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Mechanical property of paper honeycomb structure under dynamic compression ☆

Wang Dongmei, Bai Ziyou *

Media and Communication School, Shenzhen Polytechnic, Shenzhen 518055, PR China

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ABSTRACT

The early studies on mechanical model of paper honeycomb structures were always concentrated on static situation, however, paper honeycomb would meet some random events of impacting and vibration during the process of transportation. Considering the virtual working circumstance, dynamic experiments under medium and low strain rates were undertaken and corresponding models of mechanical properties were derived. There exists a certain strain-rate effect which leads to the difference of mechanical properties between dynamic and static condition. A mechanical model was given to estimate plateau stress and yield stress at different strain rates based on experimental data by employing the methods of Cowper–Symonds model and piecewise function. The conclusion can be applied to characterise and improve the compressive properties of paper honeycomb structure efficiency.

1. Introduction

As a cushioning material with advantages including light weight, excellent energy absorption property and easy recycling quality, paper honeycomb sandwich panel was widely used in the transporting and packaging process for sophisticated electronic equipments and household appliances. The basic size of paper honeycomb was illustrated in Fig. 1. The thickness T can be cut to a suitable size in practical application. It is composed of two pieces of face-paper and a piece of core paper. Its mechanical properties depend on the ratio of thickness to length (t/l's value in Fig. 1b) [1]. During this research, it is assumed that each hole is hexagonal shape.

The paper honeycomb structure has been invented for many years. Related researches were mostly focused on the static compressive mechanical properties, while the effect of strain rate was ignored in most research: Gibson's [2] research on cellular solids has important and meaningful influence on the field of honeycomb and foam structure. The mechanical properties and constitutive relation of the two types of material were derived by him. Subsequently, he described the process of derivation, calculation and related experiments. However, the paper honeycomb sandwich panel was not mentioned in these studies. A method based on energy absorption with minimum principle in plasticity was given by Wierzbicki, which provided a simple and appropriate mean to estimate the plateau stress of metal honeycombs [3]. As paper honeycomb's mechanical properties were far different from metal honeycomb, the results cannot be extended to paper honeycomb directly. The collapse phenomena under both shear and simple compression in the out-of-plane direction were analysed by Zhang and Ashby [4]. Wang [5] derived a model to estimate the yield stress of the hexagonal honeycomb structure, and this model was subsequently extended to the triangle and square shaped honeycomb. Changjie [6] developed a Y-type model for aluminium honeycomb and the out-of-plane plateau stress was deduced. Considering the effect of strain rate with Cowper–Symonds model, the calculating equation of dynamic plateau stress is developed and good agreement between the experimental and theoretical results is obtained. The constitutive equation cannot be extended to paperboard, while the method of taking strain rate into the model can be applied to paper honeycomb. Yu's work [7] proved that plateau stress of aluminium honeycomb in dynamic situation was higher than that compared to static situation. The strain rate effect of circular-cell aluminium alloy honeycombs was investigated experimentally. The result proved that the impact velocity had a significant influence on the local deformation mode and the plateau stress would increase as the strain rate increases. Kobayashi [8] studied both dynamic and static mechanical

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* Corresponding author.
E-mail address: baiziyou@szpt.edu.cn (Z. Bai).

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Nomenclature

T	the thickness of paper honeycomb board
$\dot{\varepsilon}$	nominal strain rate in compression
l	edge length of honeycomb cell
t	the thickness of cell wall
h	the drop height in dynamic compression
v	the velocity in static compression
λ	Poisson ratio of the solid cell-wall material
α	drawing angle of cell and it is 120° here
K	constraint factor
E_s	elastic modulus of core paper
σ_y	the yield stress of paper honeycomb
σ_p	the static plateau stress of paper honeycomb
σ_d	the dynamic plateau stress of paper honeycomb
σ_{ys}	the yield stress of core paper
b and k	parameters related to yield stress
B and q	experimental parameters in Cowper–Symonds model

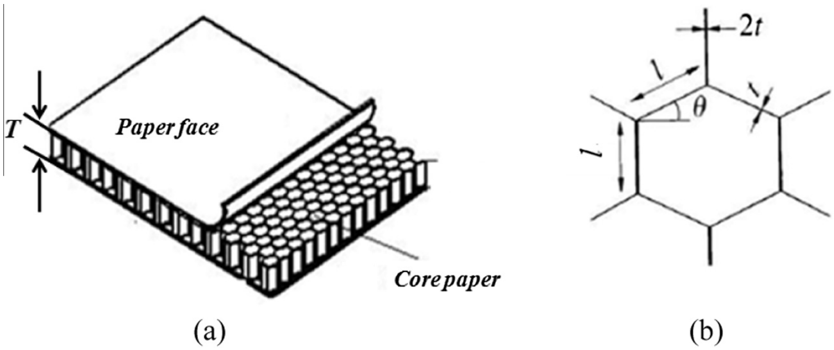

Fig. 1. (a) The structure sketch map of experiment sample. (b) The basic size of a hexagonal unit.

properties of thermoplastic honeycomb core of polypropylene and polyester, implying that energy absorption in dynamic situation was more than that in a static situation.

Through the studies mentioned above, we can see clearly that the research was dominated in static characteristics of honeycomb structure and most studies were concentrated on metal honeycomb material. The results have some reference value and build a research foundation for paper honeycomb although metal and paper materials are different mechanical properties, matrix material, application, etc.

Recent years, more studies on honeycomb cardboard's properties are accomplished, especially when it is applied in fields like packaging and transportation: Lu and Sun [9] estimated yield stress of paper honeycomb through a mechanical model of flat crush resistance. D.M. Wang and Wang [10–12] made a research on the compressive properties in out-of-plane direction of paper honeycomb. A semi-empirical theoretical model was given to estimate stress during compression and an energy absorption diagram was developed in application. On the base of Wierzbicki's research, Yuping and Wang [13,14,16] took humidity and strain rates into consideration to improve the model. An energy-absorbing model and a corresponding diagram related to ambient humidity and strain rates were given and these works are significant in the process of packaging and transporting.

Paper honeycomb is always used as a cushion in packaging and transporting process under intermediate and low strain rates. Its height ranges from 10 mm to 50 mm. As the drop height is commonly estimated in packaging in Table 1 [15], its strain rate during work ranges from $1\ \mathrm{s}^{-1}$ to $150\ \mathrm{s}^{-1}$. In this study, we mainly concern about cushioning properties of the paper honeycomb sandwich structure in these strains.

Table 1
A typical drop height for packaging.

Transporting type	Drop height (m)
1 person throwing	1.05
1 person handling	0.90
2 persons handling	0.75
Light handling equipment	0.60
Middle handling equipment	0.45
Heavy handling equipment	0.30

2. Experiments

2.1. Experimental materials

The materials used in this study were produced by the *Honicel Honeycomb Material Group* (Canton, China) and *Yuexing Paper Products Company* (Dong Guan, China). Different samples of hexagonal paper honeycomb were used. These samples were made in various thickness-to-length ratios (0.025, 0.0313, 0.0333 and 0.0417).

The material was processed in accordance with *GB4857.4-2008* with a temperature of 23° and humidity of 50. The paper honeycomb sandwich panels were cut into 100 mm × 100 mm size for static test and 80 mm × 80 mm for dynamic test. To make sure that the reliability of test data was guaranteed, we chose a larger size within the range that equipments allowed. Because the material of specimens are not uniformly, so three time tests were done for each specimen under the same conditions in static loading and five time tests in dynamic loading, and then to calculate the average of them. For there is more dispersing in dynamic tests, so the test times are increased to five.

2.2. Experimental equipments and standards

2.2.1. Testing standards

Experiments were conducted under the following standards:

(1) Testing method of static compression for packaging cushion materials *GB8168-2008*.
(2) Packaging-transport packaging temperature–humidity conditioning *GB4857.4-2008, ISO 2233-2000*.