Energy absorption of varying thickness rectangular section crash box for quasi-static axial loading

Mr. Ashutosh S. Kalshetti*, Dr. Sanjaysingh Vijaysingh Patil +

* Student , RMD Sinhgad School of Engineering, Warje ,Pune India ashutosh.kalshetti5@gmail.com

+ Associate Professor, RMD Sinhgad School of Engineering , Warje ,Pune India sanjaysingh.patil@sinhgad.edu

***Abstract*— Specific structures such as crash box and frontal longitudinal member undergo plastic deformation during an event of collision, absorbing substantial amount of kinetic energy. In case of frontal crash accident, crash box is expected to collapse and absorb crash energy prior to the other cabin parts so that damage to the occupant cabin and occupant is minimized. The design of such structures for progressive crush is very important because if these structures deform at very high crushing forces there is high risk to bio-mechanical damage to the vehicle occupants. Hence it is important that the design of such structures should be to maximize the energy absorption while maintaining the peak force below an allowable threshold. Here, progressive crush refers to a mode of axial crush that initiates near the tip of the rail and then progresses towards rear. The current work therefore aims to study, energy absorption of varying thickness crash box. This paper correlates the energy absorption and peak force of uniform thickness crash box, using numerical, experimental and finite element analysis Also the effect of changing the wall thickness and length of each segment on the energy absorption and peak load has been evaluated. By application of varying thickness tube section, peak force can be shifted towards end in the force displacement curve. Which also improves the performance of systems in energy absorption by undergoing progressive crushing. Varying thickness crash box leads to a considerable reduction in the value of initial peak crush force resulting in reducing the exerted deceleration pulse on occupants and equipment.**

Keywords - Crash box, energy absorption, thin-walled structure, varying thickness, uniform thickness, peak load, progressive crushing.

I. INTRODUCTION

Automotive accident are one of major cause of fatality. Therefore it is necessary to the study effect of impact on energy absorbing components of automobile. For energy absorption parts mounted on the front end of the vehicle are major source of energy absorption in automotive accident, which helps to protect occupant and the occupant cabin [1]. These energy absorbers are called as crash boxes which can control the initial kinetic energy and decelerating pulse of vehicle during impact. Energy absorbing devices dissipate the kinetic energy of impact via plastic deformation [2]. Fig.1 shows that the position of the crash box in vehicle.

Crash box works on principal of impact energy absorption by undergoing cyclic plastic deformation, before the energy is fully transmitted to occupant cabin. Crash box have been widely employed in crash-worthiness applications for automobile to safeguard occupant from fatality, and also largely used as kinetic energy absorbers for their robustness, high energy absorption performance and weight efficiency.

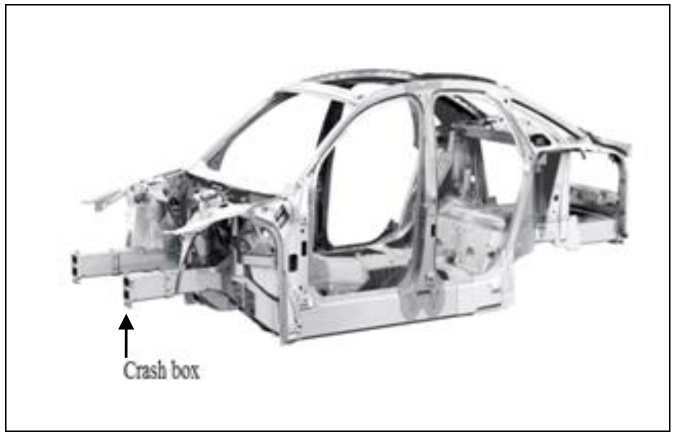


Fig.1 Position of the crash box in vehicle

Due to high weight efficiency, energy absorption and relatively low cost, thin-walled crash box have been widely used in passenger cars, trains, ships and other high-volume industrial products [3]. Crash box have a high energy absorption capability thus have played an important role in vehicle crashes development.

In most of studies have considered uniform thickness and mechanical properties of the tube wall along the length of the tube. The main goal of this paper is to investigate the axial crush behavior and energy absorption characteristics of the crash box tubes in which the thickness of the wall are not constant along the tube length.

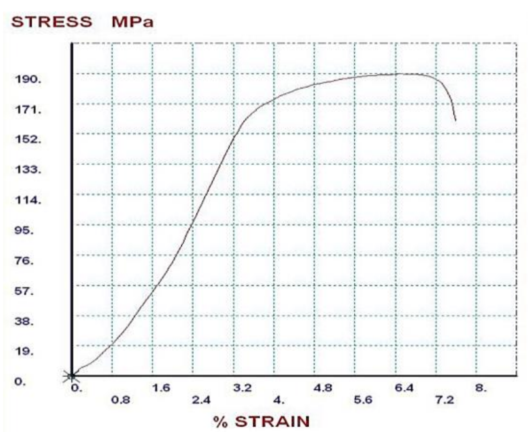
In this paper, constant thickness crash box subjected to quasi-static axial compressive loads is evaluated. Experimental crush test is carried and tensile testing of specimen cut from same crash box material is tested on universal testing machine to get the material properties. Tensile test material model is further used for CAE evaluation, and analytical calculation. Crush parameters such as Energy absorption and peak forces values where extracted from the force–displacement curves of experimental and CAE models. This values along with deformation mode shapes where matched and CAE model is validated. Then the same CAE model is used to evaluate the effect of varying thickness crash box, crush parameters such as deformation mode shapes, total absorbed energy, mean and maximum crush forces, specific energy absorption and the static energy absorbing effectiveness factor and deformed shapes.

II. EXPERIMENTAL SETUP

A. Aluminum alloys which have required machining, welding and extrusion properties are more and more used in space structures and automotive chassis application to provide a light weight solution. In present study extruded Aluminum alloy is applied to prepare crush test specimens. Material testing is carried out on Universal testing machine as shown is Fig. 2

The uniaxial tensile test sample was prepared from the tubes according to the ASTM E8 standard [16] in order to determine the mechanical properties of the test material used. Tensile test was performed using a 98 kN Universal test apparatus, at the temperature of 25 ^{o}C and the speed of 5 mm/min

Fig.2 Universal testing machine



Graph1. Engineering Stress-Strain curve

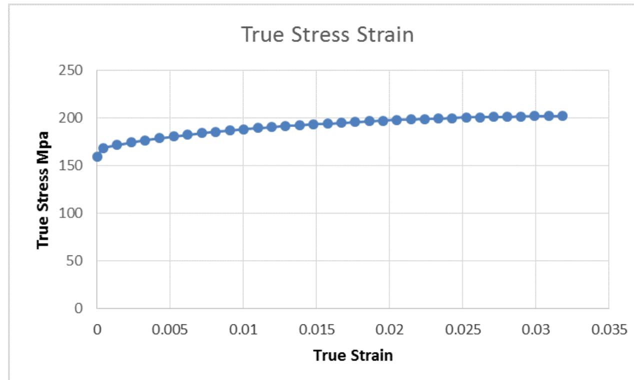
TABLE 1 Material Properties

Load Cell	98000 N
Speed of loading	5mm/min
Peak Load	3584.84 N
Break Load	3026.24 N.
Tensile Strength	189.674 MPa
Thickness	1.5mm
Break Strength	160.119 MPa
Yield strength	159.133Mpa

Experimental /Engineering stress-Strain curve obtained is as plotted in graph 3, which was convert to into true stress-plastic data points for Aluminum as shown in graph 2. Specification of universal servo-electric test apparatus and material properties obtained from tensile testing is as listed in table 1.

B. Uniform thickness Crash box Quasi-static test

A Universal servo-electric test apparatus with the capacity of 100 kN was utilized to perform the quasi-static tests as shown in Fig. 3(b). Specimens was loaded at stable speed of 25 mm/min, and the corresponding force–displacement curves were plotted as in graph. 3.



Graph.4 True static true stress strain curve

As is illustrated in Fig.3 (a), the specimen is placed between the parallel platens of the apparatus and crushed under axial compressive load. Fixture was not used to hold the specimens in place between the platens. The specimens was crushed up to 160mm at the room temperature of (25 ^{o}C).

Following are the dimensions of the crash box tube considering it in horizontal position.

Height : 38.1 mm
Width : 63.5mm
Thickness: 1 mm
Length : 200 mm

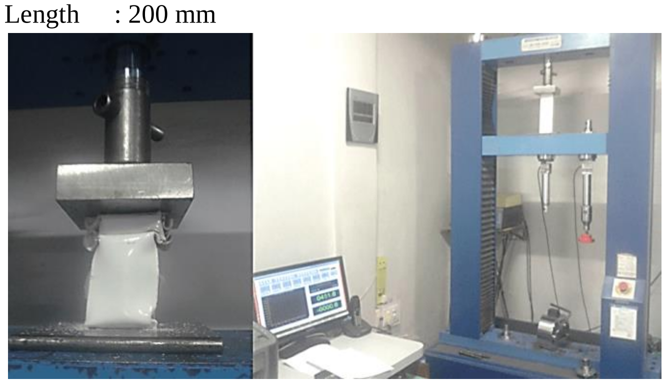
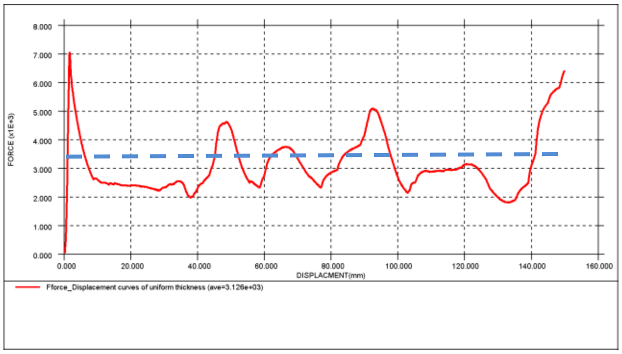


Fig.3 Quasi-static experimental test setup (a) placement of the specimen between the two platens, (b) universal servo-electric test apparatus

By analyzing the deformed shapes of the specimens and the collected data, parameters such as peak load and energy absorption where evaluated. The deformed picture of the specimens following the crush test is shown in Figs. 3(a). As it can be seen, in uniform thickness crash box, the maximum force occurs during the formation of the first fold and at the beginning of the crush range in graph.3.



Graph.3 Typical force–displacement curves of uniform thickness crash box

Also because the thickness along the tube is constant in simple tubes, the changes of the force–displacement curve along the crush length have a uniform trend until 60% to 70% of crush length. Which results in higher value of de-accelerating pulse at the start of crush. In Force Displacement curve area under the curve is the energy absorbed by the rectangular tube at the time of undergoing crush. Dotted line indicates the mean load which is 3.2 kN.

III. ANALYTICAL SOLUTION

The quasi static mean load is obtained using the equation (1) proposed by W. Abramowicz and N. Jones [5]. These equations used for the validation of analysis of rectangular tube are applicable to square tubes, however it has been found to produce reasonable results for rectangular tubes [6]. Average load is an appropriate criterion to find the energy absorption capacity of an absorber.

Mean crushing load for quasi-static loading (Pm)

$$\frac{Pm}{Mo} = 52.22 \text{ x } (c/h)1/3 \quad (1)$$

Here,

c = Average of side lengths of tube $=(\frac{63.5+38.1}{2}) = 50.75$mm

h = thickness of tube = 1 mm

Mo = fully plastic bending moment per unit length for sheet metal

$$Mo = [(\sigma_y \text{ x } h^2)/4] \quad (2)$$

Here σ_y is yield stress of the material.

Thus,

$$Mo = [(159.133 \text{ x } 1^2)/4]$$
$$= 39.75 \text{ N}$$

Thus,

$$\frac{Pm}{Mo} = 52.22 \text{ x } (c/h)1/3$$
$$Pm = 39.75 \text{ x } 52.22 \text{ x } (50.75/1)1/3$$
$$Pm = 7594.75 \text{ N} = 7.5 \text{ kN}$$

For Quasi static crush mean load is = 7.5 KN

IV. FINITE ELEMENT MODEL

A. Uniform thickness Crash box

Finite element analysis carried out to find the behaviour of the tube under axial crushing load. For this analysis is done on the LS-DYNA software.

The rectangular tube and the rigid plate is modeled with 2D shell elements. The element size used is 5mm x 5mm [7]. The tube is not constrained in any direction to simulate exact experimental condition. For both the components, no. of integration points is used as 5 and element type used is Belytschko Tsay shell.

Fig.4 shows the meshing of rectangular tube. By using rigid plate load is applied on rectangular tube in vertical downward direction. In quasi-static analysis speed of rigid plate is same as time displacement curve obtained by experimental test to simulate exact experimental condition.

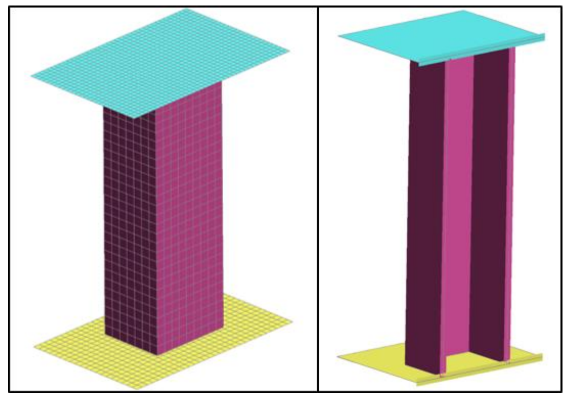


Fig.4 Meshing of the rectangular tube

B. Varying thickness crash box

Rectangular crash box of same dimension as of varying thickness is models using shell elements 5mm x 5mm.Boundry conditions and load application are also same as that for uniform. Thickness from 1mm to 2.5mm from top to bottom is applied with an increment of 0.5mm per part as shown in below Fig. 5

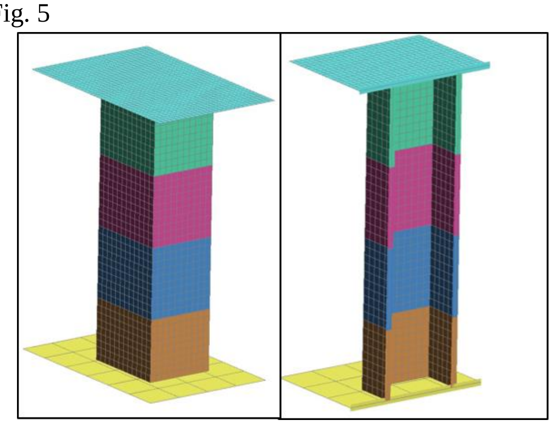
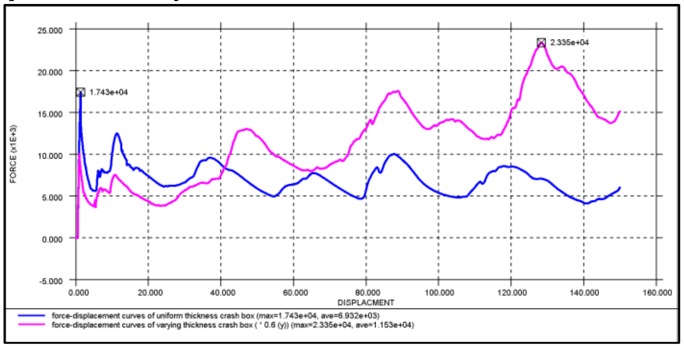


Fig.5 Meshing of the rectangular tube

Self-contact between tube walls during collapse & surface to surface contact between each rigid surface & the tube is defined by penalty based contact algorithm with contact pairs & hard contact. All surface to surface contact are of master slave type.

C. RESULTS AND DISCUSSION

Here graph 4 shows the Force Vs Deflection curve of the quasi-static analysis.



Graph. 4 Load Vs Deflection

From above Graph. 4 P_{max} indicates that the maximum crushing load which is maximum force during loading process and often occurs at the initial stage of loading when first folding happens [9] for uniform thickness crash box curve is plotted in blue colour. On contrary P_{max} for varying thickness crush emerges at the end of the crush range and during the formation of the first fold in the fourth segment providing the possibility of reduction in exerted deceleration at the moment of impact. It is possible to reduce the initial maximum force and also consequently increase crush force efficiency by controlling the length and thickness of each segment of the tube. In Force Displacement curve area under the curve is the energy absorbed by the rectangular tube at the time of crushing.

Average load is an appropriate criterion to find the energy absorption capacity of an absorber. Average load, Pmean, is obtained by dividing the measured absorbed energy to the total crushing distance [9]. Theoretical mean load which is 7kN for uniform thickness crash box and 11.5 kN for varying thickness crash box calculated using T/HIS post processer.

The effective crushing distance was approximated by assuming axial deformation to be only 73 % of the axial length, 2H of a folding unit in accordance with Abramowicz & Jones [5, 8] and this distance is 150 mm approximately.

Table indicates the comparison of analytical results and F.E.A. results and experimental results for uniform thickness crash box.

TABLE 2 Comparison of mean load values

Type of analysis	**Mean crushing load**		
	Analytical (kN)	**F. E. A. (kN)**	**Experimental (kN)**
Quasistatic	7.5	7	3.279

Comparison and correlation of mean crushing load of analytical, experimental and finite element analysis give reasonably same values for numerical and finite element analysis, but experimental value has some deviation which may be because of experimental error or non-uniformity of material properties, non-uniform gauge, manufacturing errors, even then we can find that number of crush loops and pattern of crush are same as shown in fig. 6.

Fig.6 Crushed shape of uniform thickness circular tube specimens after quasi static compression test
(a) Finite element analysis, (b) Experimental

V. CONCLUSSION

Comparison of crash box under axial quasi-static loading in finite element analysis, shows that the values of mean crushing load is in reasonably good agreement with the values obtained by using analytical equation. Test specimens were crushed under quasi-static compressive loading and the force–displacement curves obtained where evaluated for peak load and mean crushing load. Peak force occurs during the formation of the first fold and at the beginning of the crush range in uniform thickness crash box. Axial crush behavior and energy absorption characteristics of four-segmented aluminum crash box with varying cross sections were investigated in this research. Results showed that for a constant crush length, varying section crash box possess higher specific energy absorption than the uniform crash box. Additionally, following points could be highlighted:

- Comparing the trend of the force–displacement curves in varying thickness crash box and uniform thickness crash box, it was observed that in varying thickness crash box not only the initial maximum force is significantly reduced, but also maximum force peak appears at the end of crush range. In other words, variable stiffness of a varying thickness crash box along its length caused the specimen to be undergone more displacement and less impact force at the beginning of the crush range and less displacement and more impact force at the end of crush range.
- Through the variation of the thickness of each crash box segment, it possible to control the crush force within the specific crush range.
- In the varying thickness crash box, the force–displacement curves shows an ascending behaviour due to the increasing wall thickness distribution along tubes lengths.
- Folding lengths and force–displacement curve of varying thickness crash box had same trend in each segment as those of uniform crash box.
- From the analysis of force–displacement diagrams for energy absorption factor, for varying thickness crash box and uniform crash box, it can be inferred

that tubes with variation in wall thickness along the length can absorb higher impact energy rather than uniform crash box with the same weight and crush length

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