Construction and Building Materials 169 (2018) 193–204

Contents lists available at ScienceDirect

Construction and Building Materials

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

Bio-inspired vs. conventional sandwich beams: A low-velocity repeated impact behavior exploration

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HIGHLIGHTS

- A study of bioinspired beam (BHSB) repeated impact behavior vs. conventional (HSB).
- BHSB design has CFRP skins sandwiching a two-layered core (rubber and Al honeycomb).
- It reduces 50–80% damages and has 2.7–20 times lower bottom skin stresses vs. HSB.
- This is done by stress spreading action over a wide planar area via the rubber core.
- Its impact resistance efficiencies are superiorly 1.65–16.22 times higher than HSB.

ARTICLE INFO

Article history:
Received 6 September 2017
Received in revised form 26 February 2018
Accepted 26 February 2018

Keywords:
Bio-inspired
Impact resistance
Repeated impact
Sandwich beam
CFRP skin
Honeycomb core
Rubber core
Woodpecker
Impact resistance efficiency

ABSTRACT

A new bio-inspired honeycomb sandwich beam (BHSB) based on the woodpecker's head configuration was developed for repeated low-velocity impact resistance improvement. The new design contains four main layers: carbon fiber reinforced plastic top and bottom skins sandwiching rubber and aluminum honeycomb cores. Impact loadings were performed numerically and experimentally in a repeated manner with a hemispherical steel impactor for three energy levels: 7.28 J, 9.74 J, and 12.63 J. In all cases, stresses developed at the bottom skin of BHSB were significantly smaller with substantially lower damage area while sustaining more number of impact than those of conventional honeycomb sandwich beam (HSB). Also, the impact resistance efficiency indices, I_e, which assess overall performance, of both beam designs were compared. I_e of BHSB were 1.65–16.22 times higher, conclusively exhibiting its superiority to HSB in repeated impact resisting performance.

1. Introduction

Fiber reinforced composite sandwich structures have been increasingly used in many advanced engineering applications, from aircraft bodies, sports cars, ships, bridge decks and piers, to beams and columns of buildings, due to their high specific strength, high stiffness, lightweight, and corrosion resistance [1]. However, there exists accumulated evidence showing their vulnerability when impacted by heavy objects, bird strikes, tool drops, and loadings due to collision incidents. Impact loads cause severe damage to sandwich structures both internally and externally in terms of substantial reduction in the tensile, compressive, shear, and bending strength since the event is instantaneous and the corresponding load magnitude can be many times that of its static equivalent. Therefore, new strategies and designs to improve impact resistance of such structures have been continually proposed and refined, rendering them an active research topic.

The behavior of sandwich structures with numerous core types in the presence of low-velocity impact has been widely studied. Fatt and Park [2] examined the behavior of the sandwich panel with a polymer core, classifying the face sheet fracture and core shear as the common failure mode. Corrugated core sandwich structures were experimentally and numerically tested under low-velocity impact by He et al. [3]. They found that fiber damage, matrix damage, delamination of face sheets, as well as core buckling are the dominant modes under varied impact energies. Numerous material and structural concepts have been explored for construction purposes. In a comparative study, Wang and Chouw [4] found that the inclusion of coconut fiber displays a

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https://doi.org/10.1016/j.conbuildmat.2018.02.201

greater spalling and fragmentation resistance for plain concrete under impact load due to fiber bridging effect, a feature useful for protection from damaged structure. For a geopolymer matrix reinforced with fabric, Samal et al. [5] observed that the impact behavior of carbon fiber composites is comparable with E-glass composite. In general, the former is lighter with higher bending stiffness and strength while the latter absorbs more energy. Meng et al. [6] noticed that strengthening structural insulated panel with a 3 mm glass fiber laminate skins improves its capacity to resist windborne debris impact although further skin thickness increase is not effective due to the damage mode change. Yang et al. [7] investigated the energy absorption of foam-filled sandwich panels with six types of skins. Panels with carbon reinforced skins showed poor impact resistance, while those with glass fiber reinforced skins displayed the most preferred properties among all the specimens. In the study of Ji and Li [8], the damage resistance and energy absorption of a sandwich panel subjected to low-velocity impact load were improved by adding an aluminum hollow tube reinforced shape memory polymer core. Kueh [9] employed the plate on foundation modeling analogy incorporated with the segmentation technique to examine the compressive response of the foam core sandwich columns with triaxially woven fabric composite skins. The core microscopic dimensions played an essential role as much as its density due to microscopic makeup in influencing the sandwich buckling load. Schubel et al. [10,11] investigated the low-velocity impact and post-impact behaviors of woven carbon/epoxy skins and a PVC foam core composite sandwich panels, making a comparison between experimental results with models to determine effectiveness in predicting the indentation behavior.

During lifespan, a sandwich structure is likely subjected to a series of repeated impacts. To maintain its good performance as well as continuous survivability, the degree of severity due to such loading environment needs to be determined. While the aforementioned works discuss rather comprehensively development on the sandwich structures under impact, it is to the authors' knowledge that there exists a lack of understanding of the behavior of these structures in the presence of the repeated impact loading. This is because most existing studies focus chiefly on the impact absorbing ability of sandwich structures that is directly attributed to their failure mechanisms. The current structures often exhibit a good single impact resistance but poor or rather unknown capability for further functionality after subjected to such loading. They commonly function in a sacrificial manner, requiring repair or worse replacement for continual usage after impacted. This is obviously not economical. In this context, a new design with a high repeated load resistance is much needed. Some relevant studies have been conducted. Akatay et al. [12] experimentally investigated the influence of low-velocity repeated impacts on the residual compressive strength of honeycomb sandwich structures and compared it with a single impact behavior. The observed compressive strength was moderately reduced in the case of the single impact event, while drastically reduced in the case of the repeated impact event. Balci et al. [13] compared the behavior of repaired honeycomb sandwich structures used in the cargo panels of A319/A320/A321 Airbus with the original honeycomb sandwich structures under repeated low-velocity impacts. It was found that the repair increased the load capacity and stiffness of the honeycomb sandwich structures. The repaired structures experienced damages at 1500 N while the original structures experienced damages at 650 N. Also, it is worth noting that some new structural concept such as a dual-core design for sandwich structures has not been well-explored despite some advantages reported by Xiong et al. [14].

Motivated by the current trend towards the bio-inspired innovation, this paper concerns with the development of a new sandwich composite beam, adopting inspiration from the woodpecker's head configuration that possesses a remarkable impact performance. A woodpecker has the capability to drum the trunk of a tree 18–22 times per second with repeated high-speed impacts at 6–7 m/s and a deceleration of 1200 g, yet with no sign of brain damage [15]. Due to this observation, some studies have been carried out to understand the biomechanics of the woodpecker's head during tree drumming. Wang et al. [16] compared the mechanical properties and microstructures of cranial and beak bones of great spotted woodpecker and Mongolian skylark. They found the unique microstructure of the woodpecker cranial bone gives it a higher strength and resistance to impact injury. In another study, Wang et al. [17] examined the micro-morphology of woodpecker's head by scanning electronic microscopy and CT-scan. They concluded that the cranial bone and beak macro/micro-morphology are the main contributors to the increased impact resistance. In their numerical simulation of woodpecker pecking event, Zhu et al. [18] noticed that the stress wave was substantially reduced by the hyoid when moving from the upper beak to the back skull. Moreover, the maximum stresses in skull and brain were both minimal and within the safe level. Inspired by the woodpecker's head configuration, Yoon and Park [19] developed a new bio-inspired system to protect micro-machined devices from high-frequency excitations. Their system exhibited a failure rate of 0.7% whereas a conventional hard-resin method yielded a failure rate of 26.4% when subjected to a 60 mm smooth-bore airgun at 60,000 g.

Although some experimental works are available, no numerical study has so far been conducted on the repeated low-velocity impacts of sandwich structures. Inspired by the attractive performance of the woodpeckers in the presence of impact loading, this study, therefore, aims to investigate a new bio-inspired sandwich beam with dual-core in resisting efficiently the repeated impact loads. For impact behavior assessment, this new beam was numerically and experimentally examined while using a conventional sandwich beam design as a control case for comparison. A comparative study characterized by systematic comparison in terms of contact force response, maximum stress experienced, failure morphology, damage area, and absorbed energy will be presented. In the end, this work will demonstrate by means of the newly proposed impact performance index that, with a low penalty of mass addition due to a dual-core design, the bio-inspired sandwich beam improves considerably the overall impact behavior of that employs conventional configuration.

2. Repeated impact experiment and finite element (FE) simulation

2.1. Development of the bio-inspired sandwich beam

Fig. 1(a) shows the woodpecker's head configuration, which is characterized by four major components: beak, hyoid, spongy bone, and skull [19]. Inspired by such arrangement, the proposed bio-inspired sandwich beam was designed to consist of four main layers as illustrated in Fig. 1(b). The beak was represented with a carbon fiber reinforced plastic (CFRP) laminated layer due to its high strength. The CFRP laminated layers act as the first defense skin for protection from impact damage. The hyoid was characterized by a rubber layer as Core I for the beam in order to spread and absorb the impact excitation. A second core layer (Core II) employed the aluminum honeycomb exploiting its porosity and lightness corresponding to the woodpecker's spongy bone for further impact suppression. Lastly, another CFRP layer completed the proposed beam, which was inspired by the skull bone of the woodpecker. Note that a bio-inspired design is an entirely distinctive concept compared to that of biomimicry. The former allows flexibility in innovation while the latter imitates almost exactly the