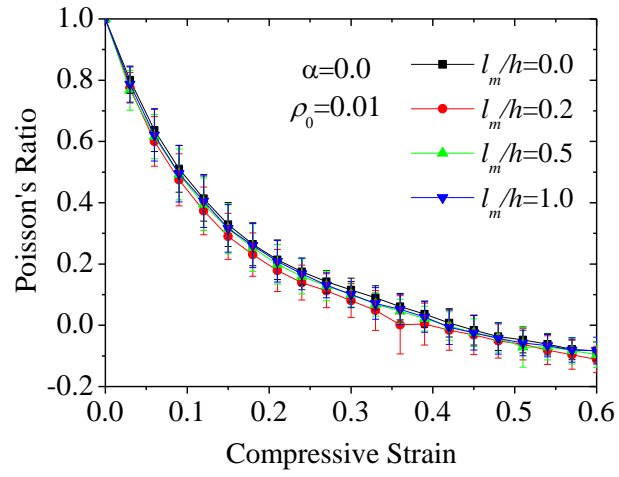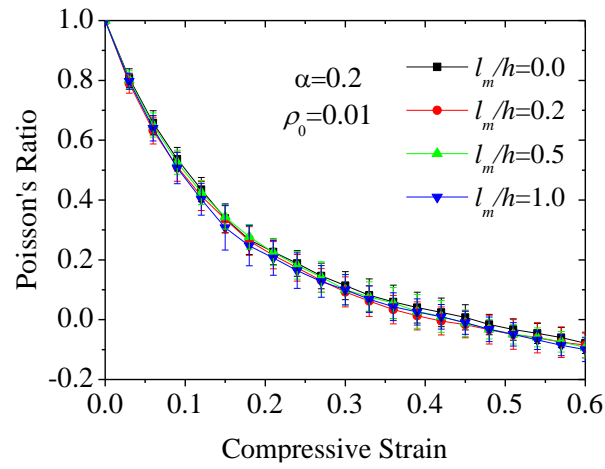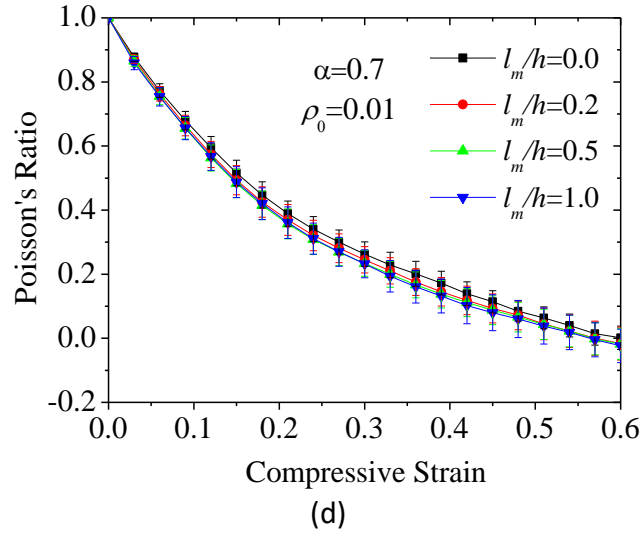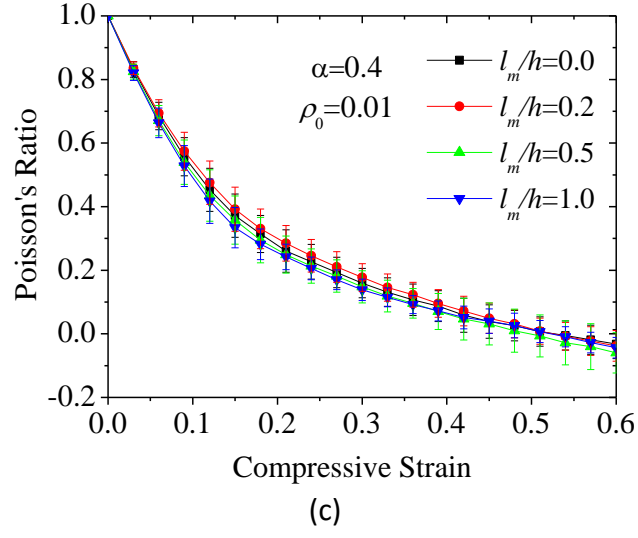
Figure 4.   Size-dependent relations between the in-plane Poisson's ratio and compressive strain of low density micro-sized irregular honeycombs with the relative density $\rho_0 = 0.01$ and different degrees of regularity: (a) $\alpha = 0.0$,   (b) $\alpha = 0.2$, (c) $\alpha = 0.4$, and (d) $\alpha = 0.7$.
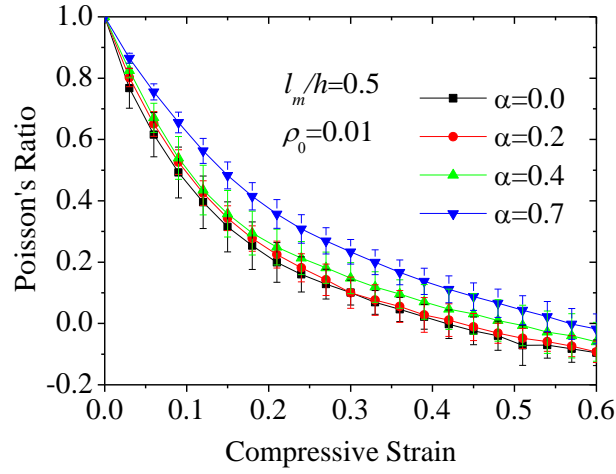
Figure 5. Effect of cell regularity on the relation between the in-plane Poisson's ratio and compressive strain of micro-sized irregular honeycombs with $\rho_0 = 0.01$ and $l_m / h = 0.5$.

(a)

(b)

(c)

(d)
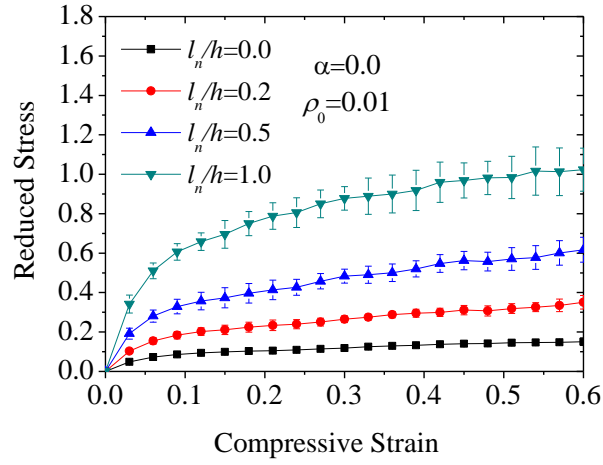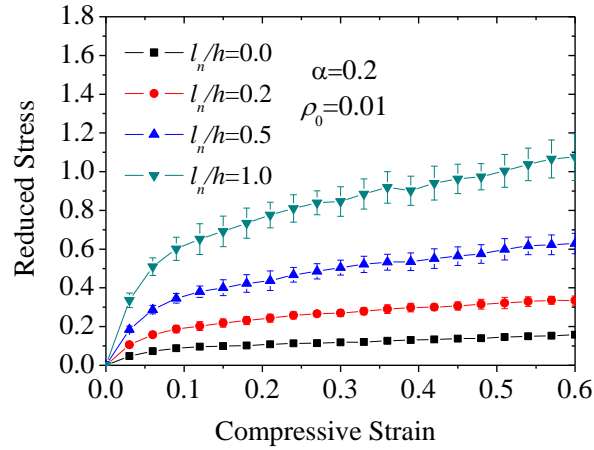
Figure 6. Size-dependent effects on the mean dimensionless stress and strain relation for low density nano-sized periodic random irregular honeycombs with ρ_0 = 0.01 and different degrees of regularity: (a) α = 0.0, (b) α = 0.2, (c) α = 0.4, and (d) α =0.7.

Figure 7. Effects of initial stress or strain on the relation between the dimensionless stress and compressive strain of low density nano-sized irregular honeycomb with $\rho_0 = 0.01$ and $\alpha = 0.2$.
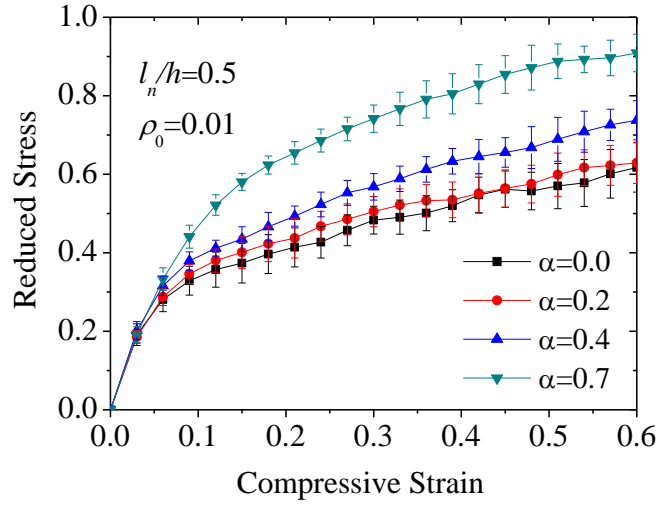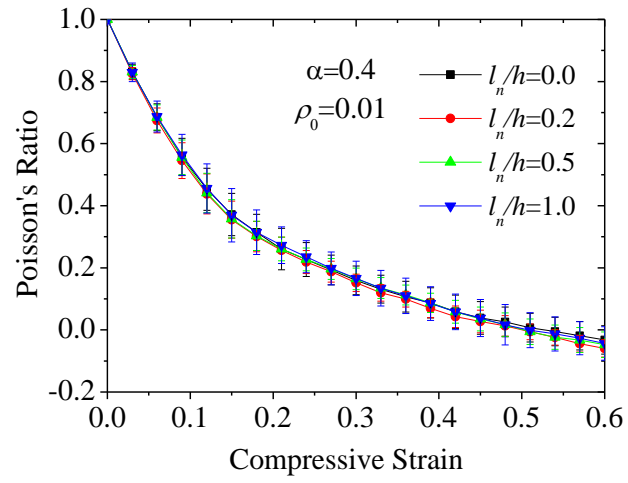

Figure 8. Effects of cell regularity on the relation between the dimensionless stress and compressive strain of nano-sized periodic random irregular honeycombs with $\rho_0 = 0.01$ and $l_n / h = 0.5$.
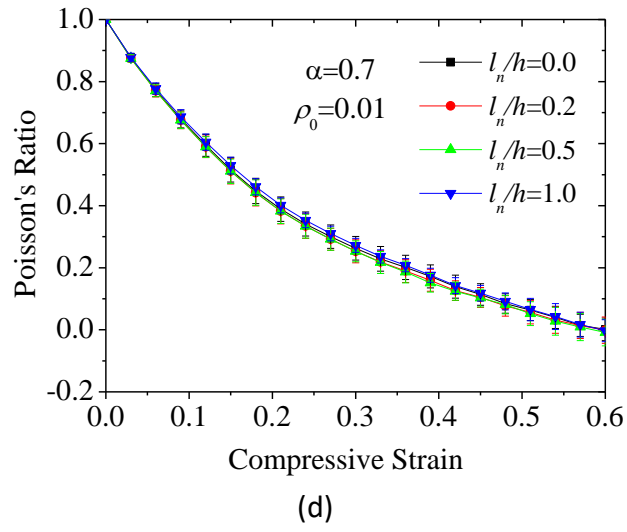
(a)

(b)

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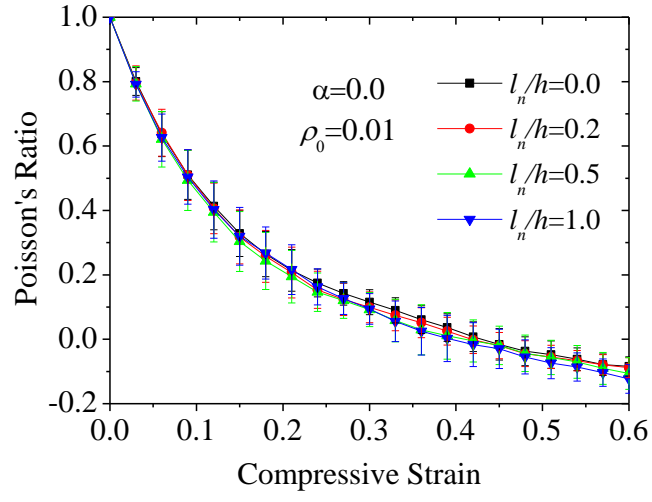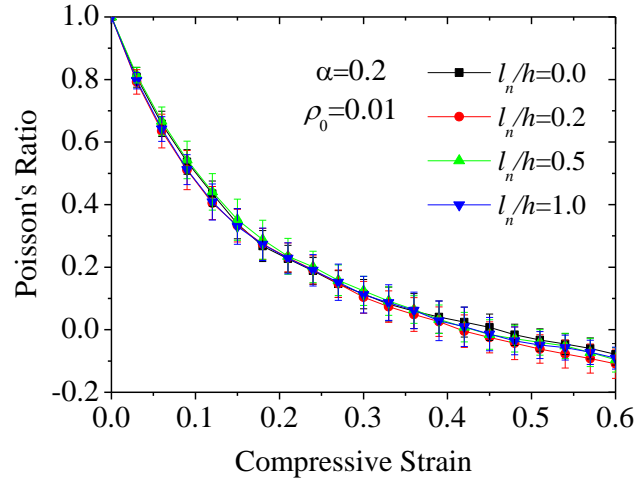
Figure 9. Effects of cell wall thickness on the relation between the in-plane Poisson's ratio and compressive strain of low density nano-sized random irregular honeycombs with $\rho_0 = 0.01$. (a) $\alpha = 0.0$, (b) $\alpha = 0.2$, (c) $\alpha = 0.4$, and (d) $\alpha = 0.7$.
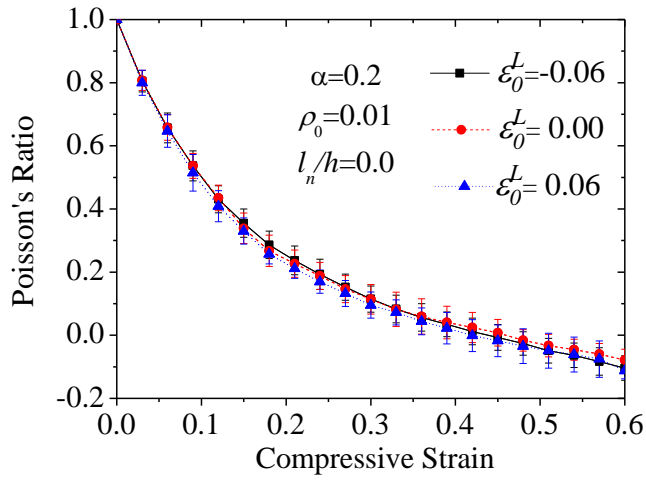

Figure 10. Effects of the initial stress or strain on the relation between the Poisson's ratio and honeycomb compressive strain for low density nano-sized periodic random irregular honeycombs with $\rho_0 = 0.01$ and $\alpha = 0.2$.
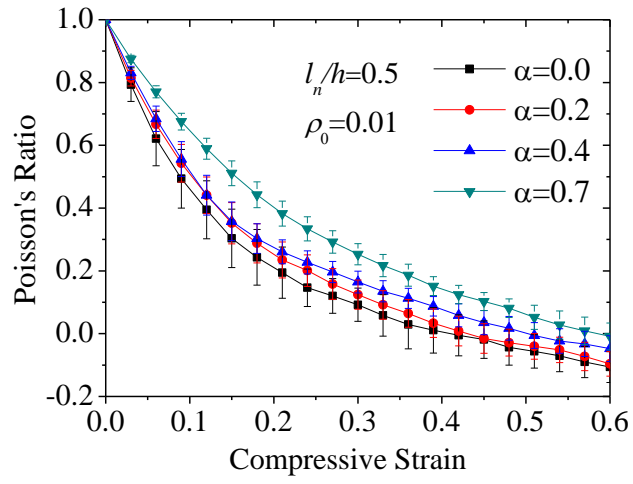
Figure 11. Effects of cell regularity on the relation between the in-plane Poisson's ratio and compressive strain of nano-sized random irregular honeycombs with $\rho_0 =$ 0.01 and $l_n / h = 0.5$.