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Energy absorption capability of composite hexagonal ring systems

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ABSTRACT

An extensive experimental investigation of inplane crushing of composite hexagonal ring system between platens has been carried out. Woven roving glass/epoxy hexagonal ring system with different angles and arrangement were employed. The rings angles are varying between 45° and 70°. Six layers of woven roving E-glass fabric/epoxy wrapped over wooden mandrel to get thickness of about 3 mm. Typical histories of their crushing mechanism are presented. Behavior of ring as regards the initial crushing load, post crushing load, energy absorbed and mode of crushing has been presented and discussed. Results showed that the crush failure loads and energy absorption capability are greatly affected by the ring geometry, arrangement and loading conditions. As the ring angle increases the energy absorption capability increases and consequently, composite hexagonal ring with 70° exhibited the highest energy absorption capability among tested specimens. It is also found that energy absorption capability for systems crushed in-plane $X2$ higher than $X1$.

1. Introduction

In the last three decades extensive and credible studies have proven the high compete ability of composite materials in the field of crashworthiness. It is also evident that structures composed of composite materials meet design requirements by the vehicles manufacturers as well as customers demand for safe vehicle with low fuel consumption and high payload. It is also interesting to note that the relatively low cost glass/epoxy composite absorbed up to twice the specific energy of steel [1], while the relatively high cost carbon/PEEK composite can absorb up to seven times [2,3]. Accordingly, crushing behavior of composite thin-walled tubular structures has received extensive research [4,5] for possible use as collapsible energy absorber devices. In the design and testing of various types of vehicles, crashworthy protection has become a challenging issue. Crashworthiness can be classified as the quality of response of a vehicle involved in or undergoes an impact. The less damaged the vehicle and/or its occupants and contents after the given event, the higher the crashworthiness of the vehicle or the better its crashworthy performance [6–9]. Crushing behavior of collapsible energy absorber devices with circular and elliptical cross-section and subjected to different loading conditions has been investigated both experimentally and numerically by the authors [10]. A number of different failure modes were reported. It is noted that the cross-sectional geometry and loading conditions significantly influenced the energy absorption capabilities [11]. However, any energy absorbing system must be insensitive to the loading directions, especially lateral loading during the side impact event. Triangular arrays of metal rings/tubes have been used as energy-absorbing devices [12]. The system was subjected to compression along the axis of symmetry and oblique compression at 15° to the axis. A 30% reduction in energy absorbed was observed for oblique impact. Carney [13] discussed practical energy-dissipating devices for highways using tube systems. A crossed-layer tube system was tested by Johnson et al. [6]. The system consisted of several layers. Within each layer, all circular tubes were parallel and tubes of adjacent layers were perpendicular to each other. When the spacing between tubes within a layer is small, each tube can be considered to be individually in compression with lateral constraints as discussed previously. Moreover, when spacing is large, deformation is no longer uniform along the tube axis direction, but is three-dimensional and the collapse mode is much more complex. Arrays of parallel, thin-walled circular tubes have been compressed between parallel flat plates by Shim and Stronge [14]. Specimens include steel, brass and aluminum alloy tubes, approximately 0.7 mm thick with both diameter and length about 12.7 mm. Such an arrangement can be an energy-absorbing system itself, but it also represents the microstructural behavior of cellular solids. Xincai and Xiaogang [15] studied the possible parameters that affecting the energy absorption and the deformation in textile composite cellular structures. They found that the fiber orientation at the interface planes has a significant effect on Mode-I interlaminar fracture toughness. Shi-Xun investigated low-velocity impact and residual tensile strength analysis to carbon fiber composite laminates [16]. However,

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studies on crushing behavior of inplane crushed composite hexagonal tubular systems are still scarce and not well understood. This was one of the motivating factors behind this paper. The objective of this paper is to examine the effect of hexagonal angle, loading direction and packing system on the crushing behavior, energy absorption, failure mechanism and failure mode of composite hexagonal rings.

2. Crashworthiness parameters

Motor vehicle accidents are due to human and environmental factors. Automobile manufacturers, by employing proper safety design and manufacturing techniques, can prevent many of the deaths and serious injuries that result from motor vehicle accidents. Accordingly, one of these techniques is to design and install an energy absorber device, to prevent the vehicle's occupants from the effects of sudden impact. They do this by converting the impact energy into plastic deformation energy in the case of metal based energy absorber devices and into fracture deformation in the case of composite based energy absorber devices. Accordingly, one of most important aspect is to keep the peak force exerted on the protected occupants below their tolerance level, to avoid fatal injuries. The collapsible energy absorber devices must also provide a long deformation path to sufficiently and gradually reduce the deceleration of the protected occupants. Therefore, when evaluating the crashworthiness of an energy absorber device, great attention should be directed to its instantaneous crush force efficiency, the stroke efficiency and energy absorption capabilities. The crashworthiness parameter can be listed as follows:

- Initial crushing load (P_i)

The initial crushing load can be obtained directly from the load–displacement response.

- Mean-crushing load (P_m)

The average crushing load can be obtained by averaging the crushing load values over the crush displacement through the post-crush region.

- Crush force efficiency (CFE)

It is the ratio between mean crush load and initial crush load. It is calculated as:

$$\mathrm{CFE} = P_m / P_i \tag{1}$$

P_i and P_m represent initial and mean crush failure load, respectively.

- Stroke efficiency (SE)

The desire energy absorber device has crushable structures, which can be defined as stroke efficiency (SE). The SE can be obtained by

$$\mathrm{SE} = \frac{u}{H} \tag{2}$$

where u and H represent the stroke and the total height of the structure, respectively. It is clear that the higher the value SE parameter, the higher the magnitude of energy absorption capability, the more optimum the design of the structure.

- Initial failure indictor (IFI)

It is the ratio between initial crush load and critical crush load. Which can be calculate as

$$\mathrm{IFI} = P_i / P_{cr} \tag{3}$$

where P_i is the initial crushing load and P_{cr} is the critical crushing load.

- Specific energy absorption (E_s)

Specific energy absorption, E_S, is defined as the energy absorbed per unit mass of material. The total work done or energy absorbed, W, in crushing of composite specimens is to the area under the load–displacement curve is

$$W = \int_0^{S_b} P\,dS \tag{4}$$

where W is the total energy absorbed in crushing of the composite ring specimen. A More characteristic property of progressive crushing mode is

$$W = \int_{S_i}^{S_b} P\,dS = P_m(S_b - S_i) \tag{5}$$

where S_b and S_i are the crush distances and P_m is the mean crush load. The specific energy absorption capability, E_S, of a composite material defined as the energy absorbed per unit mass of material is given by

$$E_s = \frac{W}{M} \tag{6}$$

where M is the mass of the structure being investigated. By substituting Eqs. (5) into (6)

$$E_s = \frac{W}{M} = \frac{P_m(S_b - S_i)}{V\rho} = \frac{P_m(S_b - S_i)}{AH\rho} \tag{7}$$

where A and H are the cross sectional area and length of the crushed portion of the composite ring specimen respectively.

3. Design parameters

The design of high performance composite energy absorber device is driven by many competing objectives such as improving the safety and optimizing the weight. Two design parameters have been used to explore and study the crashworthiness performance of composite hexagonal systems. The first parameter is geometry configuration in which six angles were used. The hexagonal angles varied between 45° and 70° with an increment of 5°. The second parameter is the effect of hexagonal system arrangement, in which two different arrangements have been used. Fig. 1 shows inplane crushing of composite hexagonal ring systems.

4. Experimental program

4.1. Materials

The principal advantage of using woven fabric laminates is that they provide properties that are more balanced in the 0° and 90° directions than unidirectional laminates [1]. It is well-known that fabrics are generally more damage resistant than tapes of the same material and consequently, woven, fabric or cloth composites present better energy management characteristics than the continuous or discontinuous filament composites. Woven roving glass fiber with orientation of [0/90] was selected