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Research Article

Dynamic Mechanical Properties and Constitutive Model of Honeycomb Materials with Random Defects under Impact Loading

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The study analyzed the influence of random defects on plateau stresses of honeycomb materials with varied relative densities and established a computational model of honeycomb materials considering random defects. The results show that the plateau stress decreases evidently as the random defects increase, which is closely related to the relative density of honeycomb materials. It also set up a functional relationship between relative plateau stresses and random defects as well as that between relative plateau stresses and relative densities. Taken topological structure, random defects and strain rate effect into consideration, and it proposed a dynamic constitutive model of honeycomb materials under low-middle impact loading. And the proposed constitutive model possesses a better applicability to match the stress-strain relationship of honeycomb materials in existing impact experiments. The proposed constitutive model could make a theoretical foundation in material design and practical application of honeycombs containing random defects.

1. Introduction

Honeycomb and foam materials, as a type of functional materials, have existed widely in nature [1] and industry [2]. Due to the integration of mechanical performances of materials and topological structures, these materials have an outstanding capacity of designability. For cellular honeycomb with high porosity, it possesses an obvious plateau stress stage in period of loading [2], which improves significantly these materials' overall energy absorption. Meanwhile, because of the excellent buffering performances, honeycomb materials have been used widely into military and civil engineering, such as radar cover, landing pad of spaceship, and automotive anticollision bars. In order for the perfect mechanical performances of this material, many researchers have studied the static or dynamic properties and microscopic topological structure of these materials via to the existing theories and tests [3].

In terms of mechanical performances of honeycombs, Yang [4] analyzed the effect of cell size on material plateau stress, and the results showed that plateau stress of materials was closer related to their cell size. Applying the SHPBs, Merrett et al. [5] studied the dynamic responses of foam aluminum under different impact velocities, and the experimental results revealed that the elastic failure strength as well as plastic strain in plateau stage of foam aluminum increase as the impacting velocity increases, which indicated that the foam aluminum has an effect of strain rate obviously. Liao et al. [6] focused on the influence of random defects on deformation mode and mechanical behaviors of foam metals and opened out the deformation mechanism of foam metals with defects. Montanini [7] carried out a dynamic experiment to investigate the relationship between efficiency of energy absorption and its strain rate, and the investigation results showed the energy absorption capacity has an obvious relevance to topological structures under the same load condition.

The existing researches have made it clear that the random defects can make a great influence on the service performances of honeycomb materials. Liu and Zhang [8] and Kou et al. [9] studied the dynamic performances and crushing properties of honeycomb materials with various random defect ratios. Those studies revealed that the crushing mode of honeycomb materials subjected to impacting varies as the random defects increase. Meanwhile, the nominal plateau stress of honeycomb materials in the same loading conditions reduces as the missing cells increase. According to the axial compressive test, Barnes et al. [10] and Chung and Waas [11] investigated the influence of cell configuration on crushing modes of open-cell foam metal as well as circular cell polycarbonate honeycombs, respectively, which revealed the mechanism of crushing modes and mechanical behaviors for various honeycomb materials with diverse cell configurations [12] as well as varied loading conditions.

Based on the existing researches, the fact can be known that their service performances of honeycomb materials are affected by multiple factors, including properties of basic materials, topological structure, cell configuration, and loading condition. Summarizing the existing studies about honeycomb materials, a recent status can be found that there have been so many studies focusing on phenomenological mechanical properties and few investigations on its constitutive model of this material. In basis of existing results, the explicit finite element method (FEM) software, ANSYS LS-DYNA, was applied for simulation of dynamic responses of honeycomb materials subjected to impact loading. This paper aims to analyze the influence of material random defects on plateau stress and establishes a constitutive model of honeycomb materials taking random defects, strain rate as well as topological structure into consideration. In the proposed constitutive model, a coefficient representing defects is introduced to reflect the influence of random defects in honeycomb on dynamic mechanical properties. It offers a reference for the further investigations about honeycomb materials and the design of cellular materials in practical engineering.

2. Honeycombs and Their Computational Models

2.1. Honeycomb Model Description. Here, the configuration of honeycomb cells is regular hexagon, and honeycombs are assembled with diverse cells with different cell wall sizes, respectively. The cell wall lengths include 2 mm, 3 mm, and 4 mm, and the wall thickness of all honeycombs is set to 0.6 mm. The sizes of the overall model specimen are $100 \times 100 \times 2$ mm. The random defects in honeycomb are generated by removing cell walls randomly, and the rate of defects in honeycombs can be represented by α. The ratio of defects [9] in honeycombs can be calculated as follows:

$$\alpha = \frac{n}{N}, \tag{1}$$

where n and N denote the amount of removing cell walls and all cell walls, respectively. Here, defects are generated randomly by removing specific cell wall, and the algorithm of random removing can be conducted via ANSYS Parametric Design Language (APDL).

Here, for the random defects, random removing of cell walls was conducted via an algorithm. In terms of this algorithm, there are three major parameters to rule this removing process. They are summation of removing cells, number of removing cell, and the summation of reserving cells, respectively. When all of the major parameters are given, the software, ANSYS/LS-DYNA, will produce a random number n_1 in span of the range $(1, N)$, where the symbol N represents the summation of all cell walls before removing randomly. Then, the cell wall labeled as n_1 was removed. Meantime, all serial numbers of reserving cell walls were reordered again. Next, another number, n_2, was produced randomly in the span of the range $(1, N-1)$, and the removing procedure will be performed again. And the removing algorithm will not terminate until the summation of removing cell walls reaches the setting value. The removing process, presented herein was ruled by a recurrence program, which be expressed as DO subroutine in APDL.

For the honeycomb structure, its topological entirety would be destroyed if its rate of defects overmatches 35%. And coherent voids would be generated when the rate of defects is over 25% [8]. So, as to ensure the stability of relative density in honeycombs with various defect rates, the ratio threshold of defects is set to 25% in this paper. Here, quantity of cell walls for the original honeycomb is 6088, while quantities of removing cell walls in honeycomb samples containing various defect ratios, including 5%, 10%, 15%, 20%, and 25%, are 304, 608, 913, 1216, and 1520, respectively. The configuration of honeycombs with random defects is shown in Figure 1.

Meanwhile, the relative density of honeycombs without defects is represented as ρ_r, which is denoted by the rate of honeycomb density ρ^* and the basic material density ρ_s. It can be calculated as follows:

$$\rho_r = \frac{\rho^*}{\rho_s} = \sum_{i=1}^{N} \frac{l_i t_i}{(L_1 L_2)}, \tag{2}$$

where i is the sequence number of reserved cell wall, l is the wall thickness of reserved cells, and L_1 and L_2 denote specimen edge sizes.

2.2. FEM Modeling. Here, the basic material is aluminum [8, 9, 13], and its mechanical parameters are listed in Table 1. The element type of models was chosen as SHELL163. There are five integral points in the direction of shell thickness. Setting automatic unilateral contact type among cells to simulate the crushing and collapse of honeycombs, the dynamic friction index was set to be 0.5. In order to make stress in specimens evenly, a rigid

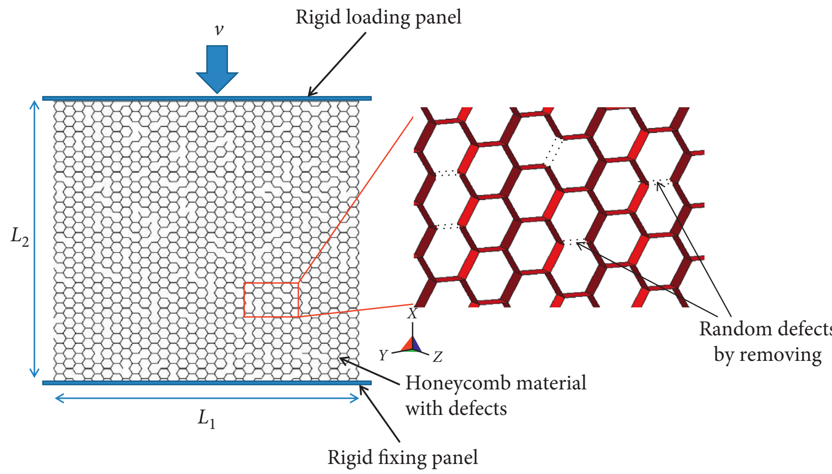

Figure 1: Finite element model of honeycombs with random defects.

Table 1: Material parameters of aluminum metal.

Elastic modulus E (GPa)	Yield strength σ_y (MPa)	Poisson's ratio ν	Density ρ_s (kg/m^3)
69	76	0.3	2700

punching plate was set on the top end of specimens and a rigid base sheet with constraints was set on the bottom of specimens. The loading condition of honeycomb specimens can be seen from Figure 1. To meet the plate stress condition of honeycombs, constraints were placed on the outside of honeycombs. In terms of loading regime, the loading type is an impact loading with a constant punching velocity, and the loading velocity was set as 20 m/s.

2.3. Validation of Model. To validate the finite element models in this study, a simulation of impact experiment [8] about honeycombs was carried out. According to the loading condition in Ref. [5], a honeycomb specimen was loaded by punching with an impact velocity of 50 m/s. The stress-strain curves of simulation result and its corresponding test are shown in Figure 2. It can be seen that the stress-strain of simulation could be meted with that of existing experiments [5] well. The only error in comparison of curves was that the plateau stress of simulation overmatches the plateau stress of the experiments a little, which may be caused by that honeycomb specimens in which test contains defects during its producing process, and the simulated specimen is intact nearly. Furthermore, the crushing mode of honeycombs is an important indicator to assess porous materials' mechanical performances. The comparison of the dynamic crushing mode in Ref. [12] and its simulation was performed, which could be seen in Figure 3. From their comparison, it can be known that the crushing mode and its collapse condition of honeycombs meet with that of existing test specimens well. Overall, the proposed FEM models here have a better capacity to investigate further the dynamic responses and mechanical performances of honeycombs.

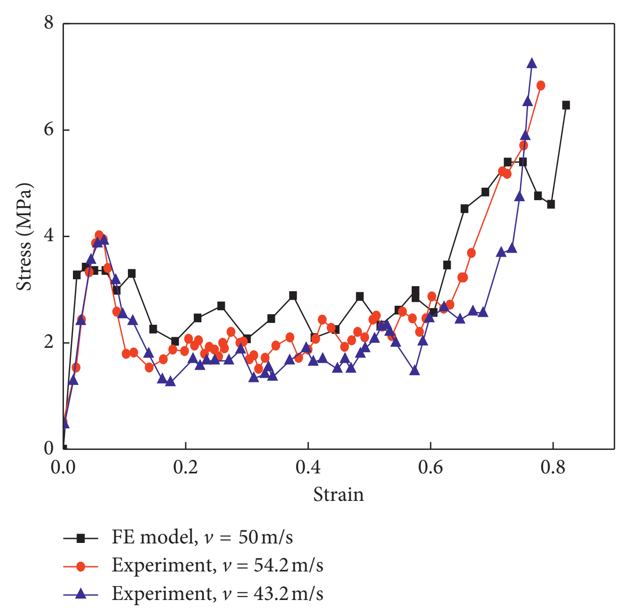

Figure 2: Stress-strain curves of honeycomb materials.

3. Influence of Random Defects on Mechanical Performances of Honeycomb

Random defects are generated inevitably during its producing process. The influence of defects on its relative density can be ignored in reality. Hence, the threshold rate of random defects in honeycombs was set among 0~25%. This section aims to investigate the effect of random defects on mechanical properties of honeycombs.

Varied stress-strain curves of honeycombs with different defect rates are shown in Figure 4. As Figure 4 shows, the

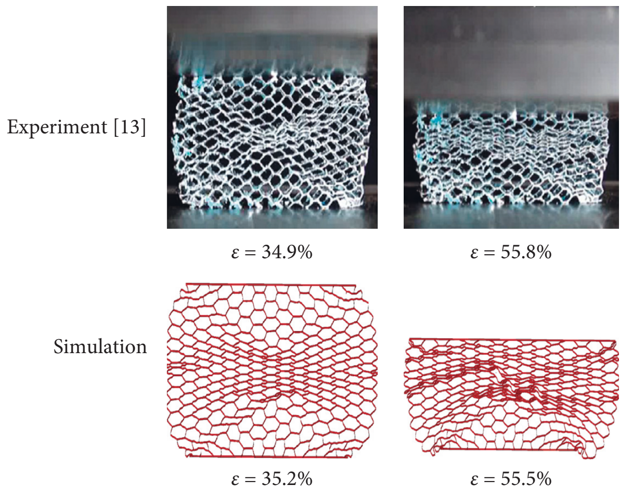

Figure 3: Comparison of deformation modes.

random defects do not affect their stress-strain trend, which still present a typical "Three Stages" curves, namely, elastic stage, plastic collapse stage, and densification stage. The stresses in the plateau zone are higher than the theoretical static stress calculated by Gibson and Ashby [14] (see equations (3a) and (3b)), which indicates the honeycombs possess the effect of strain rate:

$$\sigma_{\mathrm{pl}} = \sigma_{\mathrm{ys}}\left(\frac{t}{l}\right)^2 \frac{1}{2\left((h/l)+\sin\theta\right)\sin\theta}, \tag{3a}$$

$$\sigma_{\mathrm{pl}} = \sigma_{\mathrm{ys}} C\left(\frac{\rho^*}{\rho_s}\right)^{3/2}, \tag{3b}$$

where σ_{pl} denotes the plateau stress, σ_{ys} denotes the yield strength of basic materials, and w, l, and t denote the cell wall sizes of width, length, and thickness, respectively, θ denotes the angle among cell walls, and C is a coefficient of honeycombs about cell configuration. The difference of equations (3a) and (3b) [14] is that equation (3a) can be used for the regular honeycombs and equation (3b) is used for the irregular honeycomb materials.

Meanwhile, in this paper, the plateau stress of honeycombs can be calculated as equation (4). Furthermore, to study the influence of random defects on its plateau stress, a dimensionless analysis was conducted on plateau stresses of honeycombs with various loading conditions, and the relative plateau stress σ_{r} was used, and it is defined as equation (5):

$$\sigma_{\mathrm{pl}} = \frac{1}{\varepsilon_{\mathrm{d}} - \varepsilon_{\mathrm{y}}} \int_{\varepsilon_{\mathrm{d}}}^{\varepsilon_{\mathrm{y}}} \sigma \, d\varepsilon, \tag{4}$$

$$\sigma_{\mathrm{r}} = \frac{\sigma_{\mathrm{pl}}}{\sigma_{\mathrm{p}}^0}, \tag{5}$$

where σ_{p}^0 denotes the plateau stress of honeycomb subjected to quasistatic loading and ε_{y} and ε_{d} denote its yield strain and densification strain, respectively.

From Figure 5, the influence of random defects on its plateau stress of honeycombs can be seen. Under the load condition with low speed, plateau stresses of honeycombs with different defect rates decrease as random defects increase. And the relationship between the rate of random defects and relative plateau stress can be described by

$$\sigma_{\mathrm{r}} = \Delta(\alpha) = b_1 - b_2\alpha, \tag{6}$$

where $\Delta(\alpha)$ is the function of the random defect rate and b_1 and b_2 are fitting coefficients, respectively, which can be described as equations (7) and (8).

Figure 6 shows the fitting curves of b_1 and b_2 in basis of relevant data from simulation results and existing experimental results [9, 13]. For different honeycombs with various defect rates, b_1 and b_2 are given in Table 2, respectively:

$$b_1 = 1.0918\rho_{\mathrm{r}}^{0.068}, \quad R = 0.85, \tag{7}$$

$$b_2 = 0.00111\left(1+\rho_{\mathrm{r}}\right)^{7.535}, \quad R = 0.92. \tag{8}$$

What showed in Figure 7 indicates that the coefficients of b_1 and b_2 are related closely to its relative density of honeycombs. When relative density of honeycombs varies, the material coefficients, b_1 and b_2, also vary. The proposed equations (equations (7) and (8)) could express the relationship between relative density of honeycombs and its material coefficients well, which also be applicable to existing results from experiments [9, 13].

4. Constitutive Model of Honeycombs Taking Random Defects into Consideration

4.1. Constitutive Model. The mechanical performances are affected by mechanical parameters of its base materials as well as cell structure configurations. And under impact loading, the effect of strain rate of honeycombs should not be ignored. Therefore, the constitutive model of honeycombs subjected to impact loading should contain factors of base material property, topological structure, and loading condition. Many existing researches [14–16] revealed that the main factors, including mechanical properties of basic materials, effect of strain rate caused by punching, and topological structure, are independent. Taken those respects into consideration, a schematic diagram of the constitutive model for honeycombs is proposed in Figure 8. From Figure 8, it can be seen that the factors including topological structure, basic material properties, and effect of strain rate are represented by independent elements, respectively. And for the cells' topological structure of metal honeycomb materials, varying cell's configuration or ratio of random defects entirely will cause an obvious change of mechanical behaviors of honeycombs. From this viewpoint, effect of random defects could be seen as the same of cells' configuration. Thus, the topological structure of cellular materials can be seen as a combination of the three subfactors. Therefore, in the schematic of the constitutive model of honeycombs, the simplified model is combined with three major factors, strain rate effect, based materials, and topological structure. Furthermore, the topological structure in the constitutive

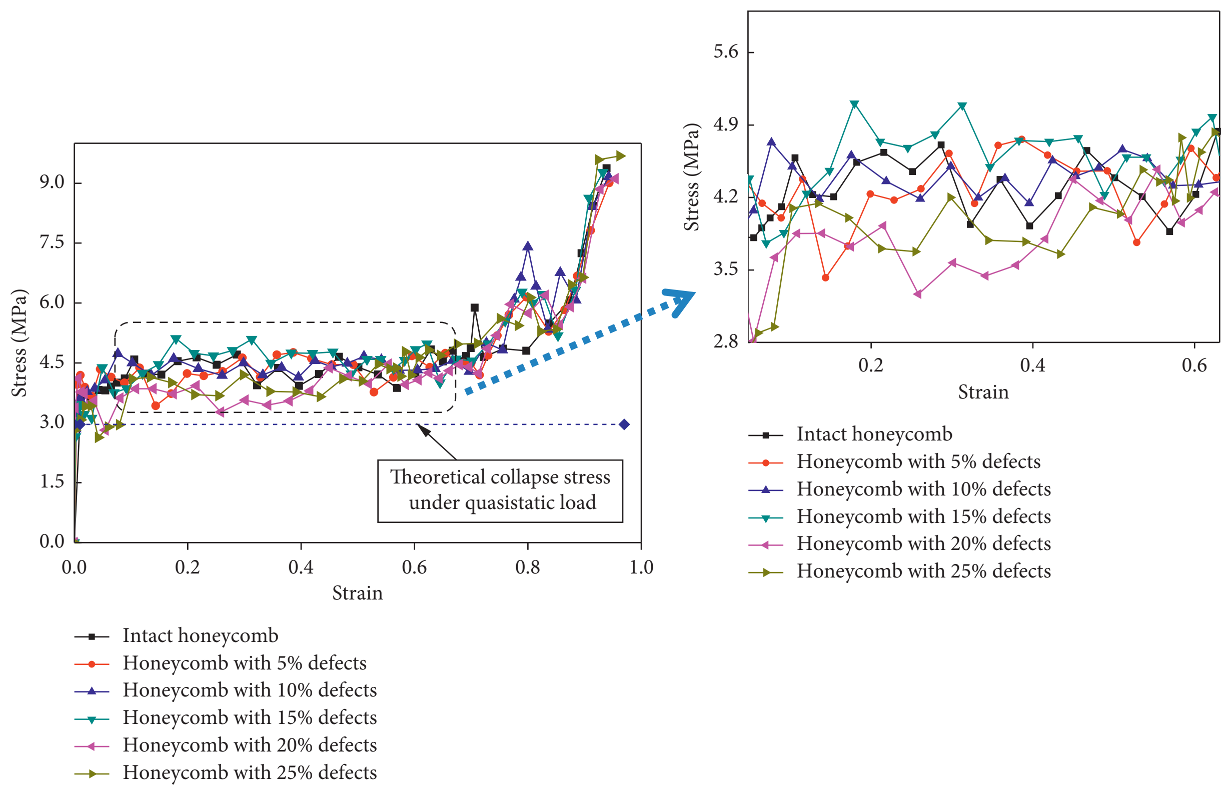

Figure 4: Strain-stress curves of honeycomb material under impact loading.

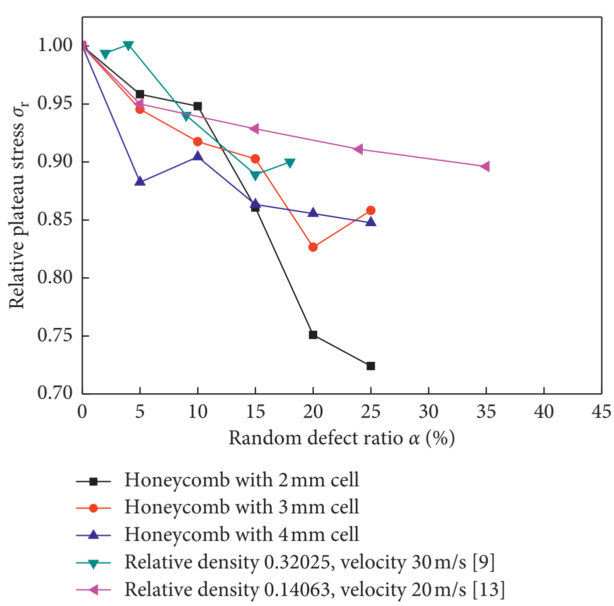

Figure 5: Effect of random defect ratio on the plateau stress.

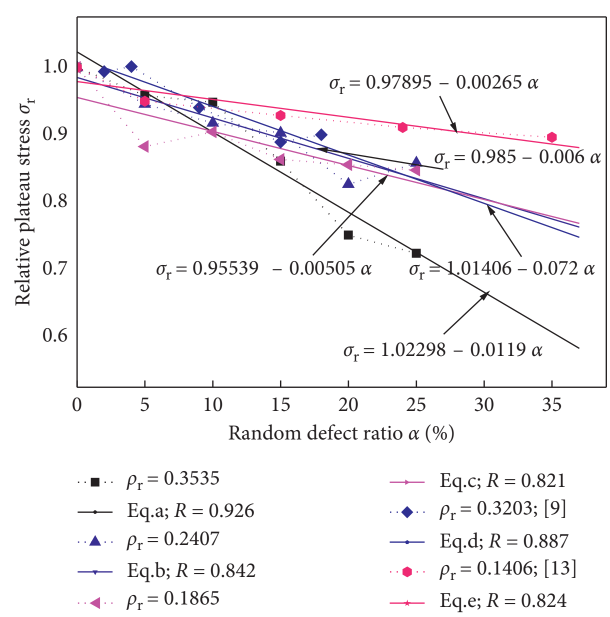

Figure 6: The relative plateau stress with random defects and its relationship.

model can be assembled with three subfactors, namely, cell configuration, cell shape, and random defects.

In the foundation of the concept diagram in Figure 8, a conceptual formula of the constitutive model is expressed by

$$\sigma(\varepsilon) = f(\alpha, \rho_r, \varepsilon, \dot{\varepsilon}), \tag{9}$$

where ε and $\dot{\varepsilon}$ denote strain and its strain rate of the specimen, respectively.

And a calculation formula about the constitutive model of honeycombs is proposed as

$$\sigma(\varepsilon) = \Delta(\alpha)\left[\sigma_{pl}(\rho_r)\right]\left\{\left(2\varepsilon^{\beta_1}\right)e^{\left[-\beta_2\left(\varepsilon-\varepsilon_y\right)\left(\varepsilon_d-\varepsilon\right)\right]}\right\}\left(1 + Dlg\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right), \tag{10}$$

Table 2: The coefficients of relative plateau stress on equation (5) and relative density of honeycomb.

Relative density σ_r	Coefficient b_1	Coefficient b_2	R	Reference
0.3535	1.023	0.0119	0.926	
0.2407	0.985	0.0062	0.842	
0.1865	0.965	0.0051	0.851	
0.3302	1.014	0.007	0.887	[9]
0.1406	0.979	0.0027	0.844	[13]

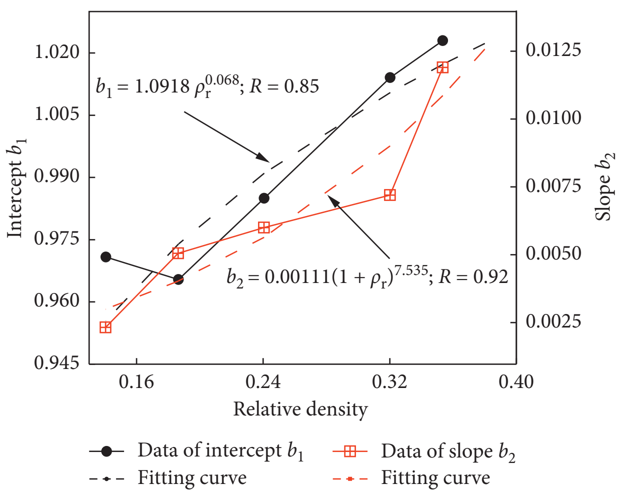

Figure 7: The relationship of coefficients and relative density of honeycomb.

where $\dot{\varepsilon}_0$ is the standard strain rate of specimens and the value of $\dot{\varepsilon}_0$ is $1\times10^{-3}\cdot\mathrm{s}^{-1}$, β_1 and β_2 are material coefficients of honeycombs, the effect of those on stress-strain curves is shown in Figure 9, D is the hardening coefficient of materials under impacting [15], which of aluminum is always 0.02~0.03, and σ_{pl} is the expression of plateau stress of honeycombs taken topological structure and relative density into consideration, which can be calculated by equations (3a) and (3b) when honeycomb cell shape is regular hexagon.

In this constitutive model, it is combined with four functions about random defects, relative density of mass, characterization of three-stage curve for porous materials, and effect of strain rate, respectively. In equation (10), the first section denotes the functional relation among random defect ratio and static plateau stress, the second section represents the function revealing the effect of relative density on static plateau stress, and the third section stands for a shape function controlling the tendency of the stress-strain curve. From existing experimental data on honeycomb metals, generally, it has been thought that the collapsing strain and densification strain are directly related to sample' relative density. Besides collapsing strain εy and demystification strain εd, other coefficients, beta 1 and beta 2, control the shape of the constitutive curve. Furthermore, after comparatively surveying existing curves in other publications, we found the slope of the subcurve during the elastic stage and densification stage is ruled by relative density of the whole piece. About the last section in equation (10), it represents the effect of strain rate on mechanical behaviors, which are accepted widely. Overall, as a combination of multiple factors, the proposed constitutive model could be thought to be a coupling function of honeycomb metals considering random defects, cell configuration, and loading regime.

It can be seen from Figure 9 that the variation of the value of β_1 and β_2 can lead to obvious change on the stress-strain curve. As Figure 9 shows, the slope of the stress-strain curve in the elastic stage decreases as the value of β_1 increases and that of the stress-strain curve in the densification stage increases as the value of β_2 increases. The relationship of stress-strain curve's shape and β_1, β_2 indicates that the coefficients of β_1 and β_2 are influenced by relative density of honeycombs. In order to reveal the relationship between relative density and β_1, β_2, the varied stress-strain curves from existing tests [5, 7, 10] and its coefficients are shown in Figure 10 and Table 3 in detail, respectively. Meanwhile, based on the results from this paper and existing researches, Figure 11 shows fitting curves of relative density and coefficients, and the calculated equations are described as the following equations:

$$\beta_1 = \frac{0.177}{(\sigma_r - 0.048)^{0.181}}, \tag{11}$$

$$\beta_2 = \frac{1.069}{\sigma_r^{0.869}}. \tag{12}$$

Significantly, it is noteworthy that the stress-strain curve of foam metal [5] in Figure 10 exists an obvious initial peak stress in the elastic stage. About elastic peak stress, there are shared points that this appearance may be correlated with loading direction as well as directional configuration of cells. A SHPB experimental data on foam metal under shock loading [17] indicated that an initial peak stress has been existed in mass around the front surface of SHPB, while that does not exists in mass around the back surface. That reveals the initial stress peak existing in the elastic stage may be caused by both inner factors and outer factors. Hence, it may be unconvincing to attribute the initial stress peak to constitutive relation of specimens. Due to the unclear mechanism of elastic peak force, initial stress peak in the curve obtained by Merrett et al. [5] is not considered in the proposed model here.

From Table 3 and Figure 11, it can be known that the proposed equations about β_1 and β_2 have an excellent capacity to meet with the existing results in the previous researches [5, 7, 10] and calculated results in this paper. At the same time, the fitting results also indicate that the coefficients in proposed equations are not only related closely to its topological structure but also mechanical parameters of basic materials, such as elastic modulus and yield strength.

According to the data in Table 3 and Figure 11, the coefficients of β_1 and β_2 indicate an obvious decline trend as the relative density of honeycombs increases. Referring to Figure 9, the fact is clear that the stress-strain curve's shape of

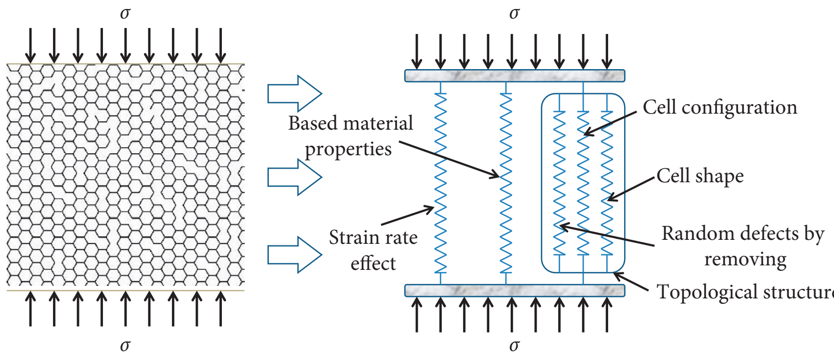

Figure 8: Schematic of simplified constitutive model.

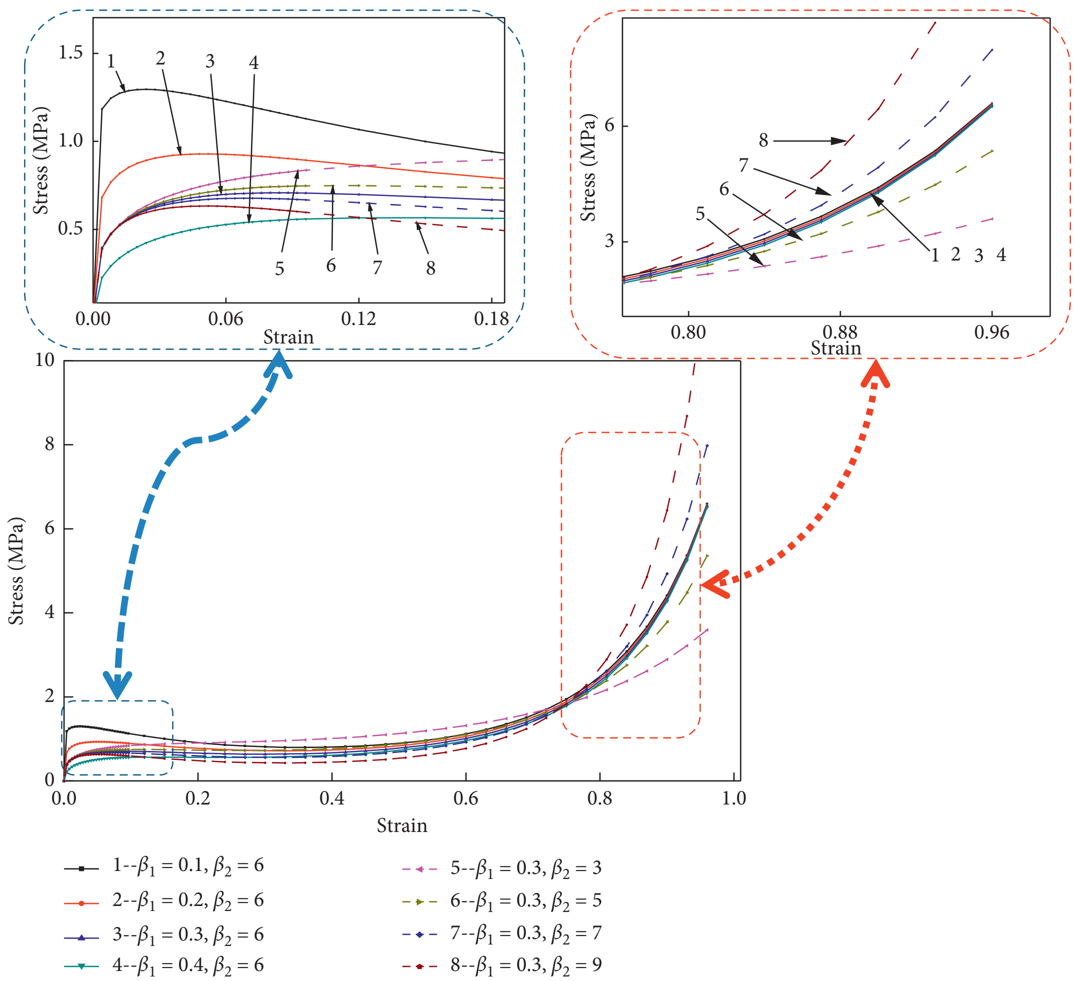

Figure 9: Constitutive model shape coefficients and its function curves.

honeycombs is affected by the value of β_1 and β_2. On the macromechanical performances, enhancement of relative density on honeycombs could cause a sharp slope of the stress-strain curve on the densification stage of cellular materials during its bearing period and a gentle slope of the stress-strain curve on the initial elastic stage. And these appearances have been observed in other existing experiments [14, 16].

4.2. Model Application. In order to verify the proposed constitutive model in this study, stress-strain curves of honeycombs under static and impact loading condition are compared with their calculated curves, respectively, which are shown in Figure 12.

From Figure 12(a), stress-strain curves under two loading conditions, including quasistatic and impact

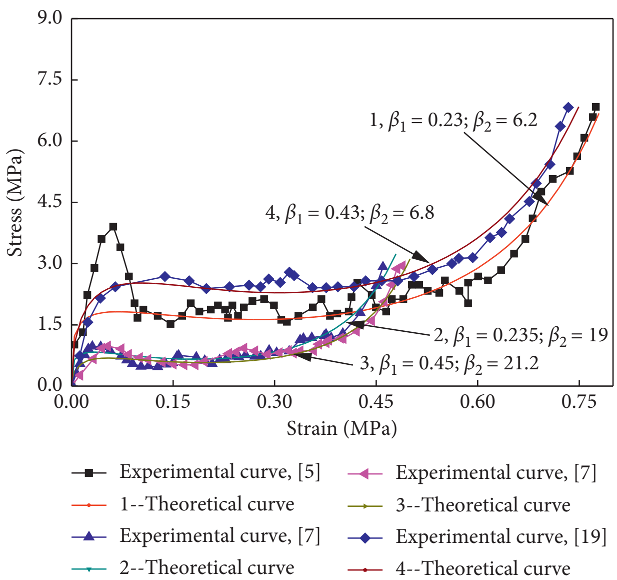

Figure 10: Experimental curves and its theoretical curves of honeycomb material.

Table 3: The relative density of honeycomb materials and its constitutive model coefficients.

Reference	Relative density	Constitutive coefficients	
		β_1	β_2
This article	0.186	0.25	2.5
	0.241	0.22	1.8
	0.334	0.24	1.8
[5]	0.085	0.3	10
	0.089	0.23	6.2
[7]	0.0723	0.235	19
	0.0563	0.45	21.2
[10]	0.0822	0.43	6.5
[19]	0.048	0.2	6

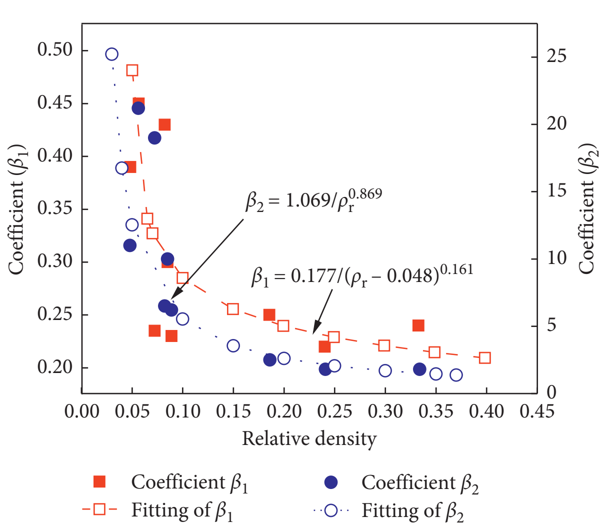

Figure 11: Constitutive model coefficients and its relative density.

loading, are given, respectively. Overall, it can be seen that the theoretical curves of honeycombs obtained by the proposed constitutive model agree well with that of simulations. For honeycombs without random defects, stress under impact loading in the identification phase is higher than the stress under quasistatic loading. And in Figure 12(b), the effect of random effect on mechanical behaviors, like trend of stress-strain curve and plateau stress, has been indicated. The comparison among different honeycombs with various defect ratios shows the plateau stress of honeycomb metals reduces as the ratio of random defects increases, which is in line with calculations obtained by the given constitutive model. Furthermore, for validating the applicability of the proposed model, experimental responses of open-cell foam metal under impact loading are demonstrated in Figure 12(c). In the case of open-cell foam metal [18], the strain rates of two loading regimes are $10\,\mathrm{s}^{-1}$ and $1000\,\mathrm{s}^{-1}$, respectively. By changing the corresponding coefficient representing strain rate, the trends of stress-strain curves with various loading conditions are changed. From Figure 12(c), stress-strain curves obtained by test and the proposed model are overall similar. But there is also a noteworthy appearance in the comparison of curves. Due to the difference of cell configuration of foam metals and regular honeycomb metals, the trends of stress-strain curves obtained by experiment and theoretical calculation have a slight deviation on the plateau stress phase and identification phase. About the deviation between stress-strain curves of foam metals, an improved constitutive model will be proposed based on this model here in the future work.

The comparison results indict that the established constitutive model of honeycombs could be used to investigate the dynamic performances of honeycombs subjected to punching whether with random defects or not. Meanwhile, the proposed model has a wide application range of cellular materials, such as foam metal and cellular honeycombs. Otherwise, when the first section of equation (10), namely, $\Delta(\alpha)$, is set to be a constant value of 1, equation (10) is valid for intact honeycombs; when $\dot{\varepsilon}$ in the last section of equation (10) is set to be the static standard strain rate $\dot{\varepsilon}_0$, the equation can be applied to the honeycombs under quasistatic loading condition.

5. Conclusions

Applying finite element analytical software, dynamic responses of honeycombs with varied defect rates are simulated. Based on simulation results and existing experimental data, a constitutive model of honeycombs taking topological structure, basic material parameters, and effect of strain rate into consideration was proposed. In this proposed constitutive model, three major influential aspects were contained, including material factor as well as loading condition. For the proposed constitutive model, coefficients of b_1, b_2 and β_1, β_2 have an obvious dependence on relative density of honeycombs, and the functional relationship between coefficients and material parameters can be obtained by statistical analysis

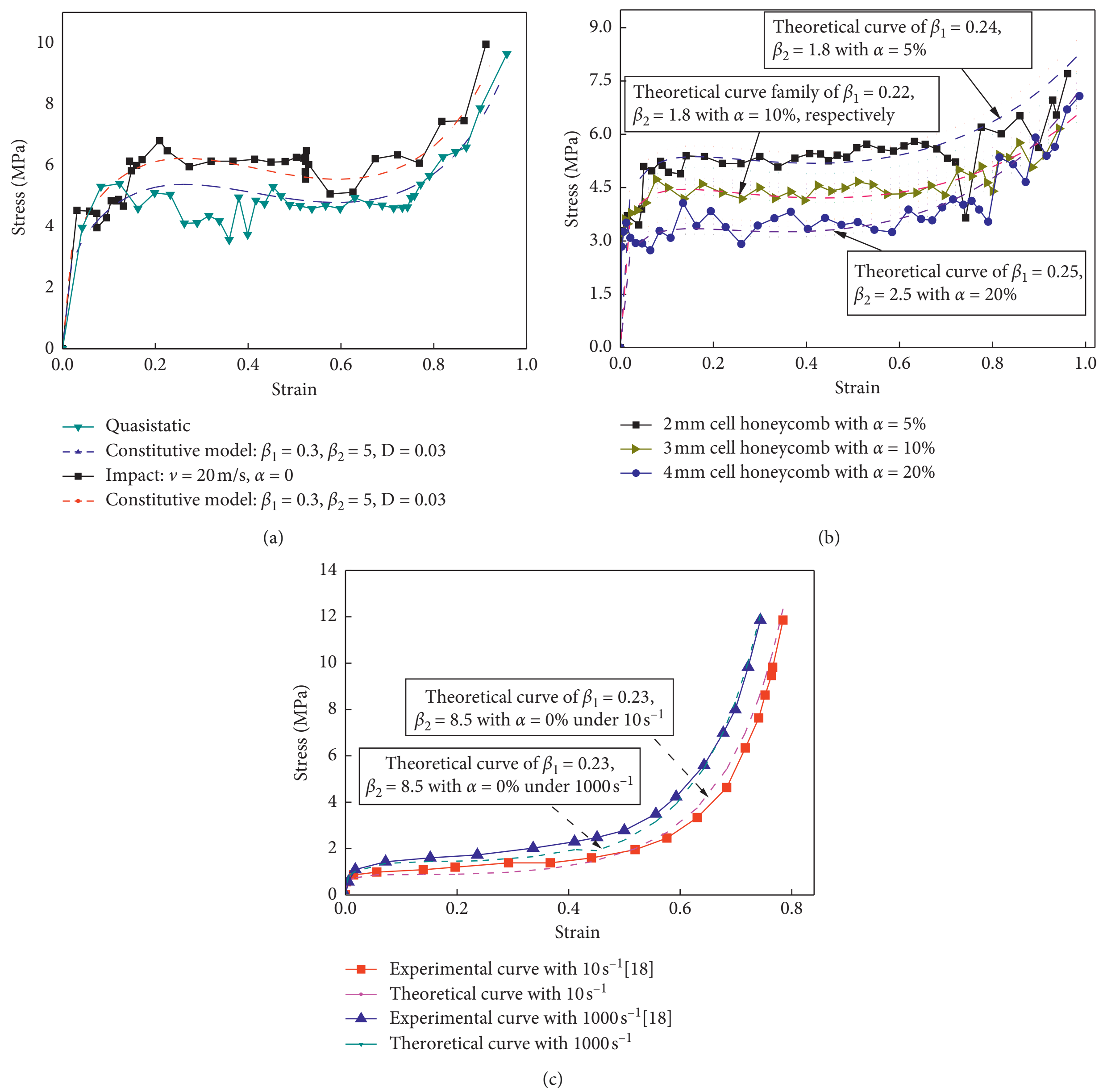

Figure 12: Stress-strain curves and its constitutive model: (a) the stress-stain curves of honeycomb without defects; (b) the stress-stain curves of honeycomb with, random defects under 20 m/s impact loading; and (c) experimental and theoretical curves of open-cell metal foam under various strain rates.

of experimental results. The proposed model has a great applicability for honeycombs under various service conditions.

Based on the proposed model, the future work about honeycomb materials containing random defects will focus on the dynamic performances, like energy absorption and impact resistance. On the other hand, the model proposed in this paper contains several empirical parameters. Explaining their engineering meanings of parameters and exploring the explicit formula among parameters and material performances may be an interesting work in future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

All the authors declare that there are no conflicts of interest regarding the publication of this article.

Authors' Contributions

Hu Jun and Ren Jianwe contributed equally to this work.

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