Finite Element Modelling for Crash Response of a Square Tube

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ABSTRACT

In this work the crash characteristics of square tubes have been studied using finite element (FE) method. The effect of material properties, thickness and trigger on energy absorption capability of square tube has been investigated. Also, effect of impact angle on the crash response of the tube has been studied. Aluminium was found to absorb energy more than steel under axial dynamic loading. Increasing thickness and introducing a trigger enhanced the energy absorption of the tube. Tubes with 1.5 mm thickness gives lowest peak load of 33.2 kN and highest SEA of 20.4 kJ/kg. Introducing trigger at 5 mm from impact end of the tube decreases initial peak load by 23%. 5° impact angle provides high CFE and SEA values of 54.8% and 15.2 kJ/kg respectively. Specific energy absorption (SEA) and crush force efficiency (CFE) decrease as the impact angle increases. The findings of this study are useful in designing high energy absorption vehicle crash box.

Keywords: Crashworthiness; Crash box; Finite element method; Specific energy absorption; Square tube

INTRODUCTION

Automotive crash has been considered a major health problem worldwide. Design of vehicle frontal rails with high energy absorption is an important method of reducing severities of injuries to the occupant during road collisions. Crash box shown in Figure 1, is a thin wall component that dissipates kinetic energy in the event of crash, there by transmitting lower deceleration to the vehicle and hence protecting the occupants (Han, Taheri, & Pegg, 2007).

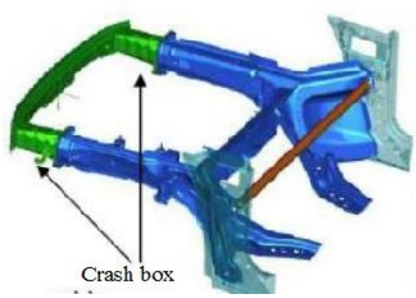


Figure 1: Crash box (Moch, Anindito, Siswanto, & Nafisah, 2016)

Energy absorption of thin wall components is very vital as it improves crashworthiness of vehicle by absorbing impact energy through plastic deformation and fracture with little increase in vehicle body weight. Finite element simulations have been applied by many researchers in the design and optimization of energy absorption structures of various geometries and thickness because physical testing is costly. Steel thin wall tubes specifically with square shape have been one of the most efficient energy absorbers as they crush in a stable and progressive manner. Square tubes deform through axial crushing under axial load and absorb high energy. Under oblique impacts however, the tube tends to bend there by absorbing less energy.

Investigation of energy absorption of thin wall structures had been reported by many researchers (Z. Ahmad, 2009; Han et al., 2007; Mamalis, Manolakos, Ioannidis, & Kostazos, 2005; Mat, Ismail, Ahmad, & Rejab, 2016). FE analysis has been applied in studying crashworthiness of various steel sections including square, circular, frusta and hybrid structures made from metal and composites with the aim of obtaining high energy and light weight structural components (Abbasi, Reddy, Ghafari-Nazari, & Fard, 2015; Alkhatib, Falsafi, & Demirci, 2017; Marzbanrad, Abdollahpoor, & Mashadi, 2009; Marzbanrad, Mehdikhanlo, & Pour, 2009; Moch et al., 2016; S. Salwani, Sahari, Ali, & Nuraini, 2012; Türkmen, Mecito, Uluda, & Alt, 2011). Square tubes have been recently used as energy absorption crash box because of their light weight and effective crashworthiness performance. Energy absorption behaviour of empty (Aljawi, 2002), foam filled (S. Salwani et al., 2012) and multi cell thin wall square tube columns (Wu et al., 2016) have been investigated. Effect of steel material properties on energy absorption of various column section under axial and oblique loading, has also been reported by Abbasi et al. (2015). Several other works deal with improving energy absorption of square tubes by introducing a trigger (Khalili, Tarlochan, Hamouda, & Al – Khalifa, 2015; Sandeep, 2006). There are still limited studies on the investigation of effect of some crash parameters on performance of square tubes using finite element modelling. The objective of this study is to investigate the effect of material properties, wall thickness, and trigger as well as impact angle on energy absorption and crush behaviour of square tubes.

Method of Investigation

This section provides definition of crashworthiness parameters for axially and obliquely loaded square tubes, methods of finite element modelling of the tube and impactor, model validation and results and discussions.

Crashworthiness parameters

Energy absorption performance of thin wall tubes is evaluated using load-displacement response. Load-displacement curve also allows for the determination of peak load and mean load. Energy absorption E_a is computed by integrating the load displacement curve:

$$E_a = \int_0^{\delta_{max}} P\delta d\delta \qquad \text{(i)}$$

Where P is the instantaneous crushing load, δ and δ_{max} are the current and maximum attainable deformation. Energy absorbed per unit weight (m) known as specific energy absorption (SEA) is particularly important when weight reduction of structure is required. It is defined as:

$$SEA = \frac{E_a}{m} \qquad \text{(ii)}$$

Initial peak load (P_{max}) also known as crush force in the load-displacement response determines the deceleration transmitted to the vehicle occupant in crash event. It is therefore need to be minimized. The mean load, P_{mean} is also related to energy absorption:

$$P_{mean} = \frac{E_a}{\delta} \qquad \text{(iii)}$$

Crush force efficiency defines the uniformity of crush loads. It is desired to be high for an energy absorber. It is expressed as:

$$CFE = \frac{P_{mean}}{P_{max}} \times 100 \qquad \text{(iv)}$$

Finite element model development

To verify that the square tube FE model represent physical tube under crash condition, deformation modes of FE model is compared with existing experimental results from Aljawi (2002) where square tube of 30 mm × 30 mm × 100 mm as well as 1.25 mm wall thickness was hit by rigid plate at a given velocity. To simulate this experiment, an investigation was carried out using explicit finite element code Ls-dyna (Hallquist, 2006). The tube was modelled using Belytschko- Tsay shell element with five integration points through its thickness. 8-noded solid element was applied for the impactor as shown in Figure 2.

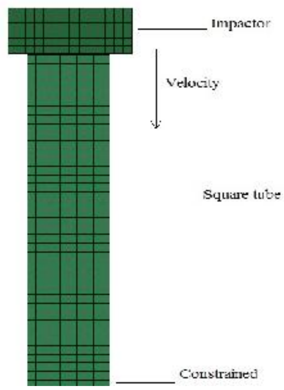


Figure 2: simulation setup

Impactor was constrained to move in z-axis with an initial velocity of 7 m/s. Piecewise linear plasticity (material type 24) was used to model steel and aluminium material properties of the tube. Convergence study was conducted and the FE model converged at element size of 2.8 mm because incorrect mesh size results in error in the findings (Ahmad, Ismail, & Mat, 2013). Contact automatic surface to surface algorithm with 0.3 and 0.2 static and dynamic coefficient was employed between the tube and rigid plate to avoid lateral movement. The bottom end of the tube was constrained from displacement and rotation using Boundary single point constraint option. Contact automatic single surface was used to avoid interpenetration between elements in the model. After the validation, further work was done to investigate the effects of various parameters on the energy absorption of the tube. Table 1 shows the attributes of sample designs used in the simulations.

Table 1: Simulation samples

Simulation No.	Material	Thickness (mm)	Trigger distance from top end (mm)	Impact angle
1	Steel	1.25	-	-
2	Aluminium	1.25	-	-
3	Aluminium	1.50	-	-
4	Aluminium	2.00	-	-
5	Aluminium	2.50	-	-

Simulation No.	Material	Thickness (mm)	Trigger distance from top end (mm)	Impact angle
6	Aluminium	2.00	5	-
7	Aluminium	2.00	25	-
8	Aluminium	2.00	50	-
9	Aluminium	2.00	25	5^o
10	Aluminium	2.00	25	15^o
11	Aluminium	2.00	25	30^o

Model validation

The crushing behaviour of the tube FE model was confirmed by comparing the crush force-deformation curve with experimental results obtained from Aljawi (2002). As seen in Figure 3, the difference in peak crushing force is about 6%. The number of lobes formed by the steel column during crash corresponds well with experimental results. Within the deformation stroke of about 60 mm, 3 lobes were formed which can be ascertain by the number of major peaks in the curve.

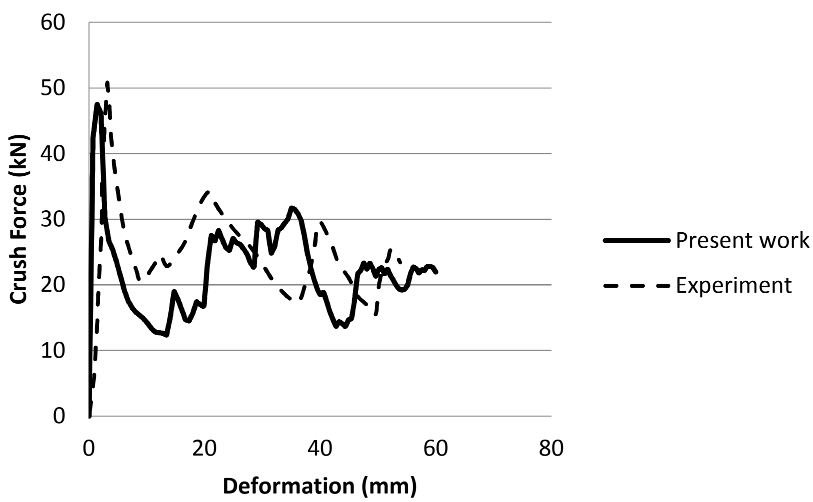


Figure 3: Crush force-deformation curve comparisons for FE model and experiment

Table 2 presents comparison of FE model and experiment in energy absorption and deformation. It is seen that there is good agreement with a difference of less than 10%. Thus, the FE model is verified and could therefore be used to study the effect of material properties, thickness, trigger and impact angle on the crashworthiness characteristics of the tube.

Table 2: Comparison of crashworthiness parameters of FE model and experimental results

Parameter	Experiment (Aljawi, 2002)	FE model (Present study)	% difference
Energy absorption (kJ)	120	112	6.0
Deformation (mm)	6.2	6.5	4.8

RESULTS AND DISCUSSIONS

Effect of material properties

It is obvious from Table 3 that steel tube results in high crushing force on impact and deforms less than aluminium. Internal energy absorbed by steel tube is higher than that of aluminium, while the specific energy absorption of aluminium is higher than that of steel. Thus, tubes made from aluminium have advantage over steel tubes in weight reduction. Though steel tube has high CFE, aluminium crash box provides lower peak and mean load on impact and lower deceleration would be transmitted to the vehicle occupants. Aluminium has benefit over steel in terms of SEA.

Table 3: Comparison of crashworthiness parameters for steel and aluminium tube

Simulation No.	Material	Peak load (kN)	Deformation (mm)	Energy Absorption (kJ)	Mean load (kN)	Weight (kg)	CFE (%)	SEA (kJ/kg)
1	Steel	47.5	95.3	2070	21.7	0.2	46	11.8
2	Aluminium	22.8	117.2	1100	9.4	0.1	41	18.1

Effect of tube wall thickness

The effect of thickness was studied using aluminium tube, since it was found to have better crashworthiness ability than steel as observed above. Table 4 shows the effect of thickness on crashworthiness parameters. It is clear that peak and mean load increase with increase in thickness of the tube. Higher thickness results in high internal energy absorption but lower SEA. This is because high thickness means more material volume to undergo deformation on impacts. Since thickness increases the weight of the tube, the SEA becomes low. Lower thickness of 1.5 mm deforms more than the higher thicknesses of 2.0 mm and 2.5 mm and provides lower mean and peak load. Because of low thickness the SEA of 1.5 mm tube is high. Moderate SEA and CFE values can be observed in 2.0 mm thickness tube.

Table 4: Effect of thickness on crashworthiness parameters of aluminium tube

Simulation No.	Thickness (mm)	Peak load (kN)	Deformation (mm)	Energy Absorption (kJ)	Mean load (kN)	Weight (kg)	CFE (%)	SEA (kJ/kg)
3	1.5	33.2	112.3	1450	12.9	0.0710	39	20.4
4	2.0	45.2	95.8	1890	19.7	0.0946	44	19.9
5	2.5	60.2	78.7	2187	27.8	0.1183	46	18.5

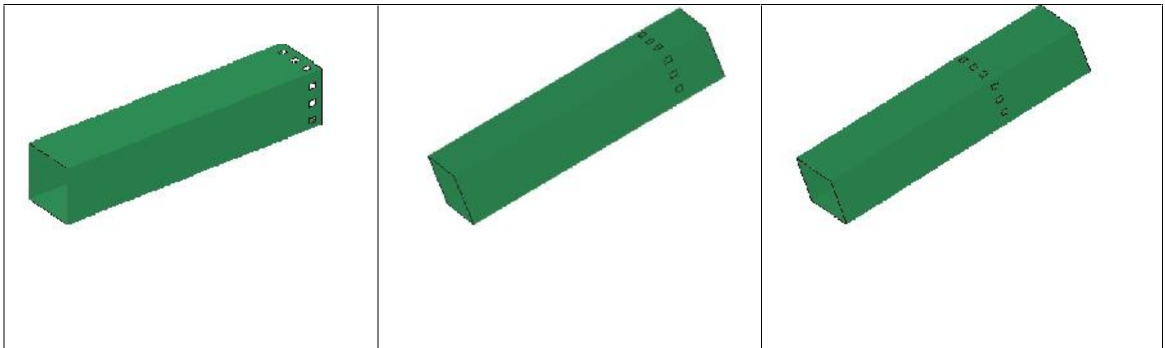
Effect of triggering the tube

Introducing an imperfection in the form of a square hole to the aluminium tube could help in reducing the peak and mean load. It is seen in Table 5 that, locating a square shape trigger at 5 mm from top end of the tube decreases the initial crush load from 45.2 kN for 2 mm thickness (Table 4) non-triggered tube to 34.7 kN. Peak load increases as the position of the hole from top end increases. This is because holes close to the impact end cannot with stand initial crush force there by producing lower initial load. Low peak load means high CFE.

Table 5: Effect of trigger on crashworthiness performance of square tube

Simulation No	Trigger position (mm)	Peak load (kN)	Deformation (mm)	Energy Absorption (kJ)	Mean load (kN)	Weight (kg)	CFE (%)	SEA (SEA) (kJ/kg)
6	5	34.7	96.2	1910.0	20.0	0.096	57.2	19.895
7	25	37.1	94.1	2007.9	21.3	0.096	57.5	20.916
8	50	38.3	96.0	1989.0	20.7	0.096	54.0	20.719

When the trigger is located at 25 mm and 50 mm from the top end as shown in Figure 4, the crush force reduces by about 16%. It is obvious from Table 5 that introducing trigger enhances the CFE and SEA values of the aluminium square tube.

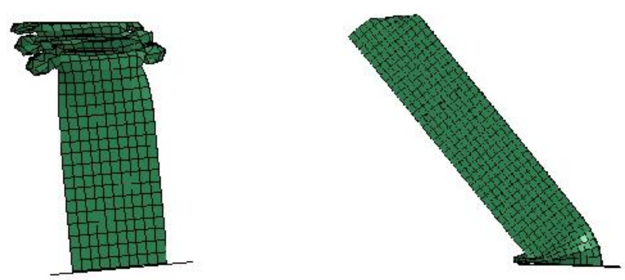


3 no. 3mm square trigger on 4 sides @5mm	3 no. 3mm square trigger on 4 sides @ 25 mm	3 no. 3mm square trigger on 4 sides @ 50 mm

Figure 4: Position of the trigger on the tube

Effect of impact angle

In oblique impact, vehicle crash box experienced both axial and bending modes. Federal Motor Vehicle Safety Standard (FMVSS), 208 requires that oblique crash test against rigid barrier be conducted on vehicles between 0° to 30° for speed of up to 48 km/h. Dynamic oblique test has been reported to be difficult to be conducted experimentally (Z. Ahmad, Thambiratnam, & Tan AC, 2010). It can be observed from Table 6 that SEA and CFE decreases with increase in impact angle. This is because at high impact angles, the deformation is not progressive folding as shown in Figure 5. The energy absorption is mainly as a result of tube bending. The same phenomena was observed by (M. S. Salwani, Aidy, Sahari, & Nuraini, 2011).



5° impact angle 30° impact angle

Figure 5: Crash response of square tube under oblique dynamic loading at 130 ms simulation time

Table 6: Effect of impact angle on crash performance of square tube

Simulation No	Impact angle	Peak load (kN)	Energy Absorption (kJ)	Weight (kg)	Mean load (kN)	CFE (%)	SEA (kJ/kg)
9	5^o	17.6	1460.0	0.0960	14.6	54.8	15.2
10	15^o	30.5	992.6	0.0960	8.7	28.6	10.3
11	30^o	17.6	590.0	0.0960	4.7	26.0	6.1

CONCLUSIONS

The findings of this study proved that a well validated FE model could be used to study crashworthiness performance of structures without necessarily using experimental tests which is costly and consumes time. The analysis shows that aluminium exhibit high energy absorption than steel. SEA and CFE values increase with increase in thickness. Applying triggers enhanced energy absorption of the tube. Square tubes absorb less energy at higher impact angle.

REFERENCES

Abbasi, M., Reddy, S., Ghafari-Nazari, A., & Fard, M. (2015). Multiobjective crashworthiness optimization of multi-cornered thin-walled sheet metal members. *Thin-Walled Structures*, *89*, 31–41.

Ahmad, M., Ismail, K. A., & Mat, F. (2013). Convergence of finite element model for crushing of a conical thin-walled tube. *Procedia Engineering*, *53*, 586–593. http://doi.org/10.1016/j.proeng.2013.02.075

Ahmad, Z. (2009). *Impact and Energy Absorption of Empty and Foam-filled Conical Tubes*. Queensland University of Technology.

Ahmad, Z., Thambiratnam, D., & Tan AC, C. (2010). Dynamic energy absorption characteristics of foam-filled conical tubes under oblique impact loading. *Int. J. Impact Eng.*, *37*(5), 475–488.

Aljawi, A. A. (2002). Axial crushing of square tubes. In *The 6th Saudi Conference* (Vol. 3, pp. 4–18). http://doi.org/10.1016/0020-7403(83)90080-2

Alkhatib, S., Falsafi, J., & Demirci, E. (2017). Numerical modelling of steel tubes under oblique crushing forces Numerical modelling of steel tubes under oblique crushing forces. In *International Research and Innovation Summit*. http://doi.org/10.1088/1757-899X/226/1/012012

Hallquist, J. O. (2006). *Theory manual*. Livermore Software Technology Corporation.

Han, H., Taheri, F., & Pegg, N. (2007). Quasi-Static and Dynamic Crushing Behaviour of Aluminium and Steel Tubes with a Cutout. *Thin-Walled Structures*, *45*, 529–551.

Khalili, P., Tarlochan, F., Hamouda, A. M. S., & Al – Khalifa, K. (2015). Energy absorption capability of thin-walled aluminium tubes under crash loading. *Journal of Mechanical Engineering and Sciences*, *9*(December), 1734–1743.

Mamalis, A. G., Manolakos, D. E., Ioannidis, N. B., & Kostazos, P. K. (2005). Numerical simulation of thin-walled metallic circular frusta subjected to axial loading. *International Journal of Crashworthiness*, *10*(5), 505–513.

Marzbanrad, J., Abdollahpoor, A., & Mashadi, B. (2009). Effects of the triggering of circular aluminum tubes on crashworthiness. *International Journal of Crashworthiness*, *14*(6), 591–599. http://doi.org/10.1080/13588260902896458

Marzbanrad, J., Mehdikhanlo, M., & Pour, A. S. (2009). An energy absorption comparison of square , circular , and elliptic steel and aluminum tubes under impact loading. *Turkish J. Eng. Env. Sci*, *33*, 159–166. http://doi.org/10.3906/muh-0904-11

Mat, F., Ismail, K. A., Ahmad, M., & Rejab, M. R. M. (2016). Foam Filling Effectiveness of Conical Aluminium Tubes Under Dynamic Axial and Oblique Loading. *ARPN J. Eng. Appl. Sci., 11*(12), 7741–7747.

Moch, A. C., Anindito, P., Siswanto, E., & Nafisah, A. H. (2016). Crash Energy Absorbtion of Multi-Segments Crash Box Under Frontal Load. *Jurnal Teknologi*, *5*, 347–350.

Salwani, M. S., Aidy, A., Sahari, B. B., & Nuraini, A. A. (2011). Crash of automotive side member subjected to oblique loading. *International Journal of the Physical Sciences*, *6*(31), 7125–7131. http://doi.org/10.5897/IJPS11.594

Salwani, S., Sahari, B., Ali, A., & Nuraini, A. (2012). Optimization of Partially Filled Column Subjected to Oblique Loading. *World Academy of Science, Engineering and Technology*, *6*, 1056–1060.

Sandeep, K. S. (2006). *Finite element modeling of energy absorption characteristic of hybrid structure - composite wrapped on a square ...* Wichita State University.

Türkmen, H. S., Mecito, Z., Uluda, N., & Alt, E. Õ. (2011). A numerical and experimental study on the impact behavior of box structures. *Procedia Engineering*, *10*, 1736–1741. http://doi.org/10.1016/j.proeng.2011.04.289

Wu, S., Zheng, G., Sun, G., Liu, Q., Li, G., & Li, Q. (2016). On design of multi-cell thin-wall structures for crashworthiness. *International Journal of Impact Engineering*, *88*, 102–117. http://doi.org/10.1016/j.ijimpeng.2015.09.003

