Thin-walled compound composite cylinders for improved specific energy absorption

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Abstract. Thin tubular structures are widely used as crush cans in the automobiles to absorb energy sacrificially. As the world looks forward to greater fuel efficiency, the adoption of lightweight materials like composites becomes imperative for vehicular structural part designs. The crush cans made of composite exhibit better specific energy absorption characteristics during an impact compared to their metallic counterparts. The paper discusses how the specific energy absorption capacity of thin-walled tubes can be further enhanced using the concept of compound cylinders which induces a pre-stress in the crush can. It further compares the specific energy absorption capacity of a composite tube against metallic designs.

1. Introduction

The Automotive technology across the globe has been undergoing massive changes and the trend is likely to continue for the future. One of the notable changes has been the migration from the traditional IC engine based powertrain towards electric mobility. Whatever be the power source, the need to ensure the vehicle is of low weight for guaranteed fuel efficiency without compromising on the overall safety of the driver and passengers has been constant [1]. Composites besides being light in weight have good specific energy characteristics to absorb energy as sacrificial parts during collisions and accidents. Vehicle body made of composite materials such as CFRP has good strength to weight ratio. Additionally, it can act as a good shield against EMC hazards in electric vehicles besides being a very good contributor to eliminate or absorb acoustic noises.

Pre-stressing concepts are widely adopted by the civil engineering community in designs of varieties of structures to achieve a good overall size to strength ratio [2]. The pre-stressing of the structure is achieved using either pre-tensioning or post-tensioning techniques. In the case of pre-stress induction using post-tensioning, the component or structure is subjected to a tensioning load, after the making or manufacturing of the same. For the case of the crush can, pre-stress can be inducted into the tube after the manufacture of the tube by the application of constant internal pressure and sealing it [3]. The induction of pre-stress to improve energy absorption capacity requires additional equipment and arrangements like non-return valves [3] and/or gas generator/inflator [4]. Also, a pressurized crush can lead to catastrophic issues [4] with regards to safety around the vicinity of the vehicle but can improve energy absorption capacity drastically.
In this study, a safer method of pre-stressing which is based on the pre-tensioning technique is proposed and studied. In this approach, the pre-tensioning is introduced into the thin circular tubes during the process of manufacturing. To achieve this, instead of being a single circular tube, the crush can be made as a compound tube which is achieved by the interference of two thin-walled tubes.

2. Solid Mechanics of thin walled cylinders

Theoretically, a thin cylinder or tube is one which has thickness “t” to radius “r” ratio is less than 1/20. When such a tube is subjected to an internal pressure “P”, the tube expands radially outside. When such expansion happens, the longitudinal stress is given by \( P \times r / (8 \times t) \) [5]. This longitudinal stress creates an opposing force which resists the compression of the tube and thereby increases its energy absorption capacity [4].

2.1. Compound Cylinders Tubes

A compound tube is one which is formed by shrink fitting two tubes. In the case of compound cylinders, the outer radius of the inner tube shall be more than the inner radius of the outer tube. During the process of shrink fit, the outer tube exerts a compressive force on the inner tube and the inner tube exerts a tensile force on the outer tube. As a result, the combined resultant tube shall have an outer radius which shall be a little higher than the outer radius of the outer tube [5]. This means the shrink fit gives rise to a radial tension in the compound tube which is analogous to the application of internal pressure. This internal pressure also gives rise to longitudinal stress which in turn produces an opposing force that resists the tube compression [4].
3. Crushing of thin-walled tubes

3.1 Compound Cylinders Tubes

For a thin tube of length “L”, Internal radius “r” and thickness “t” made of a material with Young’s modulus “E”, the compressive displacement for a force “P” is given as \( \frac{P \times L}{E \times A} \). Here “A” is the area of the cross-section of the tube. This relation holds good if the tube does not buckle under the load “P”. For metallic tubes, the failure criteria to be considered is based on Von-Mises equivalent stress and the behavior is expected to be linear if the equivalent stress is below the yield strength of the material [5].

3.2 Tubular compression for composites

A thin tube of length “L”, Internal radius “r” and thickness “t” made of a CFRP (Carbon fiber reinforced Polymer) material exhibits anisotropic behavior. The thickness “t” for the tube is achieved by making it with several layers. With the assumption that the fiber angle is oriented along the longitudinal axis of the tube, wherein the directional Young’s Modulus is \( E_1 \), the compressive displacement for a force “P” is given as \( \frac{P \times L}{E_1 \times A} \). Here “A” is the area of the cross-section of the tube. This relation also holds good if the tube does not buckle under the load “P”. For CFRP tubes, the failure criteria to be considered can be based on Maximum principal stress as the material is expected to be brittle and the load is along the direction of the fiber. Here also the behavior is expected to be linear if the maximum principal stress is below the compressive strength of the material. If the same is equivalent or more than the compressive strength of the CFPR material, the damage gets initiated in the material. Post damage initiation, further application of additional load leads to complete fracture is called damage evolution [6].

3.3 Parameters of significance for energy absorbers

As can be seen from literature, thin circular tubes are mostly used as energy absorbers during an impact or accident for a vehicular frontal structure. To study the effectiveness of a component or design as an energy absorber and compare multiple designs made of multiple materials, there a host of multiple
parameters [7]. But the most important parameter that is used to compare the designs made of different materials is the specific energy absorption capacity. This is defined as the energy absorbed by the tube for the unit weight for the same level of compression [7]. The typical force Vs displacement diagram for a thin tube used as energy absorber during an impact by compression is shown in figure 3. The product of force with displacement(Compression) during the impact divided by the weight of the tube indicates its specific energy absorption capacity.

![Figure 3: Typical force-displacement curve for an impact energy absorber](image)

4. Study approach

4.1 Study methodology

As part of the study, a CFRP tube is first compressed by a small distance until the damage gets initiated in the tube and the corresponding force required is observed, and the specific energy absorption capacity is computed using finite element software Ansys [8]. Then the same amount of displacement is applied for metallic tubes of similar geometry and the specific energy absorption capacities are computed. The computed values are compared against the theoretical values [5].

The same studies are repeated for compound tubes and the specific energy absorption capacity of the compound tubes is compared against those of compound tubes. The shrink-fit process of the compound tubes (pre-tensioning) is simulated using the interference simulation approach based on finite element methods [8].

4.2 Material properties used

For the study, the material properties as listed in Table -1 were used.
Table: 1 Material properties used

| Material          | Young’s Modulus (MPa) | Poisson Ratio |
|-------------------|-----------------------|---------------|
| Steel [7]         | E                     | 210000        | 0.3000        |
| Aluminium [7]     | E                     | 70000         | 0.2800        |
| CFRP [9]          | E1                    | 58903         | 0.0154        |
|                   | E2                    | 58903         | 0.5356        |
|                   | E3                    | 8759          | 0.1575        |

Failure Strengths of CFRP [9]

Allowable Compressive Strength in 1/2/3 Direction(s): 555/555/500 (MPa)

4.3 Geometric model used for metals

Figure 4 shows the geometric configuration used for the thin metal tubes. The tube has an inner radius of 25 mm and is 100 mm in length. The thickness of the tube is 3 mm.

![Figure 4: Schematic cross sectional configuration of metal tube(s) used for the study](image)

4.4 Geometric model used for composite(CFRP) tube

To achieve the trigger configuration a chamfer angle of 45° is provided [11 and 12] at the top of the tube. The normal length of the tube is 98.5 mm and the trigger has been accommodated over a length of 1.5 mm. The configuration of trigger (With trigger angle mentioned as q, Internal diameter as Di, overall thickness as t and the overall length as L) is shown in Figure 6.
4.5 Trigger configuration for composite tube

To achieve the trigger configuration a chamfer angle of 45° is provided [11 and 12] at the top of the tube. The normal length of the tube is 98.5 mm and the trigger has been accommodated over a length of 1.5 mm. The configuration of trigger (with trigger angle mentioned as \( \theta \), internal diameter as \( D_i \), overall thickness as \( t \) and the overall length as \( L \)) is shown in Figure 6.

4.6 Interference in tubes

Since CFRP material has a very low percentage of elongation for failure, very high interference can lead to failure during shrink-fit [5]. Hence two thin CFRP tubes whose thickness is exactly half of the single CFRP tube shown in figure 7 have been chosen for the study with interference equal to 1 layer thickness (0.1 mm).
4.7 Interference simulation

As described in earlier sections, two thin circular tubes each of thickness 1.5 mm (Each of 15 layers) and each with a 45° trigger whose combined thickness is equal to that of the single tube are taken. It has been assumed that the inner diameter of the inner tube is equal to that of the inner diameter of the single CFR tube with a 3-mm thickness. A contact pair is defined between the outer surface of the inner tube and the inner surface of the outer tube. The outer diameter of the inner tube has been assumed to be higher by 0.1 mm (1 layer) compared to the inner diameter of the outer tube. Solving the contact pair using the finite element method [8] calculates the stresses at the interface of the inner and outer tubes and the overall dimensions of the compound tube, with pre-stress induced. Figure 7 shows the configuration of the tubes used.

![Figure 7: Schematic cross sectional configuration of CFRP tubes used for interference](image)

In the case of metals, the geometric configuration used for compounding is the same as that of CFRP. But there is no trigger configuration provided for the metals as the same is not required for metals [7].

5. Specific energy absorption calculations

As per literature, composite tubes are proven to exhibit [13] more specific energy absorption capacity compared to metallic tubes. Also, the compounding of cylinders/tubes is expected to improve their strength. Hence the computation of specific energy absorption capacity is performed for the single and compound tubes to verify the same.

5.1 Specific energy absorption calculations for normal tube(s)

For the calculation of specific energy absorption, first, the CFRP tube with a thickness of 3 mm is initially compressed downward by an arbitrary distance of 0.3 mm. For this compression, no failure was observed when the damage contours were observed. For about a deflection of more than 0.45 mm, it was observed that the damage gets initiated in the CRFP tube with a trigger provided at the top edge. Hence a displacement slightly more than 0.45 mm and which is equal to 0.5 mm is applied and the CFRP tube is compressed downward.

Ansys software [14] which has been successfully calibrated for experimental correlation for composite and metallic material models to study damage initiation/evolution and yield/plastic behavior has been
used for the study. The reaction force corresponding to compression of 0.5 mm in the respective tubes has been computed using Ansys software and tabulated.

For verification of Ansys predicted values, the values of force required for tubes made of respective materials have been computed using theory [5] and the results have been compared and tabulated as in Table-2. The finite element model used for metal tube and for CFRP with a double bevel trigger are shown in figures 8(a) and 8(b) respectively.

Table 2: Specific energy absorption capacity of single tube

| S. No | Material | Density of material (Kg/mm³) | Reaction force from FEM study (N) | Reaction force Calculated theoretically(N) | Specific energy absorption KJ/Kg |
|-------|----------|-----------------------------|----------------------------------|--------------------------------------------|---------------------------------|
| 1     | Steel    | 7.8 E-09                    | 4.7192E05                        | 4.98E05                                    | 6.31E03                         |
| 2     | Aluminum | 2.8E-09                     | 1.6765E05                        | 1.66E05                                    | 6.55E03                         |
| 3     | CFRP     | 1.45E-09                    | 1.3651E05                        | 1.39E05                                    | 9.93E03                         |

5.2 Specific energy absorption calculations for the compound tube

The specific energy absorption capacity for the compound tube made up of respective materials is studied using finite element software Ansys using 2 load cases. In the first load case, the inner and outer tubes are modeled with interference. A contact surface is created between the two interfering surfaces and the model is solved to predict interference stresses and hence the pre-stress. In the next load step, a compression of 0.5 mm is applied for the compound tube and the reaction force required to achieve this compression is calculated. Based on the compressive force required, the value of specific energy absorption is computed for the respective composite tubes. The results are tabulated in Table-3 for comparison. The finite element models of the compound tube (For metal and CFRP) are shown in figures 9(a) and 9(b).

Table 3: Specific energy absorption capacity for compound tube

| S. No | Material | Density of material (Kg/mm³) | Reaction force from FEM study (N) | Specific energy absorption KJ/Kg |
|-------|----------|-----------------------------|----------------------------------|---------------------------------|
| 1     | Steel    | 7.8 E-09                    | 4.96E05                          | 6.63E03                         |
| 2     | Aluminum | 2.8E-09                     | 1.76E05                          | 6.87E03                         |
| 3     | CFRP     | 1.45E-09                    | 1.40E05                          | 10.2E03                         |
6. Discussion on results

For the case of single tube compression, the theoretically calculated values compare well with the values obtained through finite element calculations.

As can be seen from the results (Table-1), the composite tubes have a more specific energy absorption capacity compared to the metallic counterparts. CFRP has the highest specific energy absorption capacity followed by Aluminum. Steel owing to its high density has poor specific energy absorption capacity. Since the density of CFRP is almost half to that of Aluminum, CFRP tubes have higher specific energy absorption capacity making it suitable for lightweight vehicles. The stress results for the steel and CFRP tube for the normal tube configuration are shown in figures 10(a) and 10(b) respectively. As can be seen from the pictures, Steel being isotropic, the compression results in uniform stress along the length. For the CFRP, since the trigger forms a stress concentration, the peak stress is seen at the top (trigger vicinity).

A comparison of the results between Table 2 and Table 3 reveals that compound tubes absorb more energy than their normal counterpart due to the introduction of pre-stress in the form of interference in the tubes. The percentage of improvement of specific energy between normal thin tubes and those with pre-stress are tabulated and shown in Table 4.
| S. No | Material | Specific energy absorption J/Kg for normal tube | Specific energy absorption J/Kg for compound tube | Percentage increase in specific energy absorption due to compounding |
|-------|----------|-----------------------------------------------|-----------------------------------------------|--------------------------------------------------|
| 1     | Steel    | 6.31E03                                       | 6.63E06                                       | 5%                                               |
| 2     | Aluminum | 6.55E03                                       | 6.87E06                                       | 5%                                               |
| 3     | CFRP     | 9.93E03                                       | 10.2e06                                       | 3%                                               |

Due to the presence of trigger the improvement of compound CFRP tube is seen to be a smaller value. But when a full-pledged dynamic impact analysis is performed, the specific energy absorption capacity could be higher for CFRP tubes. Due to the nature of compounding, contact stresses are developed at the interface of the tubes that are compounded. The contact stress distribution for the steel and CFRP tubes at their respective interfaces is shown in figures 11(a) and 11(b) respectively. As can be seen from the results, steel being stronger than CFRP, the contact stress is more for steel tube than that of CFRP tube.

**Figure 11(a): Contact stress at interface for steel metal compound tube**

**Figure 11(b): Contact stress at interface for CFRP compound tube**

### 7. Conclusions

- A FEM based computation approach for the study of the energy absorption capacity of composite tubes subjected to pre-stress has been developed and presented.
- In place of single thin-walled tubes made of metal and CFRP material, two thin-walled tubes with half the thickness and assembled as a shrink-fit with interference have been subjected to compression to verify the feasibility of the compound cylinder concept.
- Pre-tension gets developed in the compound cylinders that shall oppose the compressive force.
- As can be seen from the results, a shrink-fit compound tube develops a pre-stress that shall improve the specific energy absorption capacity.
- Simulation based on finite element method can be effectively used to compute induced pre-strains and assess the amount of pre-strain that can be induced without damaging the tube.
- The approach proposed for FEM based simulations demonstrates that thin-walled tubes can absorb more energy when made as compound tubes.
- The concept proposed here does not require any special and additional equipment to induce pre-stress in the tubes and hence very advantageous compared to pre-stress induction through internal pressure.
- The crash accelerations to be impacted by the people in the vehicle can be reduced by the pre-tension technique, wherein the safety rating of the vehicle can be improved without adding additional weight.
8. Future Scope

- The Current study was made for tubes made of a single material (Either metal or CFRP) and with the interference of one layer. It could be possible to achieve more interference by using a combination of materials such as FML (Fiber metal laminates) and/or MMC (Multiple metallic composites).
- The concept of pre-stress through interference and shrink fit in the form of compound cylinders has been currently performed considering only damage initiation for the CFRP material to verify the concept. A full pledged dynamic impact simulation incorporating damage evolution modeling is also suggested for the future study.

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