Dynamic oblique crushing of single and bi-tubular aluminium conical tubes with imperfection

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Abstract. This paper aims to study the crashworthiness response of single and bi-tubular aluminium conical tubes subjected to oblique loading. The influence of imperfection on crashworthiness criteria is studied by introducing circular cutouts to the single and bi-tubular conical tubes. The explicit finite element (FE) code LS DYNA is employed to develop the FE model of the tubes. Satisfactory agreement between the developed FE model and previous experimental work has been obtained. The validated model is then employed to investigate the influence of imperfection on the tubes based on internal energy at maximum deformation. The finding shows that with the introduction of cutouts, the energy absorption capability and Specific Energy Absorption (SEA) of bi-tubular tubes are improved as high as 3.43 % and 3.44 %, respectively compared to the single tubes. Compared to the tubes without cutouts, there is a reduction of the internal energy and the SEA of the tubes with cutouts. For bi-tubular tubes, the reduction of the energy absorbed is only 6.41 % thus implies that bi-tubular tubes are better than single tubes when subjected to oblique loading. The similar pattern is also found in the SEA. Furthermore, the increase in loading angle, α reduces the internal energy and the SEA.

1. Introduction

Recently, the amount of road vehicles has increased rapidly year by year when the development of the automotive and transport industries was improved. In the matter of fact, vehicle crash accident has become a major health problem worldwide. An expansion interest about vehicle safety or crashworthiness has been analytical, numerical and experimentally conducted in evaluating the response of energy absorbers during crash [1], [2].

Various types of thin wall tubes are frequently used especially in automotive industries as energy absorbers. A single tube consists one piece of the tube, while the bi-tubular tube consists of two single tubes which are combined. Tran et al. used a multicell with triangular section to increase the energy absorption capability of the tubes [3]. Djamaluddin et al. [4] performed numerical analysis on bi-tubular circular tubes, with or without aluminium foam as filler. It is found that foam filled double tube exhibit higher energy absorption capability compared to foam filled single tube and empty double tubes.

To further enhance the capability of the tubes, the imperfection has been introduced. Various types of imperfection have been examined such as cutouts and grooves [5], [6]. During impact, energy absorber collapses in complex ways. The tube collapses by the global bending when the oblique load is applied and hence reduces the capacity of energy absorption [7]. Conical tubes have shown lower tendency for global bending collapse to occur during oblique loading [8]. As such, the overall design of crushable structures should also consider the oblique loading. Therefore in the present work, the
crashworthiness performance of single and bi-tubular tubes is compared with the introduction of imperfection under oblique loading condition.

2. Finite element development
The model for the straight tube was developed based on previous study [9]. The radius of the model for tube is 69.82 mm with 0.60 mm thickness. The tube’s length was 50.94 mm. Once the model validated, the model is employed in later analysis for single and bi-tubular conical tubes. The radius and the length of the single tube are 34.715 mm and 50.53 mm, respectively. For the bi-tubular tubes, the inner and outer radiuses are 17.3575 mm and 34.715 mm, respectively. The length for single and bi-tubular tubes is kept constant at 50.53 mm. Figure 1 shows the finite element (FE) model for the tubes.

Figure 1: The finite element model for the (a) straight and (b) conical tubes

3. Validation
To ensure that the developed FE model was satisfactory and sufficient, it was validated by experimental in the literature [9]. Based on the Table 1, the model shows good correlation with the existing experimental results.

Table 1: Internal energy of empty straight tube.

| Outer Diameter (mm) | Length (mm) | Energy Absorption (J) at 13 mm deformation (J) | Error (%) |
|---------------------|-------------|-----------------------------------------------|-----------|
| 69.82               | 50.94       | Mat et al. [9] Simulation                      | 10.5      |
|                     |             | 77.89                                         | 86.04     |

4. Results and discussion
The energy absorption response of obliquely loaded tubes with and without imperfection for various loading angles, $\alpha$ of 10° and 30° are compared. Figures 2 and 3 show the force-deformation curves of single and bi-tubular tubes. Based on the results, it can be seen that the introduction of cutouts to the conical tubes reduces the deformation length of the single tubes. Similar observation can be observed on the bi-tubular tubes. On top of that, the increase of load angle from 10° to 30° demonstrates further
reduction in impact force and hence reduces the energy absorbed. To compare between the tubes with imperfection and without the imperfection, it is profound that the tubes with cutouts exhibit higher impact force but smaller deformation length. In contrast, the tubes without cutouts show lower impact force but larger deformation length.

Figure 2: Effect of imperfection for single tube

Figure 3: Effect of imperfection for bi-tubular tube

As shown in Table 2, bi-tubular tubes demonstrate higher internal energy compared to single tubes for tubes with and without cutouts. In fact, the bi-tubular tubes with cutouts demonstrate as high as 3.43% increase of internal energy. However, there is a reduction of internal energy for both single and bi-tubular tubes with cutouts compared to the tubes without the cutouts. The reduction of the energy absorbed is higher for single tube with cutouts as high as 9.07% when comparison is made between tubes with (169.52 J) and without imperfection (186.42 J).

For bi-tubular tubes, the reduction of the energy absorbed is only 6.41% thus implies that bi-tubular tubes is better than single tube when subjected to oblique loading. The reduction of the energy
absorbed is also observed in previous research [10]. The introduction of rectangular and slotted window reduces the energy absorbed of the rectangular tubes studied.

To consider the lightweight criteria, Specific Energy Absorption (SEA) is tabulated in Table 3. As expected, the SEA of the tubes demonstrates similar patterns as observed for internal energy since the SEA is calculated based on internal energy gained by the tubes. The bi-tubular tubes with cutouts exhibit 3.44% higher SEA compared to the single tubes. On the other hand, the SEA reduces when comparison is made between tubes with and without cutouts for single and bi-tubular tubes. This scenario implies that the use of multiple tubes able to enhance the energy absorption capability of the tubes under oblique loading.

In top of that, the influence of load angle is more significant at higher load angle. As the load angle increases, the internal energy and SEA reduces. However, Cheng et al. has shown that the introduction of circular cut-outs increases the energy absorbed as well as the SEA [11]. The opposite patterns might be contributed by the geometry of the tubes as square tubes are used in the study. In fact, tube’s geometry has shown significant effect on the dynamic response of the tubes under axial and oblique loading conditions.

### Table 2: Internal energy at maximum deformation

| Load Angle , $\alpha$ | Without cut-out (J) | Percentage Difference (%) | With cut-outs (J) | Percentage Difference (%) |
|----------------------|---------------------|--------------------------|-------------------|--------------------------|
|                      | Single              | Bi-tubular               | Single            | Bi-tubular               |
| 10°                  | 186.42              | 187.02                   | 0.32              | 169.52                   | 175.35                   | 3.43                      |
| 30°                  | 172.73              | 175.75                   | 1.72              | 161.66                   | 167.01                   | 3.31                      |

### Table 3: Specific Energy Absorption (SEA) of single and bi-tubular tubes

| Load Angle , $\alpha$ | Without imperfection (J/kg) | Percentage Difference (%) | With imperfection (J/Kg) | Percentage Difference (%) |
|----------------------|----------------------------|--------------------------|--------------------------|--------------------------|
|                      | Single                     | Bi-tubular               | Single                   | Bi-tubular               |
| 10°                  | 11387.90                   | 11424.56                 | 0.32                     | 10355.53                 | 10711.67                 | 3.44                      |
| 30°                  | 10551.62                   | 10736.10                 | 1.75                     | 9875.38                  | 10202.19                 | 3.21                      |

5. Conclusions

This study examined the dynamic response under oblique impact loading of single and bi-tubular tubes with the introduction of cutouts as imperfection. Good agreements have been observed between the developed FE model and experimental results from previous literature. The validated FE model is used to gain insight into the oblique crush response and to quantify the internal energy and specific energy absorption (SEA) for load angle variations. With the introduction of imperfection, bi-tubular tubes exhibits higher increase in energy absorption compared to single tube. While smaller reduction of the internal energy is observed for the bi-tubular tubes with imperfection compared to the ones without imperfection. Similar observations can be seen for SEA. These findings show that bi-tubular conical tubes are effective energy absorbing devices as they can withstand an oblique impact load. This study has shown that in impact applications where oblique impact load was expected, conical tubes with
imperfection appear to be advantageous and this research information can be used in applications involving oblique loading such as vehicle crashworthiness.

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