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Crushing analysis of multi-layer aluminum honeycomb – experiment and numerical simulation

To investigate the performance of multi-layer aluminum honeycombs under compression, experiments have been carried out, where crush behaviours were compared between two combinations by using finite element program ANSYS/LS-DYNA, and the validation of the FE model was approved by comparing the simulation result with the data from the experiment. The results show that the force-displacement curves of a multi-layer aluminum honeycomb reflect a trend, in which the peak forces decrease gradually with the increase of layers and the plateau stage is getting shorter with the curves becoming increasingly smooth. This trend is viewed as being beneficial to the compressive process when the specimens are fully crushed. The energy absorption is basically linearly proportional to the number of layers. The staggered arrangement should be given priority due to its energy absorption property.

Keywords: *Multi-layer, aluminum honeycomb, crush, numerical simulation*

1. Introduction

Aluminum honeycomb is widely used in packaging, aerospace, shipbuilding, construction and other fields due to the energy-absorbing property [1]. The out-of-plane direction has been determined to be the strongest direction which absorbs a signiûcant amount of energy during deformation [2]. Therefore, the focus of many studies has been on the out-of-plane energy absorption and dynamic mechanics of the aluminum honeycomb [3-8]. The out-of-plane crushing behaviour of four types of aluminum hexagonal honeycombs was extensively investigated by Xu et al. [9], and their experiment demonstrated that the mean plateau force was linearly related to the specimen dimensions. Some signiûcant research results about velocity sensitivity of the aluminum honeycomb under high-speed axial impact were obtained by Wang et al. [10]. Uniaxial compression experiments on aluminum honeycomb were performed to investigate localization of deformation in cellular materials by Mohr et al. [11], and these results provide a basis for the mechanical modelling of materials that evolve statistically inhomogeneous microstructures during deformation. Through analyzing one Y-shaped cross-section structure of a honeycomb cell, the formula for determining the relative density of a honeycomb with regular hexagon cell shape was derived by Liu et al. [12]. The dynamic crush behaviours of aluminum 5052-H38 honeycomb specimens under compressed dominant inclined loads were investigated by Hong et al. [13]. Quasi-static and dynamic tests were conducted for investigating the mechanical behaviour of aluminum hexagonal honeycombs under combined compression-shear loads by Ashab et al. [14].

As mentioned above, most research on the aluminum honeycomb has been limited to out-of-plane study of the quasi-static or dynamic compression of single layer aluminum honeycombs, but relatively little research has been done on multi-layer aluminum honeycombs. The multi-level aluminum honeycomb buffer structure was studied by Li et al. [15], and the results showed that the series honeycomb structures can absorb more energy than the single honeycomb structure. A cylindrical cushioning structure with the two types of aluminum honeycomb was designed and tested by Lin et al. [16]. And the results showed that a combined honeycomb buffer consisting of multi-layer honeycomb samples should be given priority in the optimized design of the aluminum honeycomb buffer. Dynamic compressive performance of the combination of aluminum honeycomb was also investigated by Cao et al. [17]. Results showed better shock absorbing characteristics in the combined aluminum honeycomb buffer, and that a suitable combination can smooth the stress and lower the energy applied to the testing platform.

Thus, to investigate the performance of a multi-layer aluminum honeycomb under compression, more experiments and numerical simulations were conducted in this paper.

2. Experiment

To diminish the influences from the specification and material characteristics of the aluminum honeycomb, only one kind of specimen made of Al3003-H18 was selected for constituting

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the multi-layer aluminum honeycombs, as shown in Fig.1. The size of each specimen was controlled within 100mm×100mm(±0.5mm). There were three critical parameters of hexagonal cell: t=0.04 mm (the thickness of aluminum foil), l=7mm (hexagonal side length), h=10mm (height of cell). The specimens were placed at the center of the fixture. The displacement control was set at 2mm/min by universal testing machine for quasi-static uniaxial compression, as shown in Fig.2. Force-displacement data was automatically recorded through supporting software on a computer. The combinations of multi-layer aluminum honeycombs were divided into six groups.

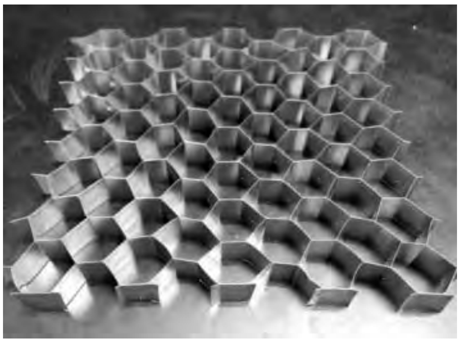


Fig.1 Specimen

Fig.2 Installation set up

3. Numerical simulationn

The single ‘Y’ cross-section model had been used to simulate the aluminum foil of honeycomb due to geometrical symmetry of hexagon [18]. Nevertheless, the ‘Y’ cross-section model is a partial model that is not sufficiently accurate to simulate the compression of the whole multi-layer aluminum honeycomb. Therefore, a full-scale FE model was made by using the ANSYS [19-21], as shown in Fig.3. The aluminum honeycombs were meshed with Belytschko-Tsay Shell with 163 elements and five integration points. The bilinear strain-hardening material model was used to represent the true stress-strain relation of aluminum alloy [22]. It was treated as rate-independent because the test was quasi-static compression. The material parameters are as follows: density ρ = 2700kg·m^{-3}, Young’s modulus E = 69.0 GPa, Poisson’s ratio

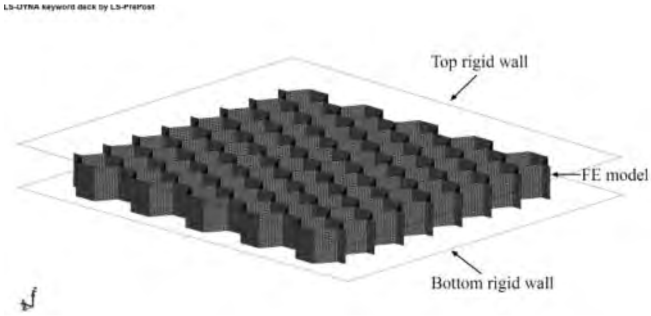


Fig.3 FE model of multi-layer aluminum honeycomb

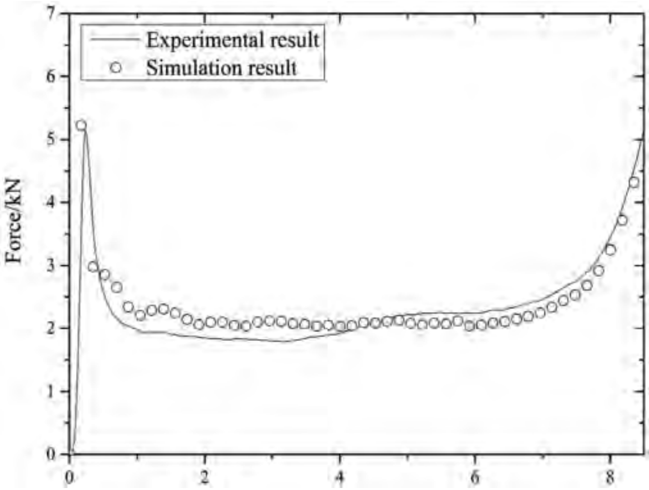
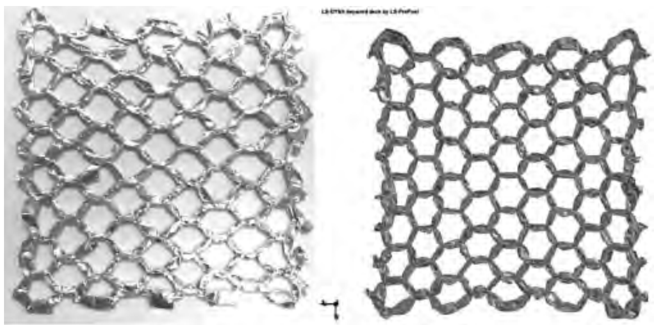


Fig.4 Comparison of the force-displacement curves



(a) Experimental result (b) Simulation result.

Fig.5 Comparison of crushed single layer aluminum honeycomb

v = 0.33, yield stress σ_y = 115.8 MPa, tangent modulus E_t = 690 MPa. The keywords including Contact-automatic-single-surface and Contact-automatic-surface-to-surface were used to define nature of the contact. The rigid walls were employed to simulate the top plate and bottom plate of the testing machine. The top rigid wall was set as the moving plate. The bottom rigid wall was set as the fixed plate.

The comparisons were made between the quasi-static experimental results and simulation results of the single layer honeycomb to validate the accuracy of simulation. As can be seen from Figs.4 and 5, the simulation curve conforms well with the test data, and the crushed specimens were similar to each other. It can be concluded that the numerical simulation results are in good agreement with the test results. Thus, the model can be used to simulate the conditions of a multi-layer aluminum honeycomb under quasi static compression.

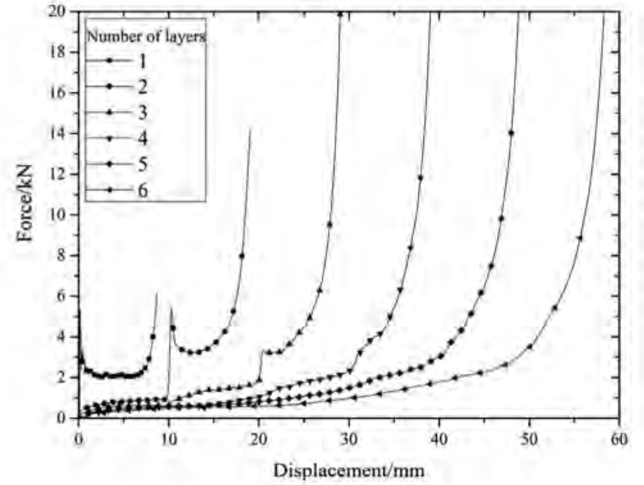
4. Results and discussion

4.1 Compressive properties

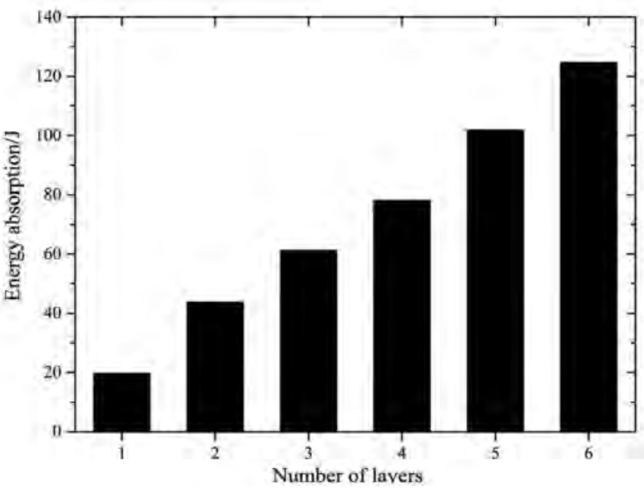
As shown in Fig.6a, the force-displacement curves of multi-layer aluminum honeycomb reflect a trend, in which the peak forces decreased gradually with the increase in layers, and the plateau stage was getting shorter with the curves becoming increasingly smooth.

Reducing the peak value of the compressive force and smoothing the force-displacement curve are beneficial to the compressive process. For the object subjected to compressive loading, the load should be less than its failure stress.

The energy absorption is basically linearly proportional to the number of layers, as shown in Fig.6b. The densified layered aluminum honeycombs are shown in Fig.7.



(a) Force-displacement curves



(b) Energy absorption

Fig.6 The compressive properties of multi-layer aluminum honeycombs

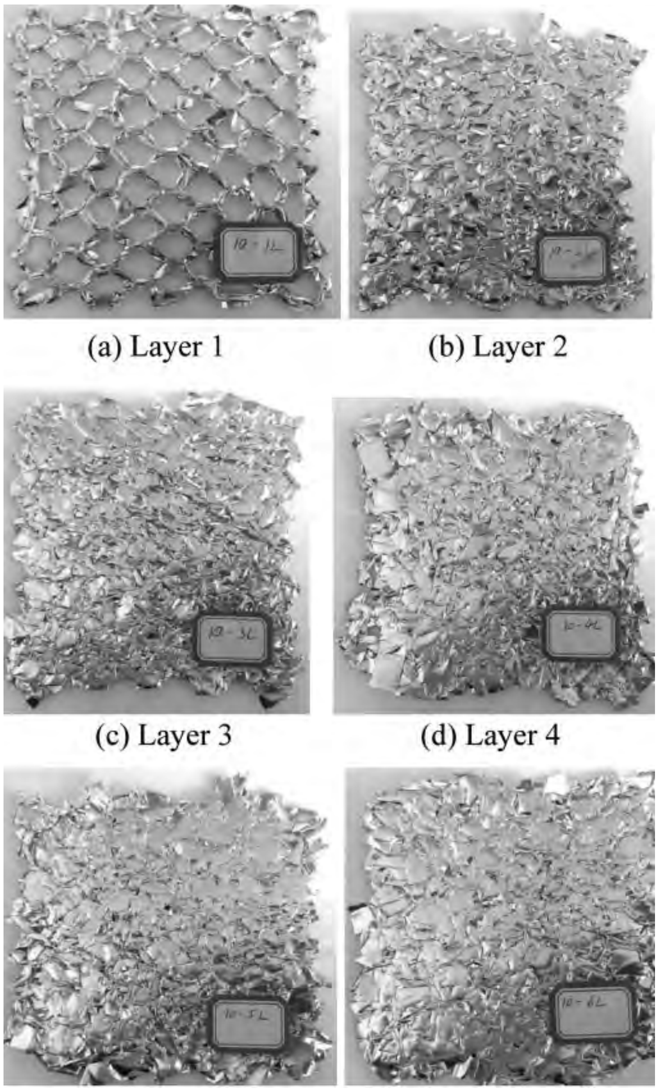


Fig.7 Densified layered aluminum honeycombs

4.2 Crush behaviour of an alternative arrangement

The multi-layer aluminum honeycombs in all experiments were set in uniform arrangement as shown in Fig.8. To investigate the crush behaviour of multi-layer aluminum honeycombs in a different arrangement, two kinds of combinations under quasi static compression were simulated. In the case of a staggered arrangement, the middle layer was rotated 90 degrees around the geometric center in-plane. In the uniform arrangement, it was found that foils of the middle layer had been tilted to a certain degree, which were elastic-plasticity bending and shear deformation essentially. However, in the staggered arrangement the mid-layer would be inserted into the top layer and bottom layer at the same time, as shown in Fig.9. In the late stage of the compression process with the combination of staggered arrangement, foils of the middle layer were also tilted to a certain degree, but there was no plastic deformation in a large proportion of the foils that kept the vertical state, as is shown in Fig.10. This explains why the compressive force of the former was slightly greater than that of the latter in “stage 1”, as shown in Fig. 11. However, in “stage 3”, the compressive force of the former was smaller than that of the latter due to many mid-layer foils which kept the vertical state from starting to deform. It can be inferred that the combination of a staggered arrangement can absorb more energy through a equal mass of both. In other words, the SEA (specific energy absorption) or the energy absorption efficiency of the staggered arrangement combination is better than the uniform arrangement combination. The densification pattern of the two combinations were similar with each other.

4.3 Empirical formula

In order to predict the force-displacement relationship of the layered aluminum honeycomb, the curve-fitting method was used. An empirical formula was proposed according to the trend of curves found in section 4.1. When the number of layers is four or more, the curves become more smooth. Therefore, based on the curve of a four layered aluminum

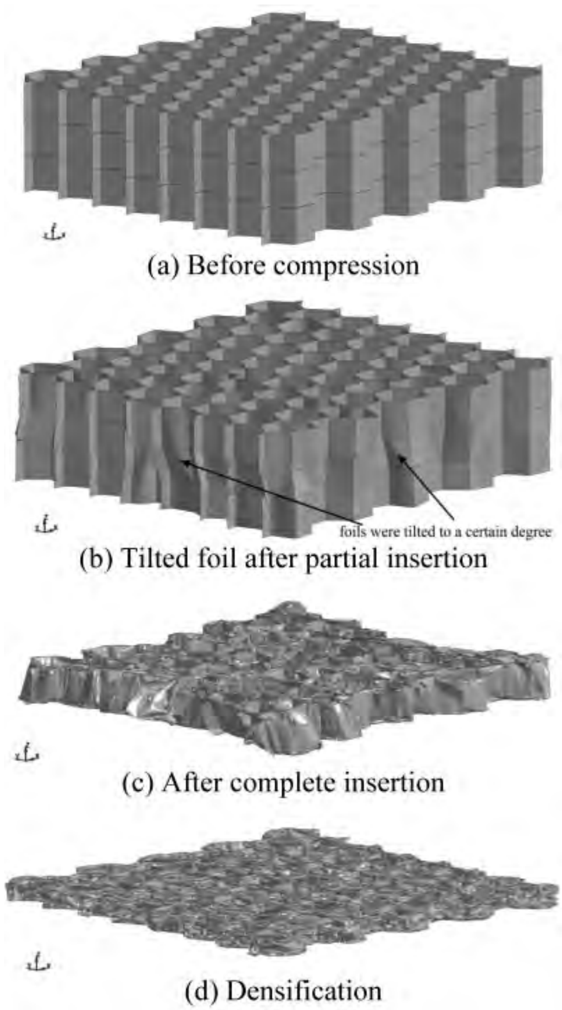


Fig.8 Compression progress of the uniform arrangement

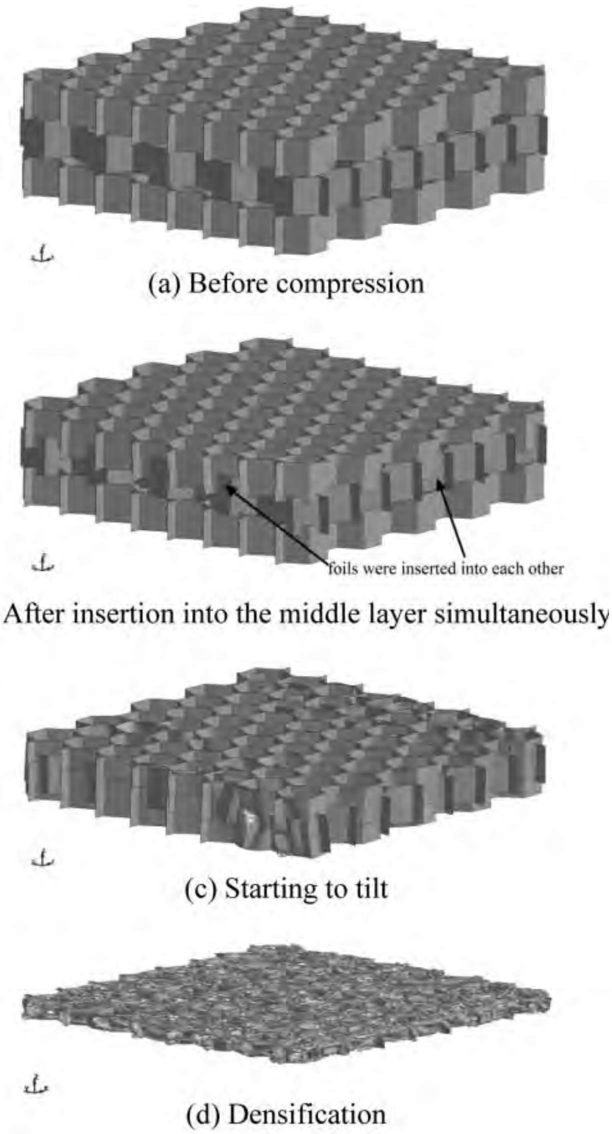


Fig.9 Compression progress of the middle layer staggered arrangement

honeycomb, the empirical formula is proposed as (1):

$$F = \{\alpha + \beta[x + 10\times(n-4)]\}^{-\frac{1}{\gamma}} \quad \cdots \quad (1)$$

where x is the displacement; F is the compressive force; n is the number of layers; α, β, γ are coefficients that can be obtained by fitting the curve: α = 1.797; β =- 4.357e-2; γ = 0.778. Standard error is 0.1868. Correlation coefficient is 0.9988. As a result, the formula was calculated as (2):

$$F = [19.225 - 0.04357(x - 10\times n)]^{-\frac{1}{\gamma}} \quad \cdots \quad (2)$$

As shown in Fig.12, the residuals scatter point vibrated within a range of -0.5 to 1. To further verify the accuracy of the empirical formula, the original data of five and six layered aluminum honeycombs under compression were compared to the fitted curve when the parameter n was set to 5 and 6

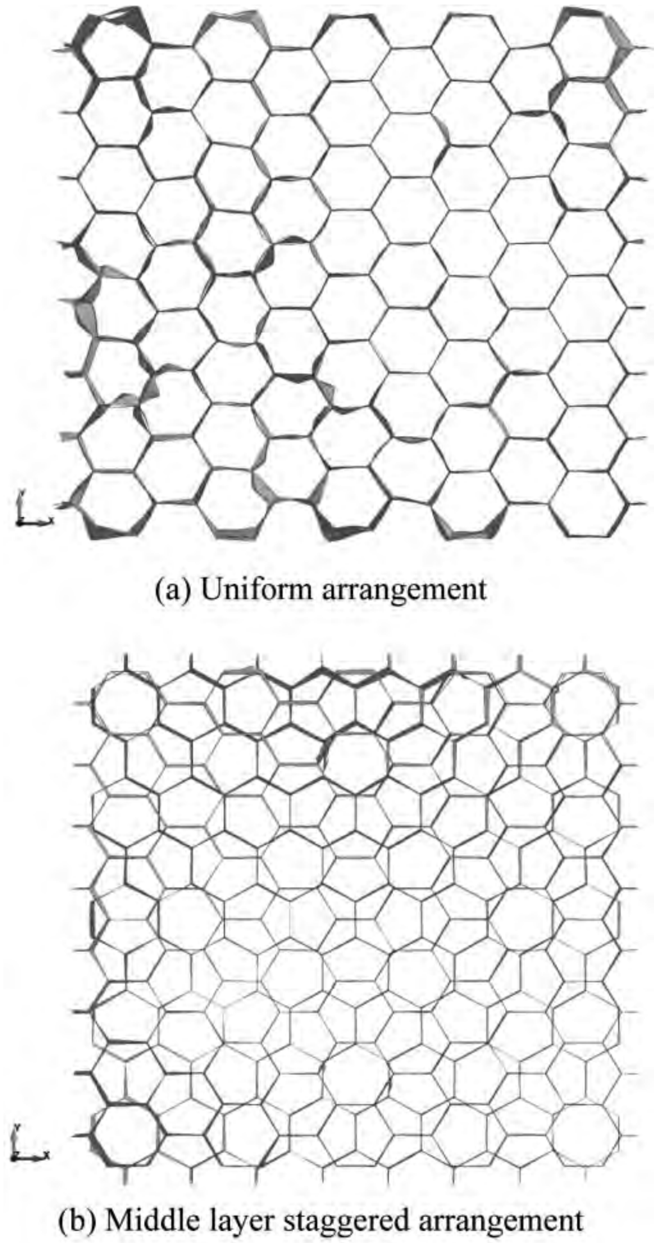


Fig.10 Top view of compression progress

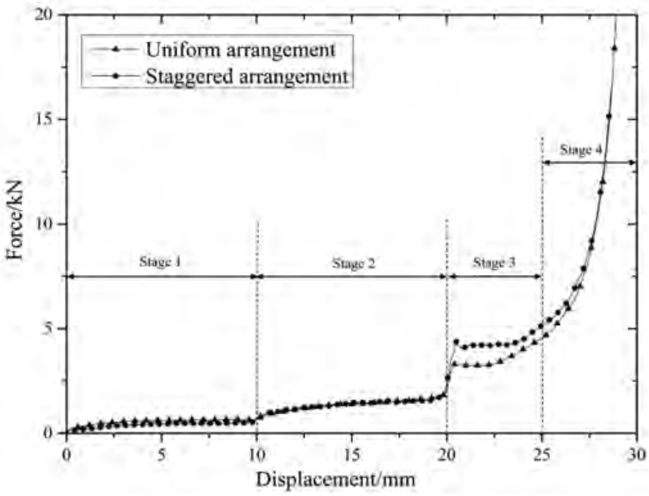


Fig.11 Force-displacement curves with different arrangements

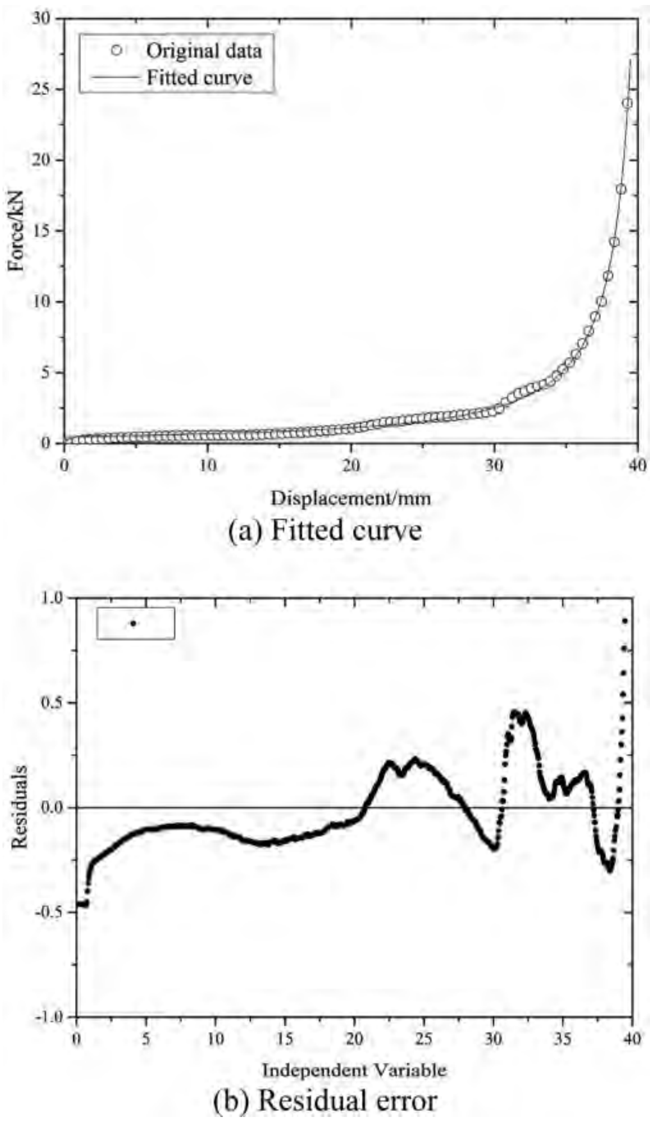


Fig.12 Fitted curve of four layered aluminum honeycomb

respectively. As shown in Figs.13 and 14, the fitted curves conform well to the force-displacement scatter points in the inserting stage and compression stage, and slightly deviated in densification stage. However, the residuals are controlled within a range of -0.5 to 5. It is proved that the curves conform well to the original data and the empirical formula can basically predict the force-displacement relationship of layered aluminum honeycombs.

4.4 Discussion

Through experiments, it has been determined that the peak force is almost 2~3 times higher than the mean plateau force in compression of a single layer aluminum honeycomb. In fact, the initial peak force was the threshold of energy

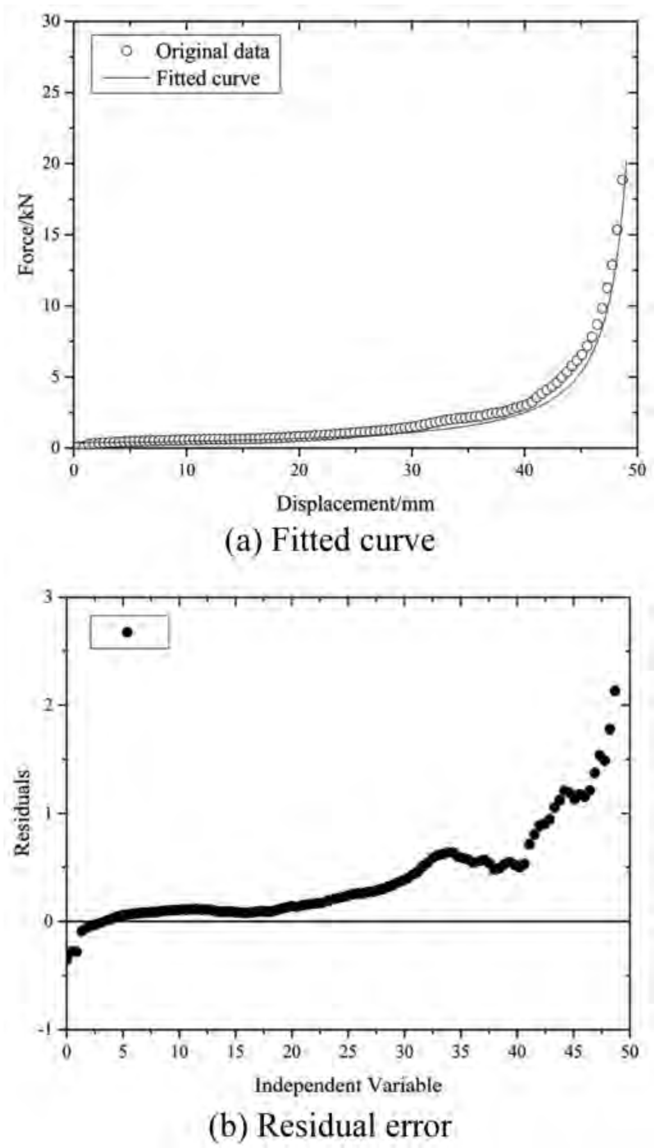


Fig.13 Fitted curve of five layered aluminum honeycomb

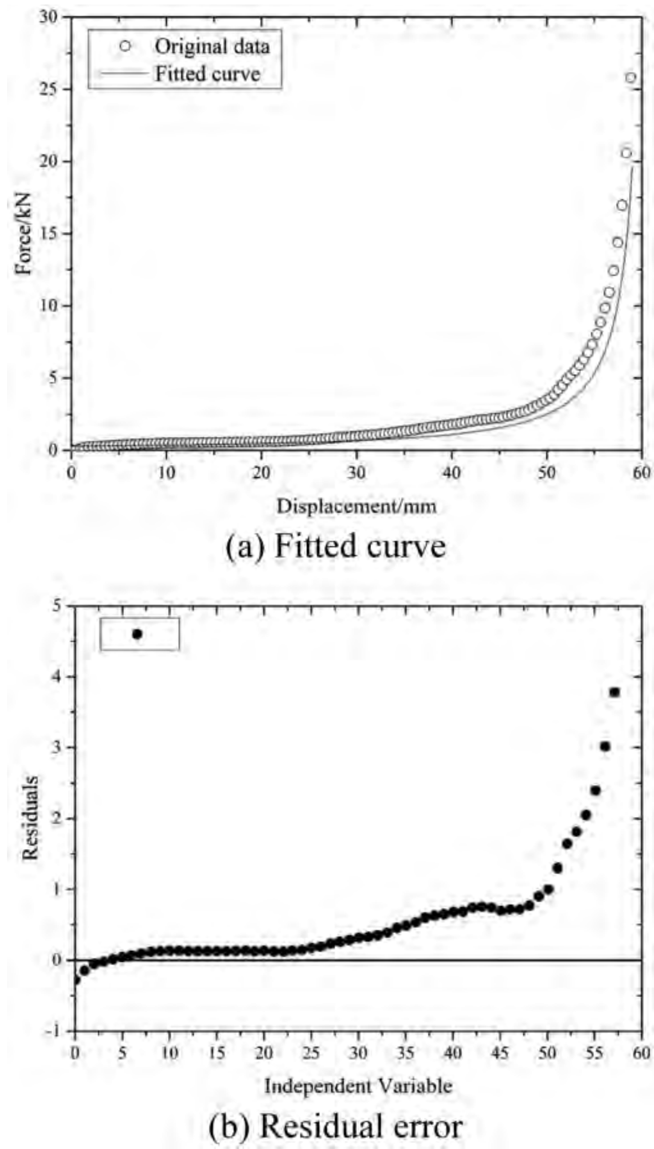


Fig.14 Fitted curve of six layered aluminum honeycomb

absorption, because the premise of energy absorption is that the compressing force must be greater than the initial peak force.

Additionally, it should be noted that the empirical formula has some limitations. It can be only used to predict the force-displacement relationship of layered aluminum honeycombs with over four layers. A theoretical or semi-empirical formula is expected to be proposed to predict the force-displacement relationship based on the mechanical properties of materials and the geometrical parameters of a hexagon.

5. Conclusions

The experiments and full-scale numerical simulation of multi-layer aluminum honeycombs under quasi-static compression have been carried out. The validation of the FE model was proved by comparing the simulation result with the data of experiment. The results showed that the force-displacement curves of the multi-layer aluminum honeycomb reflect a trend, in which the peak forces decrease gradually with the increase of layers and the plateau stage is getting shorter with the curves becoming increasingly smooth. The trend is viewed as being beneficial to the compressive process when the specimens are fully crushed. The energy absorption is basically linearly proportional to the number of layers. The staggered arrangement should be given priority due to its energy absorption property.

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