Effect of Crushing Speed Rate on Crashworthiness Parameters and Energy Absorption Capability of Composite Materials

Hakim S. Sultan Aljibori¹, Firas K. Mohamad Alosfur² and Noor J. Ridha²

¹Department of Air-conditioning and Refrigeration Engineering, University of Warith Alanbyaa, Kerbalaa, Iraq
²Department of Physics, College of Science, University of Kerbala, Kerbala, Iraq

Corresponding Author: hakimaljobori@gmail.com

Abstract. Improvement of energy absorber in automotive and aircraft industry is a demanding requirement. Crashworthiness parameters designed to special interesting and could ensure the passengers safety and reduce fuel costs. Thin shells are the main structures of energy absorbing in transportation applications for collisions; it is very important to check their energy absorption and performance. In the present paper, composite materials of glass and epoxy conical shell structures of slipping solid steel cone are studied experimentally. The effect of crush rate and crushing behaviour on failure modes and energy absorption are investigated in details. The specific and volumetric energy absorption capabilities are studied and failure modes for quasi-static analyses were investigated. One type of semi-vertex angle (β) of conical tubes was 10 degrees with stacking sequence of 90/45/-45/90. The composite material specimens were loaded and compressed at various crush speed rates of 5, 10, 15 and 20 mm/min. The results of composite structures are demonstrated and showed that the conical shapes with speed rate of 5 mm/min absorbed high specific energy and displayed more stability in load-stroke curve.

Keywords: Composite, Conical Shells, Energy Absorption, Laminated and Failure Mode

List of Symbols and Abbreviations

FWL Filament wound laminated
FRP Fibre-reinforced plastic
β Semi-vertex angle of cone

Eₙ Energy absorbed/unit mass

Eᵥ Energy absorbed/unit volume

Pₘ Mean (average) crush load at post crash stage

Pᵢ Initial crushing load

Pₘₐxima Maximum peak load

D, d Maximum and minimum diameter of cone

Wₜ Total work done

Wₚ Work at post crash stage
1. Introduction

Composite material structures are being used for most applications in automotive and aircraft parts to meet the weight and manufacturing cost constraints. The modes of composite material are significantly different from the metallic materials. Recently, attempts were made to improve energy absorption capability of composite structures [1-3]. These structures have a wide area of applications due to their specific stiffness and strength value. Also, the composite materials have low thermal expansion, good corrosion resistance and non-conductive materials. Understanding of the energy absorption capability of composites has become an area of great academic and practical interest. Many researchers have studied the effect of crushing behavior on energy absorption capability [4-5]. For the metal applications, the trigger put as a chamfer, or crimps nearest to the ends of the structure (Cone, for example), however, the crash effect in these material are still limited because of the complex shape of these materials [6]. Experimental studies are important for providing most the information that concerning materials and structural factors and predicting the crash shape of these materials. For all the crashworthiness effects, thin-shell fiber and resin tubes have been the focus on various investigations, due to cost, easier of manufacturing, fabrication and excellent energy efficiency [7-8]. Experimental findings explained that the composite shells deform in a shape different from components made of conventional materials, such as metals and polymers, since micro-failure modes such as delamination, matrix cracking, fiber breakage and so on. They depend on the geometry of structure, material characteristics and testing procedure and parameters [9-10].

The present paper, reported on an experimental test and analysis of the failure mechanism and crushing behavior to the stable mode of thin-shell fiber glass conical shell under axial slipping loads. The shape of structure was designed by slipping of rigid steel cone to laminated fibre/epoxy cone to predicting the loads and the energy absorbed during the collapse procedure. However, there is a poor of experimental work as well as dynamic pushing of solid structures into hollow structures. The idea comes from: the high energy absorption can be produced if the properties of material (especially, longitudinal properties) are staring utilized and effect in application. The objective of this research paper is to determine with detail the contributions of fiber deformation and cracking to energy absorption in these materials.

2. Design Parameters

2.1 Energy Absorption Capability

Fiber-reinforced materials are low strain to fracture, but it found now has been good characteristics for structures made from these materials and can have energy absorption capability and better than such materials those have other properties and made from some metals. As we kno and that the total work ($W_t$) of the structure is the area under the curve of load and distance as shown in Eq.1:

$$ W_t = \int \Delta F ds = W_t = \int P ds $$

At the Post and advance stage, the work ($W_p$) can be calculated as shown in equation 2:
\[ W_p = \int_{s_p}^{P} P \, ds \Rightarrow P_m (s - s_p) \]  \hspace{1cm} (2)

and the specific energy absorption per unit mass (kJ/kg) may be representing from the equation 3:

\[ E_s = \frac{P_m(s - s_i)}{\rho \times V} = \frac{W_p}{M} \]  \hspace{1cm} (3)

Where,

\( P_m \): The mean (average) load,

\( A \): Cross-section area of hollow tube,

\( \rho \): the density of the material,

\( V \): volume of structure and \( M \): mass of structure.

So, the energy absorption per unit volume \( (E_v) \) calculated by equation 4:

\[ E_v = \frac{E_s \times M}{V_s} \]  \hspace{1cm} (4)

The volume at current structure occupied by the cone shape before the failure can be calculated from:

\[ V_{con} = \frac{\pi H}{12} \left[ D^2 + Dd + d^2 \right] \]  \hspace{1cm} (5)

2.2 *Stroke Efficiency (SE)*

From the experimental tests noticed that the length of crushing (Stroke) depends on the specimen geometry and on the method that structure is dispersed. The stroke-efficiency may give by eq. 6:

\[ SE = \frac{S_p - S}{H} \]  \hspace{1cm} (6)

2.3 *Crush Force Efficiency (CFE)*

The evaluation of efficiency and performance of composite structures depend on the loads that support the structure, these loads are average loads and maximum load cause the failure. This loads are demonstrated by evaluating and assessment of this efficiency (CFE), this is calculated by eq. 7:

\[ CFE = \frac{P_m}{P_{max}} \]  \hspace{1cm} (7)

3. **Fabrication Procedure of Cone**

The winding procedure of fibre filament was used to manufacturing the specimens of the glass fibre filament laminated as conical shape as shell. Epoxy resin was mixed with epoxy hardener, and then fibres are pulled to the resin bath across tension devices to wood mandrel for good impregnation. The wet cone is curried out and kept at room temperature for 24 hours for optimum and better combined and then extracted the composite cone from the mandrel. The schematic diagram of the winding procedure is shown in Figure 1. The winding factor and parameters (winding speed, winding tension, resin content and winding timing) were kept constant level during fabrication procedure. BENSO machine was used for cutting and trimming to obtain the desired cone shape. Cutting and finishing processes are shown in Figure 2. The specimens of solid steel cone and glass fibre and epoxy composite conical shell used for slipping test were fabricated and tested as shown in Figure 3.
Figure 1. Schematic Representation of the Wet Filament Winding Process

Figure 2. Cutting and finishing processes
3.1 Define a Composite Layers

The sequence of micro-fracture leading to the formation of the stable crush depends on the shape and arrangement of the fibers inside the tube wall and the materials that used in the fabrication. Each layer name must be unique and also need to make the thickness of the layer, angle of orientation to be maintained within the plane of the layer, and then it will specify the overall composite orientation. It is to be noted that (0° angle) with the x axis and a (90° angle) with the y axis. This is to be repeated for as many layers as required. The unidirectional laminates in which fibres are positioned parallel to each others in a matrix and the layers oriented at an angle ($\theta$) from reference axis (x and y) to principal material coordinates system 1 and 2 as shown in Figure 4.

On the other hand, one of the most common forms of fibre-reinforced composite structure is the stacking sequence laminate (angle ply-laminates), in which the fabricator lay-up a sequence of fibre reinforced with different fibre orientation $\theta$ in alternate layers ($/\theta/-/\theta/-/\theta/-/\theta$) as shown in Figure 5. The conical shell structure has four layers of different fibre orientation. Arrangement of fibers from 90/45/-45/90 within the thickness is shown in Figure 6.

![Figure 4. Definition of Principle Material Axes](image)
4. Crushing Process
A total of 16 specimens of filament laminates were tested under axial crushing test and slipping of rigid steel cone into glass fibre as a composite shell with cone angle (β) of 10° and fibre orientations form (90/45/-45/90) as a sequence. Crushing tests were carried out using an digital machine with loading capacity of machine is 250 KN. The entire specimens were compressed and loaded by stroke at various crush rates of 5, 10, 15 and 20 mm/min. The load and stroke were recorded by memory data system. The results are represented by the average of the four typical tests under same conditions. All the specimens were fabricated with height of 100 mm and outer diameter was 80 mm. Some photographs during the test were taken, thus photographs show the specimen at different crushing stroke to provide the history of their crushing process. Test procedure and slipping of rigid cone to composite cone are shown in Figure 7.
5. Result and Discussion
The load-stroke curves and energy absorption relations as well as the deformation history and failure modes for composite conical structures are presented in this section. The load-stroke curve was obtained from average of the load-stroke points for four replicated tests with same-crushing speed rate and the same testing conditions. In addition the effect of the crushing speed rate on energy absorption capability is discussed. The energy absorbed by all the cones was evaluated and calculated by numerical methods of the load-stroke curves.

5.1 Loading responses
Figure 8 shows the typical load-Stoke curve for FWL conical shell at first crushing speed (V1) of 5mm/min. To check the strain rate, four variables and parameters was evaluated these are: load at first initial zone $P_i$, maximum load $P_{max}$, stroke at initial zone $S_i$ and stroke at complete procedure in post advance stage $S_p$. From the tests it is noticed that the force-stroke behaviour shows a multi-relationships prior to the initiation, and then a tiny sudden drop is observed as shown in Figure 8.
In Figure 9, the load and Stoke curves for all of the tests and crushing speed rate to failure. It is observed that both the loads at first initial failure and at the maximum peak are function of stroke at several speed rates. No clear rate dependence on either of the stroke parameters. This is due to the fact that the epoxy matrix can become brittle material as well as its stiffness decreases when the strain rate increases. As we know that the matrix controls the internal zone growth and if the failure strains of the matrix decrease with increasing crush speed rate, the internal layer crack length increases with increase of crushing speed.

![Figure 9](image)

**Figure 9.** Effect of Crushing Speed Rate on Load – Stroke Curve of Composite Cones Subjected to Slipping Crush Test  
**Note:** V1, V2, V3 and V4 stand for Crushing speeds of 5, 10, 15 and 20mm/min respectively.

### 5.2 Energy Absorption Capabilities

The main objective of this work is to improve the energy absorption ability of composite conical shell. Energy absorption capability of these devices is the main factor in measuring their performance. It is noted that most of the absorption procedure occurs at post crush zone. Crush failure modes in an initial and propagation were influenced by crushing speed rate. From the previous equations (Eq.3 and Eq.4), there are two kinds of energies were measured, during slipping rigid cone to cone. These are the energy absorption per unit mass ($E_s$) and energy absorbed per unit volume ($E_v$). Table1 summarized the results for crush energy absorption capabilities for all the tests. It can be observed that the specific energy absorption at V1 is slightly higher compared to those recorded at others speeds.
Table 1: Summarised results of the crashworthiness parameters and energy absorption capabilities of composite conical shells.

| Crushing Speed | \(P_i\) | \(P_m\) | \(P_{\text{max}}\) | CFE | SE | \(E_s\) | \(E_v\) |
|----------------|--------|--------|-----------------|-----|----|--------|--------|
| \(V_1\) (5\,mm/min) | 23.30  | 24.76  | 26.51           | 0.93| 0.66| 5.44   | 5264.5 |
| \(V_2\) (10\,mm/min) | 24.66  | 24.82  | 27.7            | 0.92| 0.64| 5.30   | 5129.1 |
| \(V_3\) (15\,mm/min) | 22.92  | 22.1   | 23.7            | 0.93| 0.62| 4.7    | 4548.4 |
| \(V_4\) (20\,mm/min) | 23.6   | 23.1   | 24.9            | 0.92| 0.55| 4.3    | 4162.3 |

5.3 Stroke Efficiency (SE) and Crush Force Efficiency (CFE)

Crashworthiness of a vehicle is measured by its ability to absorb energy and prevent any injury to the occupants. Therefore, experimental results for composite conical shell with several crushing rate subjected to slipping solid steel are presented as dimensionless ratios known as crush force efficiency (CFE) and stroke Efficiency (SE). The values of these crashworthiness parameters for all the tests are tabulated in Table 1.

6. Conclusions

The effect of stacking sequence from 90/45/-45/90 with cone angle of 10 degrees was studied experimentally. All the specimens were tested for compression case and loaded by various speed rates of 5, 10, 15 and 20\,mm/min. The load-stroke relations and the energy absorption behaviour were discussed. However the following conclusions could be drawn from the investigation:

1. All specimens followed the similar failure mechanism. This shape and mechanism are associated with crushing mechanism that involves matrix cracking, tearing of fibres and delamination between layers.
2. The effects of rate of crushing speed on the energy absorption and failure mechanism
3. All the results and modes of composite structures noticed that the cone shell with stacking sequence from 90/45/-45/90 absorb high specific energy.

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