Comparison of Energy Absorption of Aluminium-composite Tubes Subjected to Axial Loading

Tahir Abbas¹, H.H.Ya², Mohamad Zaki Abdullah³

¹,²,³Mechanical Engineering Department Universiti Teknologi PETRONAS
32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia
alitahir739@gmail.com¹
hamdan.ya@petronas.com.my²
abdullah@petronas.com.my³

Abstract. In this paper, energy absorption capability and failure modes of partially wrapped aluminium tubes have been studied. These tubes are used in the front side of automobiles and aircraft applications. Filament winding technique was used for partial wrapping of these tubes. Partially wrapping on the external surface of aluminium tubes was done with glass fibers, and epoxy resin, which is a composite material. Various composite layers and fiber angles were used in partial wrapping, which includes 4, 6 and 8 composite layers of ± 55° fiber angle. These tubes were subjected to axial crushing using the universal testing machine, and testing speed was 5mm/min. Failure modes and energy absorption analysis were carried out after testing. The experimental results revealed that partially wrapped aluminium tubes are 3.81%, 8.13% and 17.06% more efficient in energy absorption as compared to the tubes without wrapping. Furthermore, the effect of composite layers and failure modes has also been described.

1. Introduction
Nowadays, light-weight engineering materials are the best choice for reduction of vehicles weight as well as to deal with challenges of everyday higher prices of fuel [1-3]. Aluminium is one of light-weight engineering material that has plenty of applications in automobiles. One of the important applications of aluminium tubes is on the front side of vehicle structure to absorb impact. Moreover, their ease of fabrication, low cost, and low density make them more attractive for such applications [4]. Moreover, a combination of metal and composite material has been used to improve crashworthiness properties. This hybrid combination of material takes part to enhance impact properties of tubes during crash. Because high strength to weight ratio of composite material contributes to absorbing maximum energy absorption and it also takes part to change failure mode of these tubes [5]. During axial crushing, plastic deformation of metal occurs while composite material fails due to multiple fracturing of fibers, these both phenomena contribute energy absorption in these tubes [6]. Furthermore, axial and hoop strength of composite would also effect the collapse modes and energy absorption [7]. In this paper, an effort has been made to improve energy absorption capability of aluminium tube after partial wrapping of it with glass/epoxy. The basic objective of partial wrapping is to enhance its impact properties as well as to achieve weight reduction. These tubes are tested using the universal testing machine and impact properties have been analyzed in detail.

2. Literature Review
Bi-material tubes were first, studied by Mamalis [8]. Various factors like, composite and metal thickness, material properties, and geometrical construction were identified that contribute to energy absorption. These factors were documented as the key parameters for energy absorption.

Energy absorption of square cross-section aluminium tubes, externally wrapped with glass fiber reinforced polymer, were investigated by Shin [9]. These tubes were tested under axial compression. To analyze the effect of fiber orientation on energy absorption aluminium tubes, they were wrapped with three different fiber orientations, 0°, 90° and ± 45°. The process selected to develop test samples was filament winding, and prepreg sheets of glass/epoxy were used to fully wrap aluminium tubes. The most important relevant finding of this study was, aluminium tube wrapped with 90° fiber orientation indicated more energy absorption as compared to other tubes. Research on energy absorption capability of steel tubes of the hollow cross-section was published by Bambach [5, 10]. Samples were prepared according to the procedure adopted by Shin [6]. But, instead of glass/epoxy, carbon fiber reinforced polymer prepreg sheets were used for external wrapping of steel tubes. Samples were tested under static and dynamic loading. The results of this study indicated that tubes of 90° wrapping were good to hold the maximum load. It was further noted that tubes with 90° wrapping absorbed more energy. The study of the effect of composite layers on steel tubes was carried out by Kalhor [6]. The process used to prepare the sample was filament winding, and wrapping was done using fiber-reinforced plastics. In this study, samples were fully wrapped as previously done by Bambach. This study set out with the aim of assessing the effect of composite layers on energy absorption. The most obvious finding of this study was, as composite layers increase energy absorption increases. Wet filament winding process was used by Song [4], for external wrapping of steel tube samples. Three different fiber angles of glass/epoxy, for wrapping of tubes, were selected to see their effect on specific energy absorption (SEA) as well as collapse modes of tubes. The results of this research revealed that 90° fiber orientation wrapped tubes absorbed more energy. This experimental study also detected that with increasing number of layers of composite material, and fiber orientation specific energy absorption also increases. Energy absorption capability of both circular and square cross-section aluminium tubes was examined by Babbage [11]. Samples were prepared by the same process as adopted by Song [4]. The material used was glass/epoxy, and two fiber orientations, ± 45° and ± 75° were selected. The results revealed that circular cross-section tubes absorb more energy as compared to square tube. Additionally, ± 75° wrapped tube absorb more specific energy for both cross-sections. More recently, a study has been conducted by Lima [12], on partially wrapped steel tubes, to examine their energy absorption. Wet filament winding process was used to develop samples. Three fiber orientations ± 45°, ± 75° and 90° were used, for three different composite layers 4, 6, and 8. Testing was carried out under quasi-static loading. It was reported that 90° wrapped tube with 6 number of composite layers absorbed more energy. In view of all that has been mentioned so far, it is concluded that there is need to study energy absorption capability of partially wrapped aluminium tubes as well. In this paper an attempt has been made, to study crashworthiness properties of partially wrapped aluminium tubes. Glass/epoxy composite material has been selected due to its lower price as well as good energy absorption ability as shown in Fig 1[13]. Moreover, wet filament winding process has been used to develop samples. Furthermore, the sample is tested using the universal testing machine.

Figure 1. Energy absorption ability of composite tubes containing glass- carbon-epoxy combination [13]
3. Material and Methods

The ‘AA6063’ grade of aluminium tube was used, which is commercially available. Glass fiber and epoxy resin grades that were used in this research work are E-glass 1200tex, and D.E.R.™ 331™ respectively. These both grades are also commercially available. To avoid Euler buckling, the length of tubes was used 200mm; that was also suitable for proper collapse mod. Dimensions of selected tubes are given in Figure 2 and Figure 3. Additionally, Partial wrapping of aluminium tube samples, using 4, 6 and 8 composite layers of ±55° fiber angles, was carried out. The process used for partial wrapping was wet filament. The universal testing machine was used to carry out axial compression, and speed was maintained 0.08 mm/sec (5mm/min), to avoid strain rate effect. Crashworthiness parameters were obtained from Load-displacement (L-D) curves and were analyzed to calculate specific energy absorption and crush force efficiency.

3.1 Energy absorption parameters

Energy absorption parameters were calculated by using (1) to (4) [14].

\[ \text{TEA} = \int P_{\text{mean}} \, ds = P_{\text{mean}} \times (Df - Di) \]  
\[ P_{\text{mean}} = \frac{\text{TEA}}{(Df - Di)} \]  
\[ \text{SEA} = \frac{\text{TEA}}{m} \]  
\[ \text{CFE} = \frac{P_{\text{mean}}}{P_{\text{max}}} \]

Where Df and Di are final and initial crushing displacement and m represent the mass of uniform sample.

4. Results and Discussions

Equations that are presented in section-III used to calculate parameters, that are total energy absorption (TEA), Specific energy absorption (SEA), crush force efficiency (CFE). Maximum load \( P_{\text{max}} \) and average load \( P_{\text{mean}} \) are obtained from load displacement graph.

4.1 Failure modes of partially wrapped and without wrapped aluminium tubes

In Fig 4 there are clear increasing and decreasing trend oscillations of aluminium tubes deformation, subjected to axial compression. Basically, these increasing and decreasing trend lines are depicting rise and fall of the load. At the initial point, load rises which are indication of fold formation this continues until that point after which tube wall started to fold outside. At this stage, load fall rapidly, after a sharp decrease of load there is also an increasing trend which shows internal buckling of the tube. This pattern of maximum and minimum load values continue to repeat till the desired length. Furthermore, Asymmetric concertina failure modes are exhibited by all these tubes as shown in Fig 5 and Fig 6.
Moreover, it is apparent from Table I that specific energy absorption and crush force efficiencies of partially wrapped aluminium tubes have been improved, as compared to aluminium tubes as received. It is further quite clear, that SEA of a partially wrapped tube having 8 composite layers is higher than all other tubes. It is attributed to more number of composite layers. Fiber kinking and delamination are also perceived in tubes with 4 and 6 composite layers. Additionally, crush force efficiency of the partially wrapped tube with 4 composite layers found to be more as compared to other. This is due to the ratio of maximum and minimum load value. This is shown in Fig 7.

Table 1. Parameters of energy absorption

| Parameters       | unwrapped aluminium tubes | Partially wrapped tube with 4 composite layers | Partially wrapped tube with 6 composite layers | Partially wrapped tube with 8 composite layers |
|------------------|---------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| TEA (kJ)         | 2.67                      | 2.78                                       | 3.02                                       | 3.41                                       |
| SEA (kJ/kg)      | 12.13                     | 12.6                                       | 13.13                                      | 14.20                                      |
| $P_{\text{max}}$ (kN) | 65                        | 45.45                                      | 63.45                                      | 65.80                                      |
| $P_{\text{mean}}$ (kN) | 26.7                     | 27.8                                       | 30.21                                      | 34.03                                      |
| CFE (%)          | 41.07                     | 80.16                                      | 47.61                                      | 51.71                                      |

5. Conclusions
This study mainly described the effect of composite layers on energy absorption capability of aluminium tubes. To improve crashworthiness parameters, an effort has been made by the partial
wrapping of aluminium tubes with glass/epoxy composite. A comparison of crashworthiness parameters has been listed between as received and partially wrapped aluminium tubes. The results of this study clearly described that wrapped tubes are good in energy absorption. Moreover, specific energy absorption (SEA) of as received aluminium tubes has been improved to 3.81%, 8.13% and 17.06% by the external partial wrapping of them, using 4, 6 and 8 composite layers respectively. In addition to this, to see the effect of composite layers, crashworthiness parameters of partially wrapped tubes are also documented. It is examined, after axial compression, all these tubes exhibited an axisymmetric mode of failures. Additionally, it has been found that aluminium tube wrapped with 8 composite layers absorb more specific energy as compared to other tubes, this is due to more fibers participation during the crushing process to hold the applied load. Despite these promising results, further research should be undertaken to investigate the effect of gaps between composite layers and to find out a best possible combination of fiber angle, composite layer and gap between composite layers.

6. References
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