Effect of taper angle on crashworthiness performance in hybrid tubes

Murat Altın
Department of Automotive Engineering, Faculty of Technology, Gazi University, Ankara, 06590, Turkey

ABSTRACT

The present paper dealt with the finite element analysis (FE) analyzing the taper angle design of aluminum/E-glass fiber reinforced polymer hybrid tubes. This study investigated the crushing characteristics involving peak crush force (PCF), crush force efficiency (CFE) and specific energy absorption (SEA) capacity of thirty different configurations of hybrid tubes. Three types of geometries were studied numerically, including circular, square and hexagonal. The structures evaluated included circular hybrid tubes fabricated with aluminum alloy and composite. The hybrid structures were subjected to axial impact loads using a 750-kg rigid impactor with an initial velocity of 15 m/s. It was found that the crashworthiness performance increased with increasing taper angle. The SEA and CFE values of the circular hybrid tube with a 10° taper angle were high in the other square and hexagonal hybrid tubes. That hybrid structure can preferable as impact energy absorber due to the ability to withstand axial impact loads effectively.

Keywords: Hybrid tubes, Crashworthiness, Peak crush force, Crush force efficiency, Specific energy absorption

1. Introduction

Energy absorbing components are important passive safety system elements. These structures are placed between the buffer and the chassis. The cross section geometry and materials of energy absorber structures are various, so, investigating this subject is the aim of many studies.

Metal and composite structures are used in automotive components to absorb substantial amount of deformation energy. Deformation behavior of the metal structures, mostly used in automotive bodies, has been well investigated experimentally [1,2], numerically [3,4] and analytically [5,6]. Composites have wide applications in automotive [7-9], racing car [10,11], aerospace [12,13] and spacecraft industry [14,15]. The composite tubes are used to reinforce the metal tubes and enhance its energy absorption capacity. Hybrid tubes are made from several layers of composites and metals. As an efficient energy absorbing structure, hybrid tubes are widely studied by researchers in recent years. Researchers have conducted numerical and experimental studies on hybrid tubes of various
cross-sectional geometries. Hybrid tubes can have different geometry profiles, such as circular tubes [16,17], square tubes [18,19], corrugated tubes [20,21] and tapered tubes [22,23]. Kathiresan et al. investigated the low velocity axial impact and quasi-static loading deformation behavior of fiber metal laminated hybrid conical frusta in Ref. [24,25]. Reuter and Tröster [26] investigated the crashworthiness of aluminum and carbon fiber reinforced polymer (CFRP) hybrid tubes. They found that hybrid tubes showed remarkable lightweight potential, and the special energy absorption of the hybrid tubes was 37% higher than that of pure metal tubes. Zhu et al. [27] researched the absorbed energy capacity of composite, metal and metal/composite hybrid tubes under axial and oblique crushing loading. They found that different crush loading angles have effect on the crash performance of hybrid and other tubes. Mirzaei et al [28] studied circular hybrid tubes under axial crushing loading. They found that hybrid tubes have more energy absorption capacity in comparison to bare metal tubes. Energy absorbing capacity of axial crushing of hybrid tubes around aluminum tubes were numerically investigated by El-Hage et al. [29]. They found that the SEA capacity of the E-glass fiber–epoxy composite tubes was higher than those the other tubes. Costas et al [30] compared the energy absorption of different structures hybrid tubes with tube made of steel, in their study, they found that crashworthiness performance of glass-fiber reinforced polyamide was higher than hybrid tubes. Esnaola et al. [31] had examined quasi-static compression test to study semi-hexagonal cross-section composite fibers. They found that the highest energy absorption values of nearly 30 kJ/kg. Hu et al. [32] investigated the deformation characteristics and crashworthiness performance of hybrid tubes. Their results showed that the hybrid tubes the significantly affects the crashworthiness performance and energy absorption capacity. Zhou et al. [33] investigated the crashworthiness performance of carbon fiber-reinforced dual-phase epoxy–polyurea hybrid composite tubes. They showed that the crashworthiness performance of carbon-fiber reinforced epoxy hybrid tubes is greater than that of other tubes. Song et al [34] experimentally investigated the quasi-static and dynamic impact test on pure metal and FRP metallic structures. They identified four typical collapse modes for tubes including: compound diamond, compound fragmentation, delamination and catastrophic failure. In the present paper, the effects of taper angle on the crashworthiness performance of hybrid circular, square and hexagonal tubes were numerically investigated. The new design hybrid tube is proved to be a perfect crashworthiness performance with low peak crush force and very high crush force efficiency. It should also be noted that the effect of tapering on hybrid tubes has not been investigated yet in the open literature, and this paper presents a novel contribution in this subject.

2. Problem Description

Thin-walled hybrid tubes having circular, square and hexagonal cross-sections types are focused in this study. The hybrid tubes that were used in the FE analysis contained circular, square and hexagonal cross section. Those hybrid tubes were made of steel, aluminum and composite structure with a wall thickness of 2 mm and length 200 mm (see Figure 1.). To research the effect of the taper angle, eleven different taper angle values (0°, 1°, 2°, 3°, 4°, 5°, 6°, 7°, 8°, 9° and 10°) are used. The abbreviation CSGA denotes the circular steel/composite/aluminum models, SSCA denotes the square steel/composite/aluminum models, whereas HSCA denotes hexagonal steel/composite/aluminum models.

![Figure 1. Geometrical configuration](image-url)

Different parameters have been introduced in FE analysis to evaluate the crashworthiness performance of the structures. The main parameters included in this paper are listed below:

- total energy absorption ($T_E$)
• specific energy absorption (SEA)
• mean crush force (MCF)
• peak crush force (PCF)
• crush force efficiency (CFE)

Total energy absorption \( T_E \) is the area under the force versus displacement curve. \( T_E \) is calculated from:

\[
T_E = \int P(s) \, ds
\]  

(1)

where the parameter \( P \) is the force and \( ds \) is the cut-off displacement.

The specific energy absorption (SEA) is defined as the \( T_E \) per unit mass \( (m) \) of the profile and is given by:

\[
SEA = \frac{T_E}{m}
\]  

(2)

The mean crush force (MCF) can be determined by dividing the \( T_E \) by the displacement \( (L) \), and is given by:

\[
MCF = \frac{T_E}{L}
\]  

(3)

During the crash, the maximum impact force point gives the peak crush force (PCF),

\[
PCF = \max(F(s))
\]  

(4)

The crush force efficiency (CFE) is the MCF divided by the PCF, or:

\[
CFE = \frac{MCF}{PCF}
\]  

(5)

They are all very important in the crashworthiness criteria of energy absorber tubes. It is desirable that the PCF is low \( \text{SEA} \) and \( \text{CFE} \) are at the highest level.

3. Finite Element Modeling

In this study, Ls-Dyna was used to perform all simulations of finite element analysis. The approximate mesh size is set at 3 mm. The hybrid tubes are fixed on a rigid wall where it is impacted by an impact mass of 750 kg, 15 m/s impact velocity as shown in Figure 2. For the composite tube, E-glass/PET199 composite layup was chosen with materials properties listed in Table 1. Mechanical properties of the steel and aluminum tube were entered in the Ls-Dyna in accordance with the data shown in Table 2. extracted from the engineering stress–strain curve.

![Figure 2. Finite element model of hybrid model](image)

| Property | Description | Value |
|----------|-------------|-------|
| \( \rho \) | Density | 2.0 g/cm\(^3\) |
| \( E_a \) | Modulus in longitudinal (fiber) direction | 37.9 GPa |
| \( E_t \) | Modulus in transverse direction | 11.5 GPa |
| \( G_{12} \) | Shear modulus | 4.5 GPa |
| \( v_{12} \) | Major Poisson's ratio | 0.29 |
| \( v_{21} \) | Minor Poisson's ratio | 0.0811 |
| \( X_t \) | Longitudinal tensile strength | 936 MPa |
| \( X_c \) | Longitudinal compressive strength | 484 MPa |
| \( Y_t \) | Transverse tensile strength | 25.7 MPa |
| \( Y_c \) | Transverse compressive strength | 143 MPa |
| \( S_t \) | Shear strength | 16.1 MPa |
| \( S_b \) | Inter-laminar shear strength | 62.6 MPa |
| \( V_f \) | Fiber volume fraction | 70% |

The dynamic and static coefficients of friction were chosen 0.3 and 0.2, respectively. The contact between the rigid impactor and the hybrid tube is AUTOMATIC_NODE_TO_SURFACE_CONTACT. AUTOMATIC_SINGLE_SURFACE_CONTACT contact is applied between the hybrid tubes. The contact between the hybrid tube and the rigid wall is AUTOMATIC_NODE_TO_SURFACE_CONTACT.
TACT algorithm. Belytscko-Tsay shell element with five integration points is chosen. However, material of the structures (aluminum and steel) was modeled by MAT_MODIFIED-PIECEWISE-LINEAR-PLASTICITY model MAT-24 in Ls-Dyna. Material applied for the composite tube is composite, which is modeled with the MAT_ENHANCED_COMPOSITE_DAMAGE model MAT-54 in LS-DYNA. The post-processor LS_PREPOST is used for visualization and data acquisition.

4. Experimental Validation

Validation of the experimental results is critical for the acceptance of such simulations. This section describes the results of numerical FE simulation of composite tubes are compared with the experimental results. Zhang et al. have carried out experiments for composite circular tube under axial loading [35]. In their experiments they adopted composite E-glass/PET199 structures extruded tubes with lengths of 100 mm, inner diameter of 80 mm and wall thickness 2.4 mm. The comparison of the FE analysis results obtained in this study and the results presented in [35] are given in Table 3. Fig. 3 compares the force-displacement curve results obtained from the experimental [35] and finite element result.

This numerical simulation was compared to metal tubes (steel) sets of the numerical analysis result by Nagel [36]. Table 4 presents crashworthiness parameters of the steel specimens modeled in the studies. Figure 4 depicts a comparison of the deformed shape between FE analysis and experimental result at crush distance of 200 mm. The finite element results demonstrate that there is a perfect compatibility between numerical results of this paper and mentioned references.

![Figure 3. Validation of load-displacement curve of composite tube](image)

![Figure 4. Validation of load-displacement curve of steel tube](image)

### Table 3. Comparison between FE analysis and experimental results for composite tube

| Crush distance (mm) | $T_E$ (kJ) | PCF (kN) | SEA (kJ/kg) |
|---------------------|------------|----------|-------------|
| Zhang [35]          | 60         | 1.968    | 68.26       | 14.77       |
| Zhang [35]          | 60         | 1.927    | 74.36       | 14.47       |
| Present study       | 60         | 1.924    | 71.10       | 14.44       |

### Table 4. Comparison of FE analysis and experimental results for steel tube

| Crush distance (mm) | $T_E$ (kJ) | PCF (kN) | SEA (kJ/kg) |
|---------------------|------------|----------|-------------|
| Nagel [36]          | 200        | 9.036    | 199.49      | 8.53        |
| Present study       | 200        | 8.922    | 198.72      | 8.42        |

5. Result and Discussion

In this section, various angles were used for different types of analyses so as to find out the effects of taper angle. The results of the FE analysis are given in Table 5, Table 6 and Table 7, respectively. Table 5. The effect of taper angle on the crashworthiness performance of circular hybrid tubes.

For all the hybrid tubes, the increase in SEA and CFE is almost directly proportional to the increase in tube taper angle. For example, for the...
CSCA hybrid tube, the CFE increased from 0.45 to 0.70 when the taper angle increased from 0 to 10 (see Figure 5., Figure 6. and Figure 7). As for the SEA, it increased from 98.19 kJ/kg to 136.47 kJ/kg when the taper angle increased from 0 to 10 (see Figure 8., Figure 9. and Figure 10.). The increase in the angle contributed positively to both SEA and CFE. It is clear that all hybrid tapered tubes generally have better SEA and CFE than the straight hybrid tubes, especially at large load angles.

Table 5. The effect of taper angle on the crashworthiness performance of circular hybrid tubes

| Run  | Crush distance (mm) | $T_E$ (kJ)  | PCF (kN) | MCF (kN) | CFE | Mass (kg) | SEA (kJ/kg) |
|------|---------------------|-------------|----------|----------|-----|-----------|-------------|
| CSCA0| 120                 | 32.993      | 615.98   | 274.94   | 0.45| 0.336     | 98.19       |
| CSCA1| 120                 | 33.316      | 573.23   | 277.63   | 0.48| 0.324     | 102.83      |
| CSCA2| 120                 | 34.751      | 525.20   | 289.59   | 0.55| 0.311     | 111.74      |
| CSCA3| 120                 | 31.382      | 489.26   | 261.52   | 0.53| 0.299     | 104.96      |
| CSCA4| 120                 | 32.022      | 451.92   | 266.85   | 0.59| 0.287     | 111.57      |
| CSCA5| 120                 | 32.134      | 422.51   | 267.78   | 0.63| 0.275     | 116.85      |
| CSCA6| 120                 | 30.334      | 395.14   | 252.78   | 0.64| 0.263     | 115.34      |
| CSCA7| 120                 | 29.803      | 375.22   | 248.36   | 0.66| 0.251     | 118.74      |
| CSCA8| 120                 | 29.667      | 379.52   | 247.23   | 0.65| 0.239     | 124.13      |
| CSCA9| 120                 | 29.377      | 360.45   | 244.81   | 0.68| 0.227     | 129.41      |
| CSCA10| 120                | 29.340      | 348.98   | 244.50   | 0.70| 0.215     | 136.47      |

Table 6. The effect of taper angle on the crashworthiness performance of square hybrid tubes

| Run  | Crush distance (mm) | $T_E$ (kJ) | PCF (kN) | MCF (kN) | CFE | Mass (kg) | SEA (kJ/kg) |
|------|---------------------|------------|----------|----------|-----|-----------|-------------|
| SSCA0| 120                 | 29.461     | 794.92   | 245.51   | 0.31| 0.428     | 68.83       |
| SSCA1| 120                 | 28.243     | 728.52   | 235.36   | 0.32| 0.412     | 68.55       |
| SSCA2| 120                 | 30.415     | 679.15   | 253.46   | 0.37| 0.397     | 76.61       |
| SSCA3| 120                 | 29.691     | 625.58   | 247.43   | 0.40| 0.381     | 77.93       |
| SSCA4| 120                 | 29.461     | 579.00   | 245.51   | 0.42| 0.366     | 80.49       |
| SSCA5| 120                 | 28.243     | 519.77   | 235.36   | 0.45| 0.361     | 78.24       |
| SSCA6| 120                 | 27.078     | 610.90   | 225.65   | 0.37| 0.335     | 80.83       |
| SSCA7| 120                 | 26.373     | 545.81   | 219.78   | 0.40| 0.320     | 82.42       |
| SSCA8| 120                 | 26.382     | 481.07   | 219.85   | 0.46| 0.305     | 86.50       |
| SSCA9| 120                 | 25.674     | 408.51   | 213.95   | 0.52| 0.289     | 88.84       |
| SSCA10| 120               | 24.370     | 344.71   | 203.08   | 0.59| 0.274     | 88.94       |

Table 7. The effect of taper angle on the crashworthiness performance of hexagonal hybrid tubes

| Run  | Crush distance (mm) | $T_E$ (kJ) | PCF (kN) | MCF (kN) | CFE | Mass (kg) | SEA (kJ/kg) |
|------|---------------------|------------|----------|----------|-----|-----------|-------------|
| HSCA0| 120                 | 33.373     | 676.35   | 278.11   | 0.41| 0.370     | 90.20       |
| HSCA1| 120                 | 33.744     | 632.12   | 281.20   | 0.44| 0.357     | 94.52       |
| HSCA2| 120                 | 32.687     | 590.44   | 272.39   | 0.46| 0.344     | 95.02       |
| HSCA3| 120                 | 32.111     | 547.72   | 267.59   | 0.49| 0.330     | 97.31       |
| HSCA4| 120                 | 31.336     | 511.52   | 261.13   | 0.51| 0.317     | 98.85       |
| HSCA5| 120                 | 30.767     | 476.52   | 256.39   | 0.54| 0.304     | 101.21      |
| HSCA6| 120                 | 29.762     | 424.49   | 248.02   | 0.58| 0.290     | 102.63      |
| HSCA7| 120                 | 29.535     | 382.64   | 246.13   | 0.64| 0.277     | 106.62      |
| HSCA8| 120                 | 28.690     | 354.50   | 238.41   | 0.67| 0.264     | 108.37      |
| HSCA9| 120                 | 27.756     | 336.82   | 231.30   | 0.69| 0.251     | 110.58      |
| HSCA10| 120              | 26.018     | 313.93   | 222.65   | 0.69| 0.237     | 109.78      |

In spite of that both of $T_E$ and PCF values are decreasing by taper angle increasing. For instance, for HSCA hybrid tube, $T_E$ increases from 33.373 kJ to 33.744 kJ when the taper angle increases from 0 to 1, but reduces to 30.767 kJ and then to 26.718 kJ when the taper angle further increases to 5 and then to 10. This change depends on the deformation shape of the hybrid tubes. The change in the amount of total energy absorption capacity depending on the taper angle is given in Figure 11., Figure 12. and Figure 13. Similarly, an increase in the taper angle from 1 to 10 resulted in a decrease in the PCF value (see Figure 14., Figure 15. and Figure 16.).
The taper angle increased the CFE even more, even though it reduced the total energy absorption.
6. Conclusion

This study investigates the crashworthiness of hybrid tubes under dynamic axial impact. From the results obtained, the following conclusions were drawn:

- Increasing the taper angle from 0° to 10° for the circular, square and hexagonal hybrid tubes gives a decrease in PCF of around 50% for all geometries.
- Taper angle has significant effect on the TE of hybrid tubes. For circular and square hybrid tubes, TE increased to the point and then continued to decline. For hexagonal, TE continued to decrease as the taper angle increased.
- It is found for circular, square and hexagonal cross-section hybrid tubes that as the taper angle step by step increases from 0° to 10°, CFE and SAE increase.
- CSCA10 with 10° have highest CFE and SEA under axial impact loading. Specifically, the CFE of the CSCA10 hybrid tube was 226% higher than that of the SSCA0 hybrid tube. Similarly, the SEA of the CSCA10 hybrid tube was 199% higher than that of the SSCA1 hybrid tube.

6. References

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