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On the influence of structural defects for honeycomb structure

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ABSTRACT

Defect in honeycomb has been paid close attention in recent years, as it significantly threats on its performance. In this study, detailed behavior and influence were extensively investigated in terms of defect distribution, influence on the mechanical performance, as well as the improvement methodology. Firstly, quasi-static experiments were extensively conducted to directly evaluate the inhomogeneity with 12 sub-blokes divided from a given conventional man-made honeycomb core. Variances in the resultant compression history as well as strength of these sub-blocks were determined. From the experimental observation, it can be seen that the regularity and adhesive failure of cells happened in expansion process are two main reasons for strength inhomogeneity. Afterwards, parametric studies on the extensive influence on mechanical performance were discussed by employing the specimens with structural defects in terms of the irregularity, under and over stretch states and adhesive failure. As the findings cofirmed that, the structural defects hugely cut down the plateau force and energy absorption capacity. The honeycomb with regular hexagonal cells without any adhesive failure performs the best. To improve the irregularity, a Machine Vision Methodology was put forward for cells expansion supervision. Detail algorithm in vertex identifying of honeycomb cell was discussed. All these achievements shed a light on the consistency, reliability and homogeneity of high standard honeycomb structure.

1. Introduction

Nowadays, with the rapid growth of vehicle speed, safety criteria have become stricter and stricter. No matter for the autos travel on the road, or the high-speed trains run in the rail, even for the airplanes fly in the sky, seeking for better protection strategies to minimize the damage and loss in crash incident never stop [1]. For this purpose, kinds of energy absorbers were developed, from primary metallic thin-walled square tubes [2,3], circular tubes [4,5], and multi-cell tubes [6–8] to cellular structures [9–12], with consideration the factor in low density and high specific properties. In recent years, honeycomb structure gains sufficient attentions due to its perfect mechanical performance and outstanding energy absorption properties. A number of extensive constructive works have been conducted on the basic behavior [13–15], load-carrying capacity [16–18], engineering applications [19,20], and creative design [21–28], with abundant achievements.

It can be confirmed that the honeycomb structure is a good choice for energy absorber and sandwich core. However, there is still a serious problem: structural defect. It might be caused in the manufacture process, and significantly threats on its mechanical performance. As well known that the honeycomb is made of sheet foils, and there are five basic manufacturing ways of making honeycomb, including adhesive bonding, resistance welding, brazing, diffusion bonding and thermal fusion. By far the most common method is the adhesive bonding; perhaps as much as 95% are made in this way.

In general, two popular techniques can be used to convert the sheet material into honeycomb in bonding way: the expansion process and the corrugation process. Almost all of the adhesive bonded cores are made by the more efficient expansion process, As introduced in the Ref. [29] that the honeycomb fabrication process with the expansion method (see Fig. 1 (a)) begins with the stacking of sheets of the substrate material on which adhesive node lines have been printed, see step s1. The adhesive lines are then cured to form a special cubic block, called HOBE® block (Honeycomb before expansion), see step s2. After curing to give an expanded block, the given HOBE block would be expanded. Then slices of the expanded one may be cut to the desired out-of-plane dimension. Alternately, HOBE slices can be cut from the HOBE block to the appropriate out-of-plane and subsequently expanded, as the step s3. Slices can be expanded to regular hexagons, under expanded to 6-sided diamonds, and over expanded to nearly

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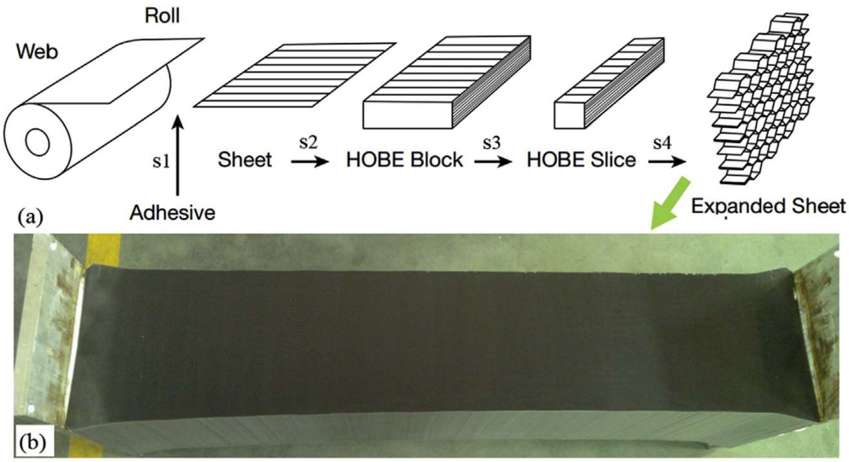

Fig. 1. The (a) stretch process of honeycomb product [29] and (b) product.

rectangular cells, see step s4. As the Fig. 1 stated that, the final honeycomb product is cut from an expanded block, by getting rid of the edge part. Obviously, structural defect in this process is unavoidable; particularly they would like to happen in expansion of the HOBE® (step s4).

On the topic of the honeycomb's structural defect, some relevant constructive works were conducted. Gaydachuk et al. [30] offers a first, comprehensive system for the classification of various manufacturing defects encountered in honeycomb composite materials sandwich structures production. This system groups all defects into four main categories with the provision for analysis of each defect down to its reason. Fan [31] investigated the dynamic crushing behavior of functionally graded honeycomb structures with random defects. In his work, the in-plane dynamic crushing behavior of functionally graded honeycomb structures with missing-wall defects is analyzed and effects of defect ratios and defect locations are discussed in detail. Results reveal that the larger defect ratio is responsible for the lower energy absorption. For the case of 70 m/s impact velocity, defects in the middle of the structure should be avoided, as they lead to inferior energy absorption. In order to investigate the effect of these defects on the whole honeycomb, Khoshravan et al. [32] conducted numerical and experimental analyses of the effect of different geometrical modeling on predicting compressive strength of honeycomb core. In their analyses, one cell was cut from the middle of a part and the effect of the lack of a cell on the whole structure was examined. By creating initial defect in honeycomb, non-uniform deformation was observed in more cells due to the generation of more cells with free wall. Chen & Ozaki studied the stress concentration due to kinds of defects in a honeycomb structure using the finite element method [33], with cell missing specimen. The numerical analysis results also revealed that there is a bending stress concentration in the cell walls at the defect tip in addition to a tensile stress concentration, and that the bending stress is generally greater than the tensile stress in the cell wall immediately at the defect tip.

Some other works were discussed about the defect influence on the mechanical behavior for sandwich panels with honeycomb core (see Refs. [34–37]). Abbadi et al. [36] carried out the study on the fatigue behavior of honeycomb sandwich panels with two kinds of defects (Brinell ball, and drilling hole) on two types of honeycomb core (aluminum and aramid fibre) under fatigue loading. Experimental results showed that the lifetime of sandwich panels is very sensitive to drilling hole type defect than Brinell one. Also, further result was performed on aluminum honeycomb sandwich panels with random skin core weld defects (see Ref. [37]), with the defect ratios are 1%, 2%, 4%, 8%, 16% and 32%. Compared with that of an intact honeycomb sandwich panel, the numerical results indicate that defects introduced by randomly removing skin/core welds caused some mechanical properties a sharp decrease in the sandwich panels (e.g. a 1% defect caused more than 50% reduction in the out-of-plane tensile failure strain), while some properties exhibit a gradual decay, i.e. the compressive load plateau.

Honeycomb structures have high sensitivity, so some connections may be destroyed or separated for some reasons during construction or cutting and building a sandwich structure, even caused in their life cycle. From the existing constructive literatures, it can be confirmed that the presence of manufacturing defects affects the overall performance characteristics of the honeycomb structure. No double that, the defect mentioned above, not only the cell missing, but also the weld missing, they are potential but rare. Furthermore, these typical defects can be avoided in manufacturing process. Different from these supposed defects, the irregularity of cell, the inhomogeneous destitution and adhesive failure, which forming during the construction, are more common. They do harm to the mechanical performance of honeycomb structure. Even though it was commonly used as an intact structure for load carrying and energy absorption, a tiny defect of any part of such structure could result in the divergence of under high impact, especially in case of long tandem honeycombs. Any tiny defect will destroy the deformation sequence and bring about structural instability if used inhomogeneous components.

Among all of the existing achievements, there have been rare investigations on the performance uniformity for a given honeycomb product, let alone the reason analyses. This paper, differing from the existing constructive works, detailed behavior and influence were extensively investigated in terms of defect distribution, influence on the mechanical performance, as well as the improvement methodology, by means of experimentally, numerically and technologically, respectively. Detailed skeleton of this paper is as the following: section 1 concluded the background and relevant works of this topic. Section 2 performed experiments with 12 sub-blokes that divided from a given conventional man-made honeycomb core. Variances in the resultant compression history as well as strength of these sub-blocks were determined. Section 3 carried out the numerical simulation by means of explicit finite element method. In this section, defect influences on mechanical performances were analyzed from the irregularity, under and over stretch, as well as shallow adhesive failure, respectively. Section 4 discussed a new irregularity improvement methodology for hexagonal honeycomb structure. Section 5 drew some important conclusions at last.

2. Specimens and experiments

2.1. Specimens and setup

As presented in Fig. 2 (a), the honeycomb is consists of a great deal of cells. It can be formulated as the foil thickness t, the cell width l, the cell edge length h, and the inclined cell angleθ, (see Fig. 2 (b)). The overall dimension of the specimen can be described as L, W and T. For