Materials Science Forum Vols. 706-709 (2012) pp 805-810
© (2012) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/MSF.706-709.805

Effect of Random Defects on Dynamic Response of Honeycomb Structures

Zhijun Zheng[a] and Jilin Yu[b]

CAS Key Laboratory of Mechanical Behavior and Design of Materials,
University of Science and Technology of China, Hefei, Anhui 230026, P. R. China

[a]zjzheng@ustc.edu.cn, [b]jlyu@ustc.edu.cn

Keywords: Cellular metals, finite element analysis, deformation mode, plateau stress

Abstract. The dynamic crushing behavior of cellular metals is closely related to their microstructure. Two types of random defects by randomly thickening/removing cell walls are investigated in this paper. Their influences on the deformation modes and plateau stresses of honeycombs are studied by finite element simulation using ABAQUS/Explicit code. Three deformation modes, i.e. the Homogeneous Mode, the Transitional Mode and the Shock Mode, are used to distinguish the deformation patterns of honeycombs under different impact velocities. The critical impact velocity for mode transition between the Homogeneous and Transitional modes is quantitatively determined by evaluating a stress uniformity index, defined as the ratio between the plateau stresses on the support and impact surfaces. It is found that the critical impact velocity decreases with increasing thickening ratio but increases with increasing removing ratio. The plateau stress on the impact surface heavily depends on the impact velocity due to the inertia effect. The random defects lead to a weakening effect on the plateau stress. For the honeycombs with randomly removing cell walls, the weakening effect is especially obvious at a moderate impact velocity. For the honeycombs with randomly thickening cell walls, the weakening effect is particularly severe at a low impact velocity, but this effect almost disappears when the impact velocity is high enough.

Introduction

Cellular metals have shown great potential applications as energy-absorbing materials. Their dynamic crushing behavior is closely related to their microstructure, especially the randomness and imperfections. Experimental investigation is the essential means to obtain the mechanical behavior of materials, but there are some limitations associated to dynamic tests of cellular metals [1]. Many types of morphological defects exist in the cellular metals, which usually result in a scatter of the responses in experiments. Moreover, homogeneity of deformation required by SHPB technique cannot be guaranteed at high velocity impact, and accurate measurement of strain distribution is nearly impossible. All these facts make experimental studies very difficult, especially when high strain rate is concerned. Finite element analyses have been extensively used to overcome the experimental difficulties [2-9].

Cell irregularity [2], cell irregularity with non-uniform cell wall thickness [3], randomly distributed solid inclusions [4,5], linearly arranged inclusions [6], randomly removing cell-walls [7], and micro-topology [8,9] have been employed in the finite element simulations to investigate their influences on the dynamic response of honeycombs under impact. Much understanding of the microstructural effects on the dynamic mechanical properties has been achieved. Two types of random defects caused by randomly thickening/removing cell walls are investigated in this paper. Their influences on the deformation modes and the plateau stresses of honeycombs are studied.

Numerical Models

A regular hexagonal honeycomb is constructed in an area of A = 103.92mm×90mm as the reference model, as shown in Fig. 1a. In this reference honeycomb, cells at the boundary are incomplete, and all cells are equivalent to 400 full cells, denoted as N = 400. The length of the cell walls is l = 3mm except that at the edges which is in half. Since each full cell contains six equal walls and every two neighboring cells share one wall, the total length of all cell walls is $3Nl$ = 3600mm. The cell-wall thickness for a regular honeycomb is uniform and can be calculated from

$$h_0 = \rho A / 3Nl, \tag{1}$$

where ρ is the relative density of the model. In this paper we choose ρ = 0.1, which leads to h_0 = 0.26mm.

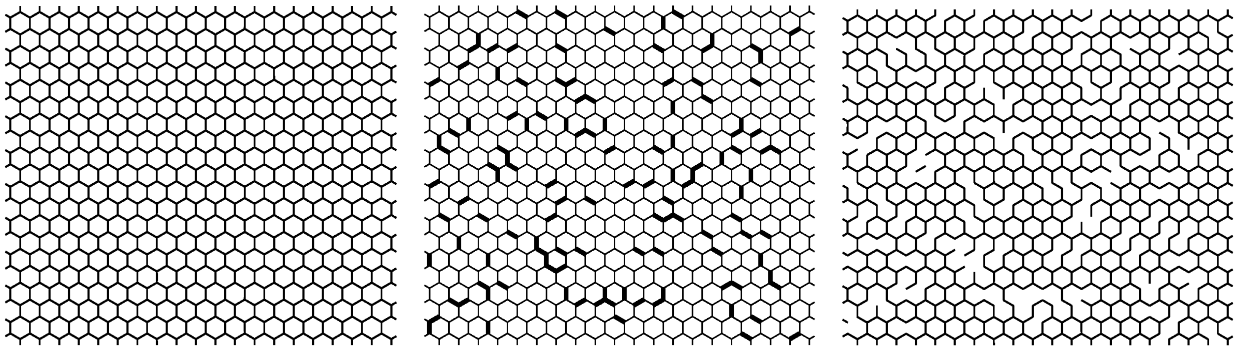
Two types of random defects by randomly thickening/removing cell walls are introduced in the reference honeycomb. They are characterized by a ratio, namely the thickening ratio or the removing ratio, defined as

$$k = nl / 3Nl = n / 3N, \tag{2}$$

where n is the number of thickening/removing cell walls and only the cell walls with full length l are considered to randomly thicken/remove. For the case of thickening, the thickness of the thickening cell-walls is doubled. To keep the relative density unchanged, the thickness of cell walls needs to be revised as

$$h = \rho A / (3Nl \pm nl) = h_0 / (1 \pm k), \tag{3}$$

where the plus and minus correspond to the cases of thickening and removing, respectively. Samples with k = 0.1 are shown in Fig. 1b and 1c. A series of k = 0.05, 0.10, 0.15 and 0.20 is considered and five random samples for each value of k are considered to obtain the statistical behavior.



(a) $k = 0$ (b) Thickening (k = 0.1) (c) Removing (k = 0.1)

Fig. 1. Honeycomb models: (a) the regular hexagonal honeycomb, (b) a honeycomb with randomly thickening cell walls and (c) a honeycomb with randomly removing cell walls

The finite element method using ABAQUS/Explicit code is employed to investigate the in-plane crushing behavior of these honeycombs. Each specimen is laid on a stationary rigid platen and compressed by another rigid platen with a constant velocity V_0. The cell walls of specimen are modeled by shell elements of type S4R (a 4-node quadrilateral shell element with reduced integration) with five integration points [2]. The length of element is 0.5mm and the length of specimen in the out-of-plane direction is 1mm. The nodes in the front and back planes are limited to moving in the corresponding planes, and each node in the back plane is limited to synchronously moving with the mirror node in the front plane by the *EQUATION command. Surface contact with slight friction is specified between all faces of cells that may contact during crushing. The friction coefficient is assumed to be 0.02. The material of cell walls is elastic-perfectly plastic with the Young's modulus, the yield stress and the Poisson's ratio being 66GPa, 175MPa and 0.3, respectively [1]. Uniaxial crushing is executed in the x and y directions. The nominal stresses on the impact and support surfaces are calculated as functions of the nominal strain ε. The plateau stress is an important property to characterize the dynamic response of cellular materials and it is defined as

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

where ε_{y} is the yield strain and ε_{D} the densification strain [10,11].

Results and Discussion

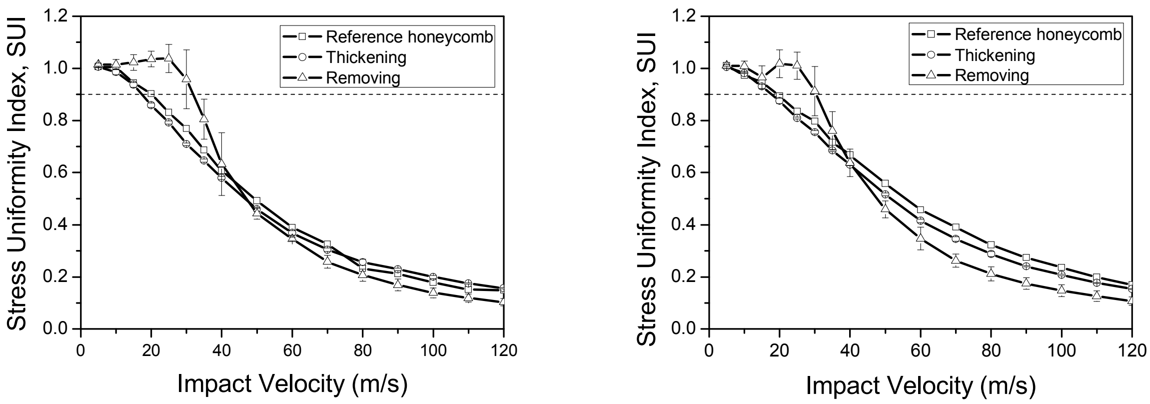
Different deformation patterns can be found in the dynamic crushing of cellular materials. With the increase of impact velocity, three different patterns, namely the "X", "V" and "I"-shaped patterns, have been reported in the in-plane crushing of regular honeycombs [12]. At a low impact velocity, the crushing bands are induced by many factors such as the weakest links, the boundary conditions and the height-to-width ratio of specimen, but at a high impact velocity the crushing bands are mainly caused by inertia [2]. For regular honeycombs compressed at a low velocity, the double-"V"-shaped pattern also can be observed [2].

More complicated deformation patterns have been observed in the in-plane crushing of Voronoi honeycombs. According to the impact velocity, they were catalogued into the Quasi-static Homogeneous Mode, the Transitional Mode and the Dynamic/Shock Mode [1,2]. In this paper, we also employ these deformation modes to distinguish the deformation patterns of honeycombs with random defects under different impact velocities. At a low impact velocity, a Homogeneous Mode takes place where multiple randomly distributed crush bands appear in the specimen and the stress is macroscopically homogeneous. At a very high impact velocity, a progressive layer-by-layer collapse band forms from the impact end, and the deformation occurs like a shock wave propagating through the cellular materials. This mode is called the Shock Mode. At a moderate impact velocity, a Transitional Mode occurs with most crush bands being concentrated near the impact end. Deformation mode maps can be constructed through the empirical observations, so the critical impact velocities for modes transition can be estimated [2,7].

When a honeycomb is crushed in the Transitional Mode or Shock Mode, it should be treated as a structure rather than a material, since the inertia is involved in the dynamic response of honeycomb and the nominal strain and strain-rate are size dependent [1]. The quantitative critical impact velocities for mode transitions are desired. The critical impact velocity for mode transition between the Homogeneous and Transitional modes is called here the first critical velocity, V_{c1}, while that between the Transitional and Shock modes is named as the second critical velocity, V_{c2}. A uniformity coefficient of plateau stress was proposed by Liu et al. [1] to determine the first critical velocity. The coefficient is here renamed as the stress uniformity index (SUI), which is defined as

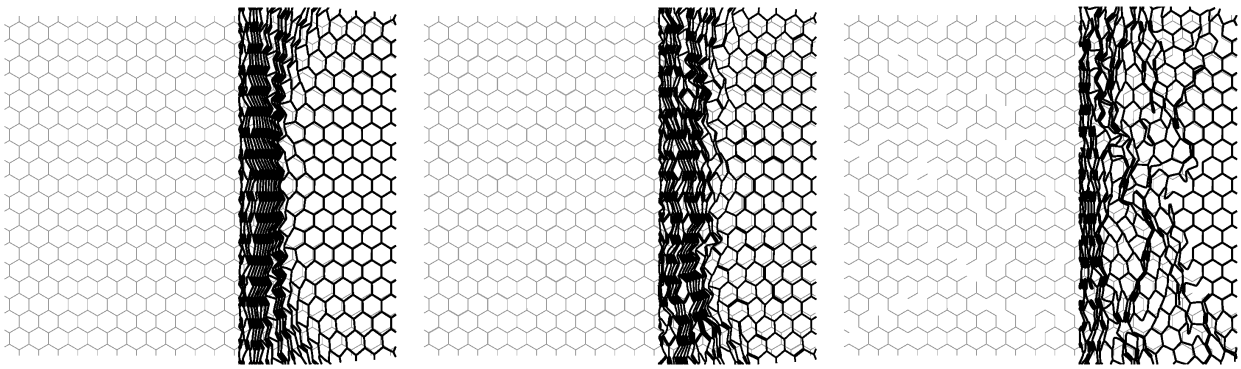
$$\mathrm{SUI} = \sigma_{\mathrm{pl}}^{\mathrm{s}} / \sigma_{\mathrm{pl}}^{\mathrm{i}} , \tag{5}$$

where $\sigma^{\mathrm{i}}_{\mathrm{pl}}$ and $\sigma^{\mathrm{s}}_{\mathrm{pl}}$ are the plateau stresses on the impact and support surfaces, respectively. When a honeycomb is compressed at a low velocity, the stresses at the impact and support ends are almost in equilibrium and the value of stress uniformity index is near one, as shown in Fig. 2. When the impact velocity is high enough, the stress uniformity index decreases rapidly with the increase of impact velocity. The first critical velocity V_{c1} is determined by setting the critical value of stress uniformity index being 90% [1]. Fig. 2 shows that the first critical velocities of the reference honeycomb in the x-direction and y-direction are both about 20m/s. The first critical velocities of the honeycomb with randomly thickening cell walls (k = 0.1) are slightly less than those of the reference honeycomb. However, the first critical velocities of the honeycomb with randomly removing cell walls (k = 0.1) are about 30m/s, much greater than those of the reference honeycomb. Some local crush bands are more easily induced by removing cell walls since the local strengths decrease, as shown in Fig. 3. It is hard to give an accurate definition of the second critical velocity V_{c2}. In our previous work [1], this critical velocity is determined by observing the deformation process. When the honeycomb is collapsed layer by layer, the honeycomb is regarded as deforming in the Shock Mode [1]. The minimum impact velocity for this mode is taken as the critical velocity of mode transition, but its accurate definition is open. For all honeycombs in this paper, the second critical velocity V_{c2} is found to be about 80m/s, regardless of the defects.



(a) Crushing in the x-direction (b) Crushing in the y-direction

Fig. 2. Variation of the stress uniformity index (SUI) with the impact velocity.



(a) Reference honeycomb (b) Thickening (k = 0.1) (c) Removing (k = 0.1)

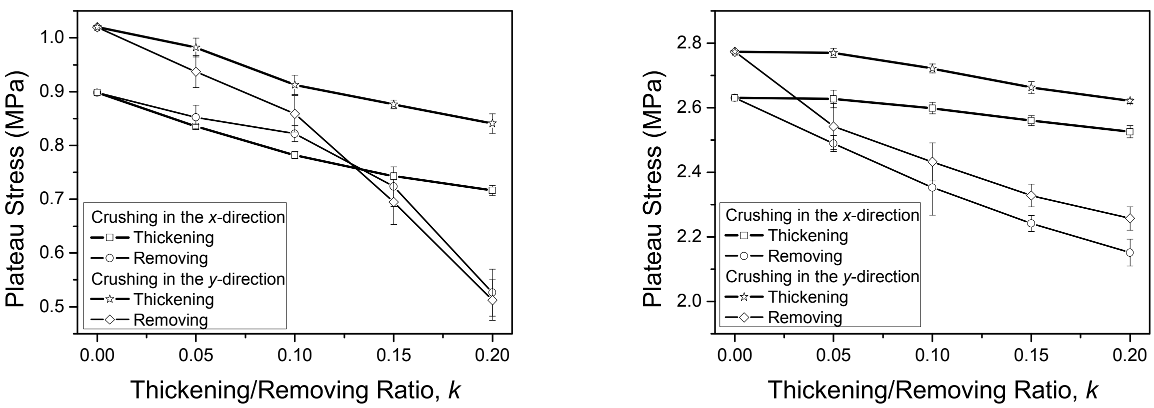
Fig. 3 Deformation patterns of honeycombs crushed in the x-direction at V_0 = 50m/s with the nominal strain of 0.6.

The plateau stress on the impact surface heavily depends on the impact velocity, but the plateau stress on the support surface is not very sensitive to the impact velocity [1]. Here, we only focus on the plateau stress on the impact surface. An anisotropy response in the reference honeycomb was found that the plateau stress in the y-direction is higher than that in the x-direction [2].

We consider two specific impact velocities, 20m/s and 80m/s, which are close to the first and second critical velocities, respectively. Variations of plateau stress on the impact surface with the thickening/removing ratio are shown in Fig. 4. It is found that the increase of the thickening/removing ratio leads to a decrease in the plateau stress, and the decrease of plateau stress in the case of removing is faster than that in the case of thickening with the same ratio. When the relative density is identical, for the case of removing, the structural integrate is lost, so the strength of honeycomb significantly decreases, although the thickness of remained cell walls increases, which compensates the strength of honeycomb slightly. On the other hand, for the case of thickening, the structural integrate is maintained, but the decrease of the thickness of most cell walls leads to a decline in the overall strength of honeycomb.

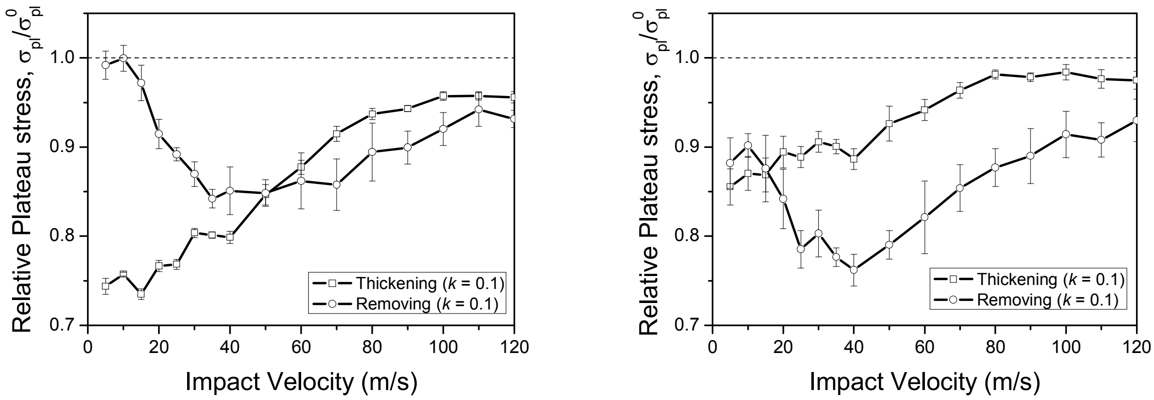
When the impact velocity is near the first critical velocity, the removing ratio may eliminate the anisotropy effect but the thickening ratio does not. The reason is that local crush bands are easily induced by removing cell walls when the impact velocity is not very high, as mentioned earlier. When the impact velocity is high enough, a honeycomb deforms in the Shock Mode, i.e. the deformation occurs like a shock wave propagating through the specimen. In this case, the defects far ahead of the wave front will not affect the response of honeycomb. Hence, no significant elimination of the anisotropy effect is found, as shown in Fig. 4b.

For the thickness/removing ratio of 0.1, variations of the relative plateau stress on the impact surface with the impact velocity are shown in Fig. 5, in which the plateau stress of regular honeycombs is denoted as $\sigma^0_{\rm pl}$. The defects caused by randomly thickening/removing cell walls weaken the plateau stress. However, it is found that the influences of these two kinds of defects are somewhat different when the impact velocity is low. For the case of removing, when the impact velocity is not high, the relative plateau stress decreases with the increase of impact velocity, and the weakening effect is especially obvious at a moderate impact velocity. On the other hand, for the case of thickening, the relative plateau stress increases with the increase of impact velocity, so the weakening effect is particularly severe at a low impact velocity. When the impact velocity is high enough, the weakening effect becomes not significant for both cases, in comparison with the inertia effect.



(a) V_0 = 20m/s (b) V_0 = 80m/s

Fig. 4. Variations of the plateau stress on the impact surface with the thickening/removing ratio.



(a) Crushing in the x-direction (b) Crushing in the y-direction

Fig. 5. Variations of the relative plateau stress on the impact surface with the impact velocity.

Summary

Three deformation modes, i.e. the Homogeneous Mode, the Transitional mode and the Shock Mode, are used to distinguish the deformation patterns of honeycombs under different impact velocities. The critical impact velocity for mode transition between the Homogeneous and Transitional modes is quantitatively determined by evaluating a stress uniformity index. It is found that this critical impact velocity decreases with increasing thickening ratio but increases with increasing removing ratio. The plateau stress on the impact surface heavily depends on the impact velocity due to the inertia effect. The random defects lead to a weakening effect on the plateau stress. For the honeycombs with randomly removing cell walls, the weakening effect is especially obvious at a moderate impact velocity. For the honeycombs with randomly thickening cell walls, the weakening effect is particularly severe at a low impact velocity.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Projects Nos. 90916026 and 11002140) and the China Postdoctoral Science Foundation (Project No. 20100470860).

References

[1] Y.D. Liu, J.L. Yu, Z.J. Zheng and J.R. Li: Int. J. Solids Struct. Vol. 46 2009), p. 3988

[2] Z.J. Zheng, J.L. Yu and J.R. Li: Int. J. Impact Eng. Vol. 32 (2005), p. 650

[3] K. Li, X.L. Gao and J. Wang: Int. J. Solids Struct. Vol. 44 (2007), p. 5003.

[4] D.P. Kou. *Effects of meso-structure on the mechanical behavior and multi-objective optimization design of cellular metals*. Dissertation, University of Science and Technology of China, 2008. (in Chinese)

[5] H. Nakamoto, T. Adachi and W. Araki: Int. J. Impact Eng. Vol. 36 (2009), p. 73

[6] H. Nakamoto, T. Adachi and W. Araki: Int. J. Impact Eng. Vol. 36 (2009), p. 1019

[7] D.P. Kou, J.L. Yu and Z.J. Zheng: Lixue Xuebao/Chinese Journal of Theoretical and Applied Mechanics Vol. 41 (2009), p. 859 (in Chinese)

[8] Y. Liu and X.C. Zhang: Int. J. Impact Eng. Vol. 36 (2009), p. 98

[9] X.M. Qiu, J. Zhang and T.X. Yu: Int. J. Impact Eng. Vol. 36 (2009), p. 1231

[10] M. Avalle, G. Belingardi and R. Montanini: Int. J. Impact Eng. Vol. 35 (2001), p. 455

[11] P.J. Tan, S.R. Reid, J.J. Harrigan, Z. Zou and S. Li: J. Mech. Phys. Solids Vol. 53 (2005), p. 2174

[12] D. Ruan, G. Lu, B. Wang and T.X. Yu: Int. J. Impact Eng. Vol. 28 (2003), p. 161