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# Experimental analysis of energy absorption capability of thin-walled composite cylindrical shells by quasi-static axial crushing test

Seyed Morteza Hosseini[a,*], Mahmoud Shariati[b]

[a] Shahrood University of Technology, Faculty of Mechanical and Mechatronics Engineering, Mechanical Department, Shahrood, Iran
[b] Ferdowsi University of Mashhad, Faculty of Engineering, Mechanical Department, Mashhad, Iran

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ABSTRACT

The energy absorption capability of thin-walled composite cylindrical shells is experimentally investigated. Effects of six parameters on absorption energy of composite shells are studied. These parameters including three geometric parameters of inner diameter, length and shell thickness and the other three parameters are layer orientation, reinforcing fibers and manufacturing process. The design of experiment was accomplished by applying Taguchi method and the axial crushing test was conducted on shells. The resulting data was statistically analyzed which led to the ranking of the six parameters and an optimized structure based on the selected parameters was proposed. Finally, different kinds of complicated failure modes controlling absorption capacity were studied. In addition, effects of the six mentioned parameters on both stable and unstable crushing modes of shells were investigated. It is found that a good correspondence exists between statistical analysis results and crushing collapse mechanisms in experimental analysis results, which both of the analysis are accorded to specific energy absorption.

## 1. Introduction

Nowadays, composite materials and structures have gained much attention and are now widely used in many industries such as aerospace and automobile industries. In addition to their excellent performance with high specific strength and stiffness, they possess good energy absorption behavior. Knowledge of energy absorption behavior is important for material selection and design of energy absorbers, crashworthiness and damage assessment of structures subjected to the accidental collision, and packaging design against impact.

Energy absorption in composite structures is a function of many parameters including fiber and matrix types, cross-sectional shapes, stacking sequence, fiber architecture, fabrication conditions, fiber content, testing rate, and triggering system. For composites, most properties are highly temperature-dependent and thus temperature should also be considered as an important factor. Most studies on the energy absorption of composites are performed on circular tubes [1].

The crush behavior of composite specimens can be generally classified as either stable or unstable. Although stable crushing results in greater energy absorption and is thus the goal of crashworthy structures, it is important to understand the failure modes associated with both stable and unstable crush behaviors.

A considerable amount of research work [2–13] has been conducted on composites to assess energy absorption. Ochelski and Gotowicki [14] performed an experimental investigation of the energy absorption capability of carbon-epoxy and glass-epoxy composites and analyzed the influence of the fiber reinforcement type, structure type, geometry and shape of specimens, orientation of fibers in a layer and stacking sequence of layers on the energy absorption capability. Specimens in the shape of tubes and truncated cones were selected for testing. On the other hand, the basic mechanical properties of composites designed for elements of energy absorbing structures, that are essential for numerical simulation of the failure mechanism during the crash test, were determined experimentally. Another important point in this paper was the higher value of the energy absorption capability of carbon-epoxy composites compared to glass-epoxy.

Palanivelu et al. [15] studied the quasi-static crushing performance of nine different geometrical shapes of small-scale composite tubes. The idea was to understand the effect of geometry, dimension and triggering mechanism on the progressive deformation of small-scale composite tubes. Different geometrical shapes of the composite tubes have been manufactured by hand lay-up technique using unidirectional E-glass fabric and polyester resin. From this unique study, it was found that the crushing characteristics and the corresponding energy absorption of the special geometrical shapes are better than the standard geometrical shapes such as square and hexagonal cross-sections.

* Corresponding author.
*E-mail address:* seyedmortezahosseini2016@gmail.com (S.M. Hosseini).

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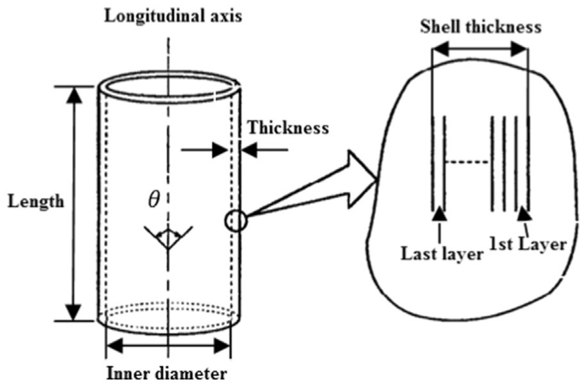


**Fig. 1.** Geometrical specification of composite shells.

**Table 1**
Fiber reinforcement type and orientation of composite shells.

| No. | Fiber reinforcement type | Fiber orientation |
|---|---|---|
| 1 | E-Glass | Unidirectional |
| 2 | E-Glass | Biaxial (90/0) |
| 3 | E-Glass | Biaxial (+45/−45) |
| 4 | E-Glass | Tri-axial (+45/0/−45) |
| 5 | (HS)-Carbon | Unidirectional |
| 6 | (HS)-Carbon | Biaxial (90/0) |
| 7 | (HS)-Carbon | Biaxial (+45/−45) |
| 8 | (HS)-Carbon | Tri-axial (+45/0/−45) |

**Table 2**
Matrix physical properties.

| Properties | Test method | EPOLAM 2040 RESIN | EPOLAM 2047 HARDENER |
|---|---|---|---|
| Aspect | | Liquid | Liquid |
| Color | | Light amber | Light amber |
| Mixing ratio by weight | | 100 | 32 |
| Mixing ratio by volume | | 100 | 39 |
| Mixing viscosity at 25 °C (mPa.s) | BROOKFIELD LVT | | 245 |
| Mixing density at 25 °C (g/cm$^3$) | ASTM D 790 | | **1.153** |

**Table 3**
Matrix mechanical properties.

| | |
|---|---|
| Tensile strength (MPa) | 71.4 |
| Strain to failure | 0.0454 |
| Young modulus (GPa) | 3.02 |

Jackson et al. [16] experimentally investigated the effect of laminate design on the crush performance of carbon–fiber/epoxy crush elements. A quasi-isotropic lay-up was found to result in the highest Specific Energy Absorption (SEA) for Four-Harness (4HS) reinforced laminates, however, a hybrid of unidirectional weave and 4HS fabric produced the highest SEA of 114 kJ/kg.

Niknejad et al. [17] studied the quasi-static crushing performance of empty and polyurethane foam-filled E-glass/vinyl ester composite tubes with different geometrical characteristics to be used in sacrificial cladding structures. A number of empty and foam-filled tubes were compressed laterally between two rigid plates. The effects of polyurethane foam filler on the crushing characteristics and the corresponding energy absorption by the composite tubes are investigated. Experimental results show that the presence of polyurethane foam inside the composite tubes suppresses the circumferential delimitation process and fiber fracturing; consequently, it increases the specific absorbed energy by the composite tubes during the flattening process.

Pickett and Dayal [18] developed the specific energy absorption characteristics of long fiber composite structures, using a numerical approach. Numerical results are compared with experiments performed elsewhere and an encouraging correlation was obtained. Kim et al. [19] evaluated the failure modes and energy absorption capabilities of different kinds of circular tubes made of carbon, Kevlar, and carbon - Kevlar hybrid fibers composites with epoxy resin. The relationship between the crushing parameters (specific energy absorption, maximum peak load, mean crushing load) and the material properties of different fibers and patterns were also investigated. The fabric carbon/epoxy tubes had the best energy absorption capability. In contrast, the tubes made of Kevlar showed the worst energy absorption capability.

Palanivelu et al. [20] described the experimental investigation of the progressive deformation behavior of unidirectional pultruded composite tubes subjected to an axial impact load. Pultruded square and circular profiles with glass-polyester and glass-vinylester combinations were used and effects of the geometry profile, triggering, strain rate and the type of resin on energy absorption of the composite tubes were studied.

The present paper presents an experimental analysis of energy absorption capability of composite cylindrical shells by the quasi-static axial crushing test.

## 2. Materials and experimental methods

### 2.1. Materials

Composite cylindrical shells were manufactured using glass and carbon–fiber reinforced epoxy according to geometrical specifications shown in Fig. 1. For the higher mechanical properties and proper speed manufacturing of stitched fiber textiles compared to woven textiles, they are the first priority in use, therefore, unidirectional and multiaxial E-glass stitched textiles and high strength carbon fibers had been used in this study which is listed in Table 1.

**Table 4**
Mechanical properties of orthotropic composite shells reinforced with glass and carbon fibers.

| Mechanical properties | E-Glass Unidirectional | E-Glass Biaxial (90/0) | E-Glass Biaxial (+45/−45) | E-Glass Tri-axial (+45/0/−45) | (HS)-Carbon Unidirectional |
|---|---|---|---|---|---|
| **Young's modulus in longitudinal $E_1$(MPa)** | 30000 | 20000 | 19000 | 22000 | 80000 |
| **Young's modulus in transverse $E_2$(MPa)** | 3000 | 16500 | 19000 | 9000 | 6000 |
| **Poisson's ratio $\vartheta_{12}$** | 0.3 | 0.3 | 0.3 | 0.3 | 0.27 |
| **Shear modulus $G_{12}$(MPa)** | 4000 | 4000 | 2300 | 14150 | 5700 |
| **Longitudinal tensile strength $X_T$(MPa)** | 600 | 370 | 207 | 390 | 1100 |
| **Transverse tensile strength $Y_T$(MPa)** | 100 | 318 | 207 | 180 | 27 |
| **Longitudinal compressive strength $X_C$(MPa)** | 400 | 246 | 143.88 | 260 | 730 |
| **Transverse compressive strength $Y_C$(MPa)** | 66 | 212 | 143.88 | 120 | 18 |
| **Shear strength $S$(MPa)** | 65 | 46 | 33.5 | 170 | 56.5 |