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**ORIGINAL ARTICLE**

# Numerical study on energy absorbing characteristics of thin-walled tube under axial and oblique impact

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**KEYWORDS**

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**Abstract** Energy absorbing characteristics (EAC) of thin wall tube during the impact are important in the automobile and aerospace industries. In this paper, energy absorbing characteristics such as mean force, peak force, energy absorption and crash force efficiency (CFE) of three different cross-sections (square, rectangular and circular) at three different thicknesses (2 mm, 2.5 mm and 4 mm) were analyzed. The analysis was accomplished using ABAQUS/EXPLICIT, and aluminum alloy (AA6063) was used as a shell material. The result of impact (or) crash-worthiness against axial load indicates that the circular cross section of 2.5 mm thickness is optimum. During the oblique (15°, 30°, 45°) impact, increasing the angle leads to less energy absorption. Also, Multilinear regression analysis was carried out to predict the energy absorption characteristics at 90°.


## 1. Introduction

Energy absorption is the ability of a material or section that absorbs energy or force during various mechanical loading conditions. Energy absorbing technique is the methodology to evaluate or identify the EAC such as crash force efficiency, specific energy absorption, peak force and mean force. This EAC of various cross-sections and materials are very much important in several applications especially in high speed automobiles that cause severe impact to the passengers and non-recyclable damage to the vehicles [1]. Furthermore, global increase in the usage of fossil fuels downs the overall weight of the car, thus increase the fatalities and collisions vice versa. Energy absorption technique predominantly covers applications such as automobile, aerospace, blast industries and recently overwhelming speed of automobiles and their light weight increases concern over the roadside poles and their relative structures [2–13]. Thiyahuddin et al. studied the impact and energy absorption of portable water-filled road safety barrier system fitted with foam. To prevent the vehicle collision on the temporary construction zone, they developed the portable barrier to prevent the accident. This numerical model consisted of a steel frame, water, plastic shell and foam which was developed and validated against the experimental test. The result indicated reduction in initial impact because the foam absorbed high energy. In addition to that using different foam materials such as polymeric foams, Aluminum foam, polyurethane foam and XPS foam revealed different energy absorption characteristics [14].

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**Nomenclature**

EAC energy absorbing characteristics
CFE crash force efficiency

Numerical method or finite element analysis is very useful for analyzing various optimization methods to reduce the material wastage, time and cost [15–17]. In this paper, numerical study of square, rectangle and circular cross-sections with three different thicknesses was analyzed and optimum parameter was found out. The main objective of this work was to study the EAC of square, rectangle and circular for required parameter with optimum time and low cost.

## 2. Materials and methods

### 2.1. Numerical study

Three types of sections were used in numerical simulation such as square, rectangular and circular. The tube material used in all numerical simulations is AA6063 aluminum alloy. In this work three different thicknesses (2 mm, 2.5 mm, 4 mm) were used. Also, in this simulation ABAQUS/EXPLICIT finite element code was used. The specification of the tube which is used for this simulation is given in Table 1. The numerical input values of aluminum alloys are given as density = 2.71 kg/m$^3$, Elastic modulus = 68,200 N/mm$^2$, Poisson's ratio = 0.3 and plastic or engineering stress–strain value is provided in Table 2. In this numerical work, three objects were considered that is moving rigid striker, deformable aluminum tube and fixed rigid plate. The boundary conditions were fixed in all direction for bottom rigid plate, moving one direction for top rigid striker, and other directions and rotations were fixed. Finally, deformable shell tube in between those rigid plates was stuffed. In the assembly of tube and rigid striker with different angles of 0°, 15°, 30° and 45° with respect to the axis of the tube. The analysis type was given as DYNAMIC/EXPLICIT crash simulation. The contact between tube and rigid plate was given as tangential behavior of rough contact and there is no penetration between them. The moving rigid striker's velocity is 2 m/s parallel to the axis of tube. The thin wall tube was modeled by using quadrilateral element with structured mesh and element size of 2.5 mm was chosen for the tube(or) shell based on the mesh convergence study.

### 2.2. Statistical study

In this study, an attempt has been made to predict the crash force for 90° with aid of displacement and crash force data of 15°, 30° and 45° angle. Here, MINITAB is used as statistical tool in order to evaluate or predict the crash force of 90°. Multilinear regression analysis was chosen for this study and the generalized equation can be given by Eq. (1),

$$Y = AX_1 + BX_2 + C \tag{1}$$

where
$A$ and $B$ are slope of regression line
$X_1$ and $X_2$ are independent value (or) variable
$C$ is intercept

For this study, displacement and angle were taken as independent variables denoted as $X_1$ and $X_2$. The value that is to be predicted as the dependent variable is the crash force which is denoted as $Y$.

$$Y = 357\ \text{Displacement (mm)} - 495\ \text{Oblique (Degree)} + 55,552 \tag{2}$$

$$S = 20203.8 \quad R - \text{Sq} = 57.78\% \quad R - \text{Sq(adj)} = 57.64\%$$

where

$S$ = Standard deviation of error term

$R - \text{Sq}$ = Coefficient of determination

$R - \text{Sq(adj)}$ = need to go for next polynomial order

The predicted equation by statistical technique indicated negative impact on the dependent variable $Y$. So whenever the angle changes, the dependent variable crash force varies negatively.

**Table 2** Stress strain value of aluminum alloy.

| Yield stress | Plastic strain |
|---|---|
| 80 | 0 |
| 115 | 0.024 |
| 139 | 0.049 |
| 150 | 0.079 |
| 158 | 0.099 |
| 167 | 0.124 |
| 171 | 0.149 |
| 173 | 0.174 |

**Table 1** Geometrical properties of three different cross-sections.

| Profile | Length (mm) | Dimension (mm) | Perimeter (mm) | Thickness (mm) |
|---|---|---|---|---|
| Square | 245 | 80 × 80 | 320 | 2, 2.5, and 4 |
| Circular | 245 | $D$ = 102 | 320 | 2, 2.5, and 4 |
| Rectangular | 245 | 95 × 65 | 320 | 2, 2.5, and 4 |

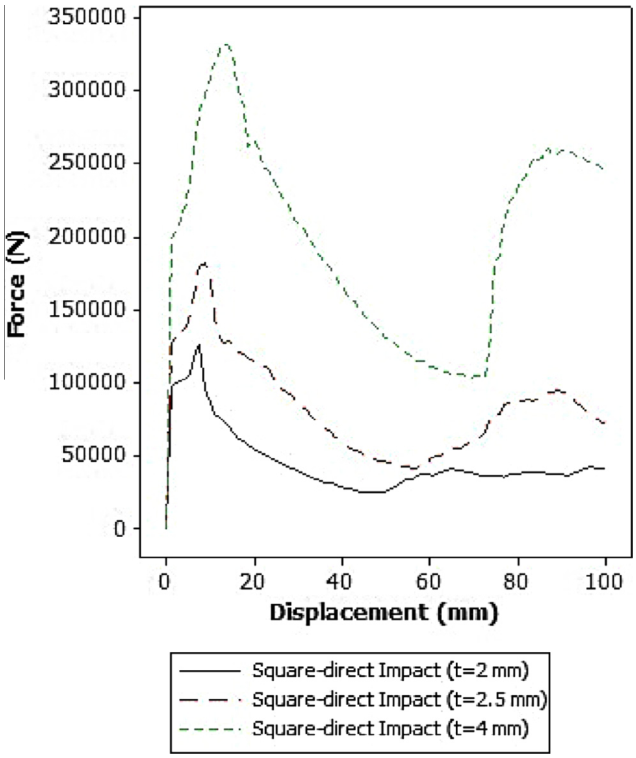


**Figure 1** Force vs displacement for square tubes with various thickness (direct impact).

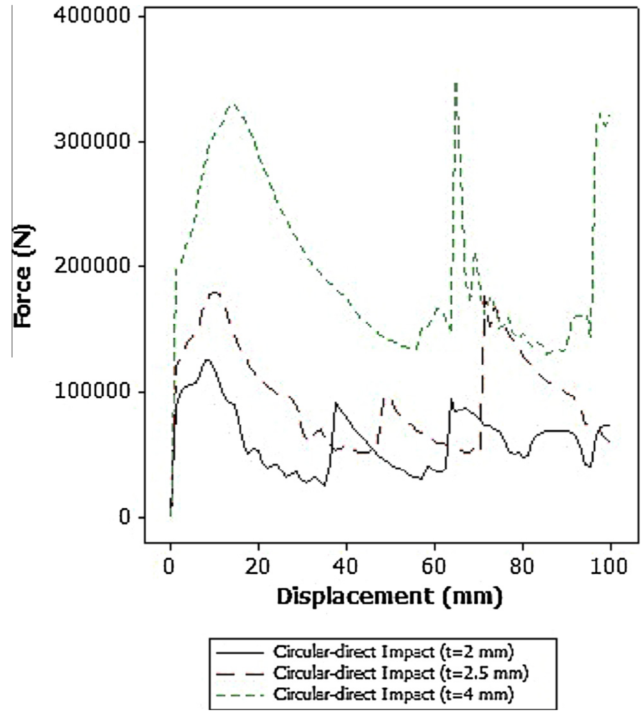


**Figure 3** Force vs displacement for circular tubes with various thickness (direct impact).

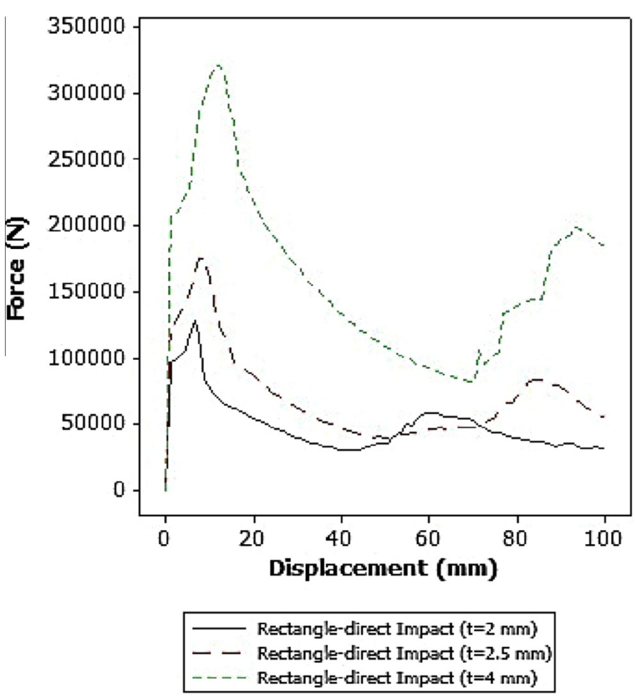


**Figure 2** Force vs displacement for rectangular tubes with various thickness (direct impact).

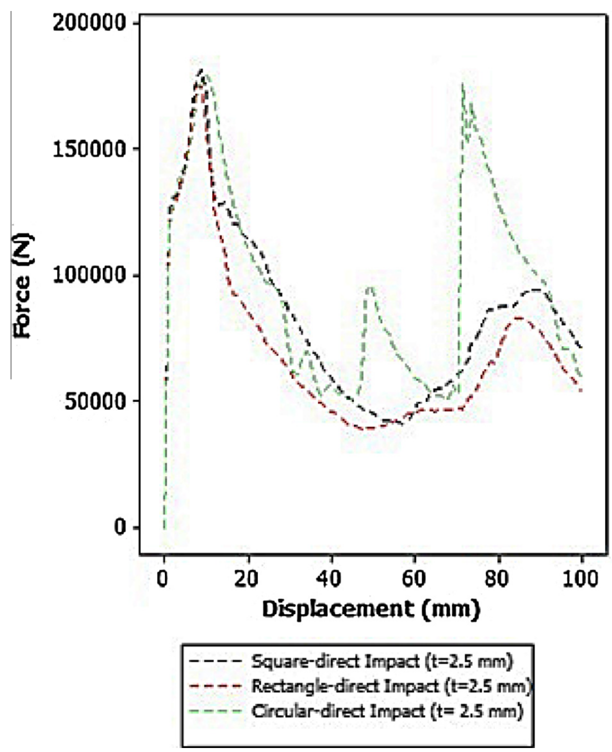


**Figure 4** Force vs displacement for three cross-sections (direct impact).

**Table 3** Energy absorbing parameters on different section and thickness.

| | Energy (kJ) | $F_{mean}$ (kN) | $F_{peak}$ (kN) | CFE | SE |
|---|---|---|---|---|---|
| Square (2 mm) | 10.12 | 51.41 | 125.74 | 0.41 | 0.798 |
| Square (2.5 mm) | 15.39 | 78.14 | 230.25 | 0.34 | 0.80 |
| Square (4 mm) | 38.55 | 196.61 | 335.87 | 0.59 | 0.796 |
| Rec. (2 mm) | 10.30 | 52.21 | 127.93 | 0.41 | 0.799 |
| Rec. (2.5 mm) | 15.18 | 77.11 | 175.15 | 0.44 | 0.80 |
| Rec. (4 mm) | 36.11 | 183.33 | 417.81 | 0.44 | 0.79 |
| Circular (2 mm) | 12.02 | 61.13 | 125.63 | 0.49 | 0.798 |
| Circ. (2.5 mm) | 17.97 | 91.67 | 179.40 | 0.51 | 0.796 |
| Circ. (4 mm) | 44.92 | 226.91 | 569.49 | 0.40 | 0.799 |

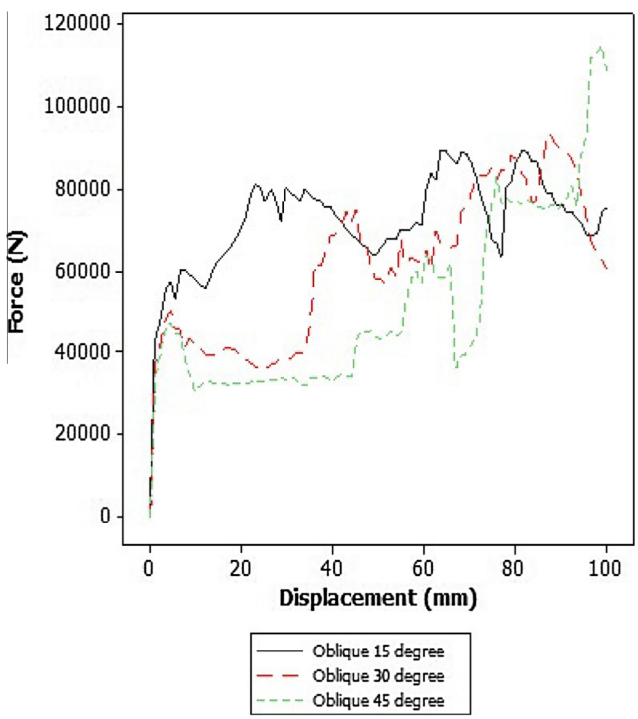


**Figure 5** Force vs displacement for different oblique impact.

### 2.3. Energy absorbing parameters

(i) Energy absorption, $U$ is

$$U = \int_0^{dmax} F\,dx \tag{3}$$

$U$ = Total energy absorbed

$F$ = crash force

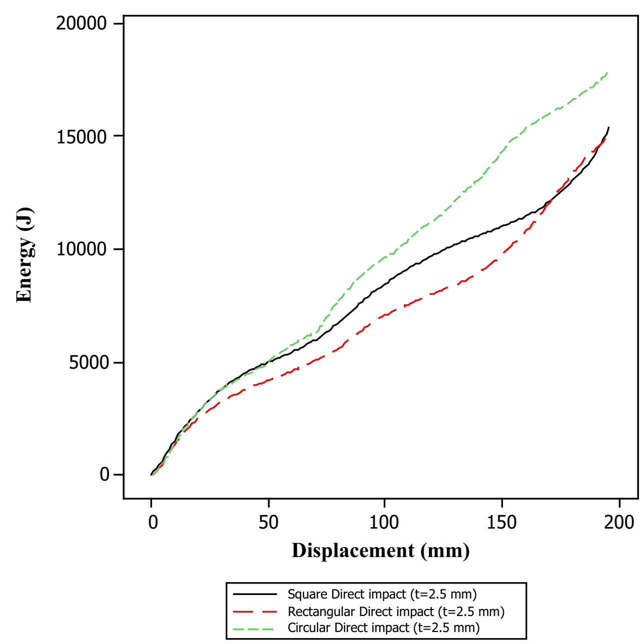


**Figure 6** Energy absorption characteristics of direct impact.

$dx$ = changes in displacement

(ii) Specific energy absorption, $E_s$ is

$$E_s = \frac{U}{m} \tag{4}$$

$m$ = mass of crashed component

(iii) Crash force efficiency, CFE:

CFE is the ratio between mean force and peak force.

$$\text{CFE} = \frac{F_{mean}}{F_{peak}} \tag{5}$$

**Table 4** The energy absorbing parameters on different oblique angles of circular section.

| | Energy (kJ) | $F_{mean}$ (kN) | $F_{max}$ (kN) | CFE | SE |
|---|---|---|---|---|---|
| Circular (15) | 16.10 | 81.92 | 130.30 | 0.63 | 0.797 |
| Circular (30) | 14.38 | 73.02 | 125.84 | 0.58 | 0.799 |
| Circular (45) | 13.52 | 68.77 | 129.18 | 0.53 | 0.798 |
| Circular (90) | 9.009 | 45.93 | 80.79 | 0.57 | 0.797 |

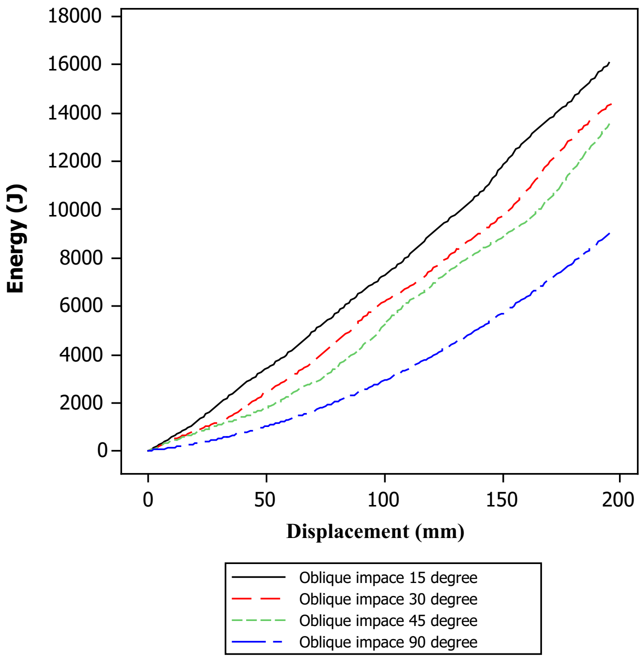


**Figure 7** Energy absorption characteristics of oblique impact.

CFE is an important parameter to identify the optimum energy absorber among various structures. A good energy absorber should have less variation between mean force and peak force and peak force is the required force to displace the permanent deformation of tube materials.

(iv) Stroke efficiency:

It is ratio between maximum displacements to the total original length of structure.

$$S_E = \frac{dmax}{l} \quad (6)$$

## 3. Result and discussion

### 3.1. Force vs displacement characteristics

The force vs displacement characteristics of thin-walled aluminum tube (different cross-sections and thicknesses) are shown in Figs. 1–4. The area under the curve denotes energy absorbed by the tube during impact loading. In square section, higher impact was absorbed than other cross-sections whereas the impact force reduced with increase in displacement value. To add further, in case of circular section the impact force absorbed by the section has not been reduced drastically when compared to the square and rectangular sections. Furthermore, literature reveals that good (or) optimum energy absorbed is the one that exhibits lesser variation between the peak force and mean force.

### 3.2. Effect of thicknesses

In case of all cross-sections, increasing the thickness absorbed more impact force. However, CFE (2.5 mm thickness) of circular cross-section was good when compared to square and rectangular. Overall, the result depicts that 2.5 mm thickness is good (or) optimum and this also indicates thickness plays a vital role in energy absorbing device. The energy absorbing parameters on different section and thickness are distinguished in Table 3.

### 3.3. Effect of cross-sections

In this study, three different cross-sections such as circular, square and rectangular were used. As stated earlier, the force vs displacement characteristics of circular cross-section with 2.5 mm thickness were noted to be optimum because of higher mean force when compared to other cross-sections. However, the square cross-section showed higher peak force than circular and rectangular, and this is because just after the initial displacement the impact force of square section reduced

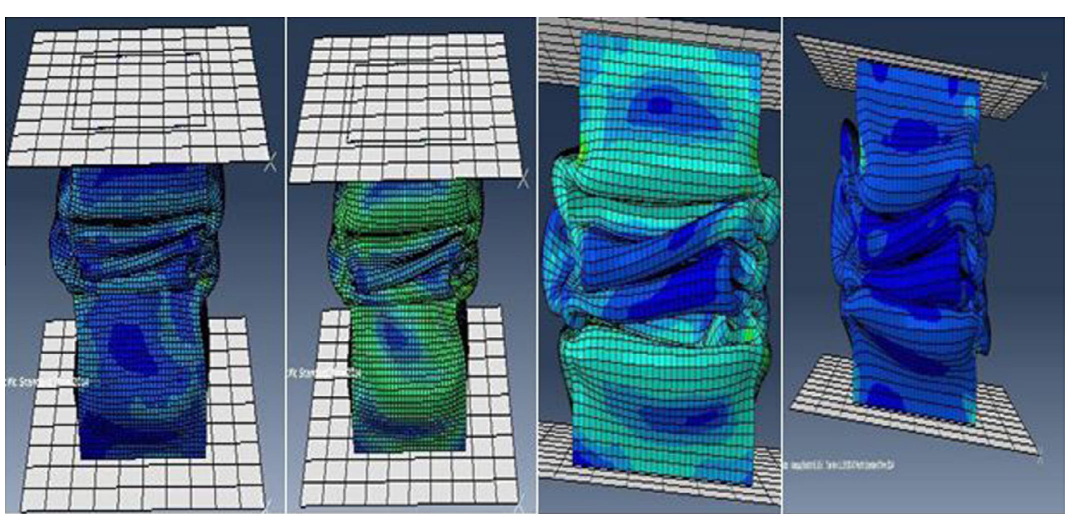

**Figure 8** Buckling mode failure for square cross-section tube under axial impact.

significantly. On the whole, the numerical results disclose that circular cross-section can exhibit better EAC.

### *3.4. Effect of oblique impact and statistical analysis*

The force vs displacement plot of oblique impact for circular cross-section is shown in Fig. 5, and one can perceive from the plot that increasing the oblique angle reduces energy absorption substantially compared to direct (or) axial impact. The prime cause for reduction in absorption of energy during oblique impact is the combined effect of buckling and bending whereas in the case of axial (or) direct impact only buckling mode of failure was evident, that is shown in Fig. 8. To proceed further, the oblique impact of 15°, 30°, and 45° was profoundly studied and the force vs displacement plots for those angles are shown in Fig. 5. Also the energy absorbing trends for those oblique angles were calculated. The results disclosed that by increasing the oblique angle, the absorbing energy and peak force reduce. Moreover, statistical analysis was conducted to predict the peak force and energy of 90° oblique angle. The study reveals the negative impact of oblique angle to the impact force. Overall, the peak force and energy absorption of 90° were less than those of other respective oblique angles because bending mode failure predominantly play a role. The energy absorbing parameters on different oblique angles of circular section are distinguished in Table 4.

### *3.5. Energy absorption*

The EAC of three different geometrical cross-sections with direct impact are shown in Fig. 6. Based on the study it was concluded that the rectangular cross-section can exhibit lower energy absorption than other two profiles under direct impact. The EAC of oblique impact of three different cross sections are shown in Fig. 7. The figures also indicate that the circular cross-section has higher energy absorption capability when compared to the other two cross-sections. Finally, CFE is optimum for circular cross-section as well as the optimum thickness was found to be 2.5 mm.

## 4. Conclusions

In this work, the study of EAC of three different profiles with three different thicknesses was investigated. DYNAMIC/EXPLICIT numerical simulation with velocity of 2 m/s was used. Oblique impact of angles 15°, 30° and 45° of circular cross-sections was carried out. The EAC of angle 90° were arrived by using statistical tool. From the above investigation the following results are derived:

(i) Among three different cross-sections, circular cross-section is a good energy absorber and rectangular is worse than the other two. Also, the simulation of direct impact delivers buckling mode collapse.
(ii) Circular cross-section with 2.5 mm thickness is optimum because CFE is good for this cross-section.
(iii) On the whole, oblique angle analysis revealed increasing the oblique angle will reduce the energy absorbing capabilities of the tubes. This disclosed that oblique impact produces combined mode of collapse (buckling and bending).
(iv) From the statistical study, energy absorbing capabilities of 90° angle are less than other oblique angles because of the domination of bending mode collapse rather than buckling collapse.
(v) Overall, the structure that is employed with an oblique impact force absorbs much less energy; thus, there is a need to improve their design to increase the energy absorbing capabilities.

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