Materials Science and Engineering C 69 (2016) 255–261

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

Compressive failure modes and parameter optimization of the trabecular structure of biomimetic fully integrated honeycomb plates

Jinxiang Chen [a], Wanyong Tuo [a,b,*], Xiaoming Zhang [a], Chenglin He [a], Juan Xie [a], Chang Liu [a]

[a] School of Civil Engineering & International Institute for Urban Systems Engineering, Southeast University, Nanjing, 210096, China
[b] School of Civil and Architectural Engineering, Anyang Institute of Technology, Anyang 455000, China

ARTICLE INFO

Article history:
Received 14 February 2016
Received in revised form 27 May 2016
Accepted 26 June 2016
Available online 28 June 2016

Keywords:
Forewing
Integrated honeycomb
Lightweight composite
Basalt fiber
Compressive properties

ABSTRACT

To develop lightweight biomimetic composite structures, the compressive failure and mechanical properties of fully integrated honeycomb plates were investigated experimentally and through the finite element method. The results indicated that: fracturing of the fully integrated honeycomb plates primarily occurred in the core layer, including the sealing edge structure. The morphological failures can be classified into two types, namely dislocations and compactions, and were caused primarily by the stress concentrations at the interfaces between the core layer and the upper and lower laminations and secondarily by the disordered short-fiber distribution in the material; although the fully integrated honeycomb plates manufactured in this experiment were imperfect, their mass-specific compressive strength was superior to that of similar biomimetic samples. Therefore, the proposed bio-inspired structure possesses good overall mechanical properties, and a range of parameters, such as the diameter of the transition arc, was defined for enhancing the design of fully integrated honeycomb plates and improving their compressive mechanical properties.

1. Introduction

Honeycomb structures are commonly used in the design of lightweight, high-strength composites [1–3]. Honeycomb structures are used in numerous applications, such as in the aerospace [4] and furniture manufacturing industries. In recent years, honeycomb structures have become increasingly important to emergency projects, such as the erection of emergency bridges [5,6] and the construction of temporary housing [7,8] for victims and the military after natural disasters (e.g., earthquakes and floods). Therefore, numerous studies on the development [9–11] and mechanical properties [12–15] of honeycomb structures have been conducted and have yielded important experimental or theoretical results [16,17]. Commercially available honeycomb sandwich plates are currently manufactured by adhesively joining plate and core components that are produced separately via different processes [18,19]. However, the side plates and core of a sandwich plate produced in this manner are easily separated, which limits both their strength and side sealing properties.

Emulating living creatures is a productive approach for overcoming the weaknesses of traditional manufacturing methods [20]. Motivated by the high strength and minimal weight of beetle forewings, as required for defense and flight, we previously investigated their three-dimensional structures and mechanical properties [21–23]. These investigations led to a new type of lightweight bio-inspired composite consisting of a fully integrated honeycomb structure with fiber-reinforced trabeculae at the corners of the honeycomb cores. Based on this structure, we developed an integrated honeycomb technology [24,25]; we investigated the compressive and shear properties of the integrated honeycomb plates [26] and used simplified models to simulate the effect [27] of replacing the long fibers in the biological prototype with short fibers. However, there have been no previous reports related to the mechanical properties of fully integrated honeycomb plates (FIHPs) with sealed edge structures. Because compressive strength is an important property of honeycomb plates, this work focused on the compressive failure modes and parameter optimization of the trabecular structure of the FIHPs. Some of the existing problems with the structure were analyzed using the finite element method (FEM), and specific measures for overcoming these problems via biomimetic approaches were identified.

2. Experimental materials and methods

2.1. Experimental materials

Based on the results of our previous studies [28], short-cut basalt fibers (length: 3 mm, diameter: 13 μm) produced by Zhejiang GBF Basalt Fiber Co., Ltd. (Jinhua, China) were used as the reinforcement material. Bisphenol A-E51 epoxy resin [29] produced by Xing-Chen Chemical New Materials Co., Ltd., Wuxi Resin Factory (Wuxi, China), was used as the matrix material. Curing Agent 593 produced by Wuxi Shuo-Hua

* Corresponding author at: School of Civil Engineering & International Institute for Urban Systems Engineering, Southeast University, Nanjing 210096, China.
E-mail addresses: chenjpaper@yahoo.co.jp, twy2014@163.com (W. Tuo).

http://dx.doi.org/10.1016/j.msec.2016.06.087
0928-4931/

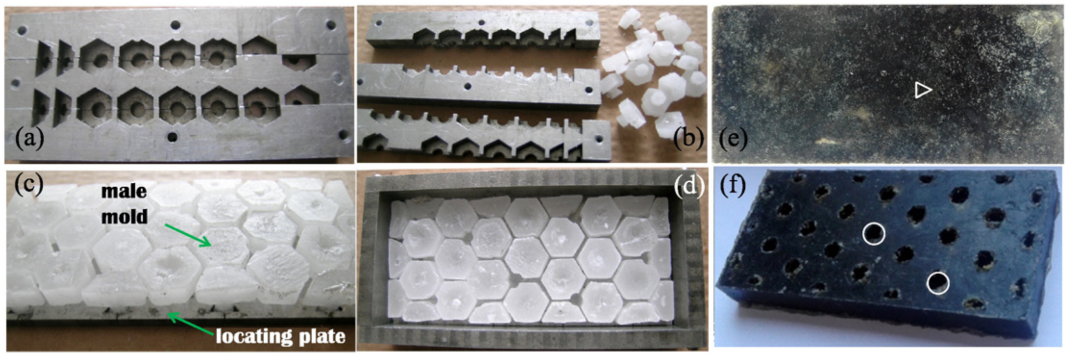

Fig. 1. FIHP molds and samples. (a) The mold for the male molds, (b) the prepared molds, (c) the male molds inserted into the locating plate, (d) the spatial relation between the male and female molds, (e) the front of a sample, and (f) the back of a sample. Circles indicate small processing holes.

Environmental Protection and New Materials Co., Ltd. (Wuxi, China) was used as the curing agent. Reactive diluent 501 produced by Wuxi Pin-Hua Chemical Co., Ltd. (Wuxi, China) was used as the diluent. The matrix material was composed of the epoxy resin, curing agent and diluent at a ratio of 10:3:1 [28]. Paraffin wax was used to manufacture the male molds. Arawana brand bean oil was used as the releasing agent for the male molds because it is not soluble in paraffin wax and its melting point is lower than that of the wax. Trial internal and external releasing agent solutions for the female molds were specially prepared for these experiments by Wuxi manufacturers.

2.2. Preparation of integrated honeycomb plates

The biomimetic FIHPs were prepared using the molds shown in Fig. 1. The specific preparation steps and processing conditions were as follows.

2.2.1. Preparing the molds

The mold surfaces were cleaned with alcohol before use. An oil layer was then spread onto the surfaces of the male molds, and a layer of the release agent was evenly sprayed onto the female mold surfaces to allow the samples and molds to be easily separated after molding.

2.2.2. Preparing the male molds

Paraffin wax was used to manufacture the male molds. The paraffin wax was melted at 100 °C in an oven and poured into the mold shown in Fig. 1a. The upper paraffin wax surface was planished once the paraffin wax had cooled but before it had hardened, and the entire mold was quickly washed with water. The mold was then separated to successfully yield the paraffin wax male molds (Fig. 1b).

2.2.3. Preparing the adhesive solution

The adhesive solution was prepared by mixing the epoxy resin, curing agent and diluent at a ratio of 10:3:1, and 0.5–1 wt‰ of the internal release agent was added.

2.2.4. Assembling the male molds and short fiber packing

A row of male molds was placed onto a locating plate (Fig. 1d), and then, short fibers were packed into the empty space; this process was repeated, row by row, until all of the male molds were positioned. Grease was spread at every interface during mold assembly for sealing.

2.2.5. Pouring and vacuum pumping the adhesive solution

The adhesive solution was poured into the mold assembly. A vacuum pump was then used to precipitate bubbles from the adhesive solution. To ensure that all of the bubbles precipitated, this step was repeated three times. The entire process took approximately 15 min.

2.2.6. Curing, demolding and pouring out the paraffin wax solution

The mold was placed in an air-drying oven and successively pre-cured for 1 h at 40 °C and for 1 h at 60 °C before being post-cured for 1 h at 150 °C. The sample was immediately demolded, and the liquid paraffin wax was poured out. A sample FIHP was thus obtained (Fig. 1e and f) in which the mass content of basalt fiber was 30%.

The samples for both the compression and bending [30] tests were designed to be cuboid in shape with dimensions of 110 mm × 50 mm × 13 mm, based on the GB/T 1456-2005 Standard [31]. The main specific structural parameters were as follows: the inscribed circle radius of a honeycomb cell was 14 mm, the wall thickness of the honeycomb cells was 1.75 mm, the trabecular diameter was 6 mm, the upper plate thickness was 4 mm, and the lower plate thickness was 2.3 mm.

2.3. Flatwise compression tests and observations of fracture of microstructures

The flatwise compressive properties of the honeycomb plates were evaluated in flatwise compression tests. Honeycomb plates sized as stated above (Fig. 1e and f) were cropped to the sample size recommended for flatwise compression testing by the ASTM C365-03 Standard [32]. Fig. 2a shows the SHT4605-W electronic universal testing

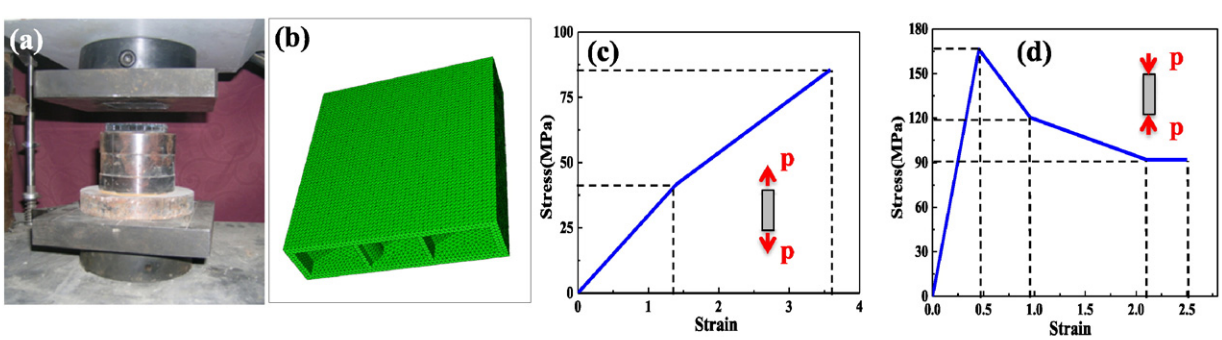

Fig. 2. (a) The flatwise compression testing equipment, (b) the meshing of the finite element model, and (c, d) the constitutive relationships used in the model.