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Effect of Oblique Loading on Energy Absorption Capacity of Rectangular Tube

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***Abstract* - Thin-walled metal tubes have been widely used as energy absorbing devices for decades in trains, passenger cars, ships and other high-volume industrial products since they are relatively cheap and weight efficient. The crash box of an automotive body is often made of thin-walled tubes which can absorb the kinetic energy of the vehicle through plastic deformation during an impact event. Here material used for the rectangular tube is hot rolled mild steel with 2.5 mm thickness. Dynamic analysis is carried out on rectangular tube in LS-DYNA software. It is meshed with Belytschko Tsay shell element with 5 mm element size. Effect of oblique loading on rectangular tube is studied. In oblique loading, usually the collapse mode is the global bending. This bending caused to decrease the energy absorption. The energy absorbing capability of obliquely loaded rectangular tube is studied with different loading angles. The collapse behavior of tube is investigated at loading angles of 0^0, 10^0, 20^0 and 30^0. Deformation of rectangular tube, mean crushing load, Peak load and energy absorptions for different load angles are observed during the analysis.**

Key words: Oblique loading, deformation process, Mean crushing load, Peak load and energy absorption capacity.

I. INTRODUCTION:

Thousands of people throughout the world are killed due to the road accidents. With the increase in vehicles, the number of collisions and fatalities has also increased. In view of this, higher demand has been advocated to ensure higher standards of safety in vehicles. The automotive industry requires that the bumper system must endure a load with an angle of 30 degrees to the longitudinal axis [1]. The energy absorption drops drastically when a global bending mode is initiated instead of progressive collapse, and it decreases further with increasing load angle. In the collapse of large load angle, the resistance load continuously decreases after initial maximum peak load as in pure bending collapse.

A. Types of loading:

Followings are the different types of loading which acts on the crush tube;

- Axial loading
- Oblique loading
- Lateral loading

Oblique loading:

Following Fig.1 shows the oblique frontal impact. ϴ is the oblique angle between rigid wall and vehicle.

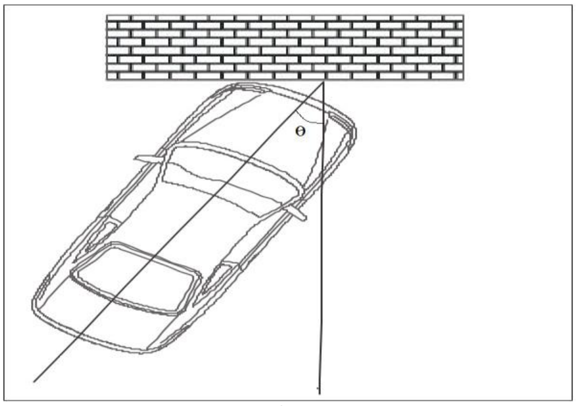


Fig.1 Oblique frontal impact [5]

During an actual crash event, the energy absorber will seldom be subjected to either pure axial or bending collapse, but rather a combination of the two modes. If the crash box experiences global bending instead of axial crushing, the energy absorption will be lower, and both moments and axial forces will be transferred to the rest of the structure. Mean load and peak crushing force (PCF) also decreases with increasing load angle. With increasing wall thickness both specific energy absorption (SEA) and peak crushing force (PCF) decreases as the load angle increases for each wall thickness [2].

There are 3 typical regions of oblique load angle. The first is the axial collapse dominant region, the second is bending collapse dominant region and the last is the transition region from axial collapse to bending collapse [3].

B. Dynamic analysis of crush tube:

In dynamic analysis crushing of the vehicle occurs at the speed of 10m/s, 15m/s and 20m/s. Due to high speed of the vehicle personal injury becomes high. In dynamic impact, maximum force is required for the folding of the first lobe after that load becomes decreases. Peak load becomes high in dynamic analysis as compared to quasi-static analysis. Crushing behavior of the tube depends up on impact of loading such as axially or oblique impact. Deformation in dynamic analysis is less as compared to quasi-static analysis it may be due to strain rate hardening or inertia effect. Energy absorption is high in axial loading of dynamic analysis. Mass of impact also effects on the energy absorption capacity in dynamic analysis [4]. Mean load in dynamic analysis becomes high as compared to quasi-static analysis.

II. DIMENSIONS OF THE RECTANGULAR TUBE

Following are the dimensions of the crush tube considering it in horizontal position. These dimensions are fixed from literature survey as well as from actual vehicles survey.

Shape : Rectangular
Height : 110 mm
Width : 60 mm
Thickness : 2.5 mm
Length : 250 mm
Corner Radius : 3 mm

A. *Material properties:*

Material testing is carried out on Universal testing machine.

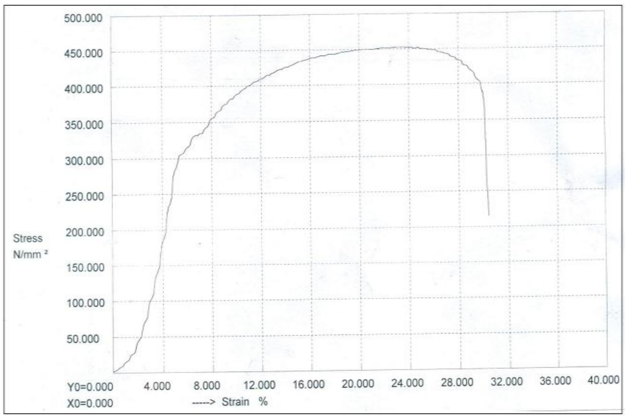


Fig.2 Engineering Stress-Strain curve

Above Fig.2 shows the Engineering stress- strain curve of standard test specimen.

Following TABLE 1 shows the material properties of hot rolled mild steel specimen. We have to use this material throughout.

TABLE 1
MATERIAL PROPERTIES

Maximum Force (F_m)	24,120N
Maximum displacement	24.300 mm
Tensile Strength (R_m)	452.533 N/mm^2
Elongation	23.375 %
Yield load	15,660 N
Yield Stress	293.809 N/mm^2
YS / UTS Ratio	0.649
Young's Modulus	207 GPa
Poisson's Ratio	0.3
Density	7700 Kg / m^3

From above graph we convert engineering stress-Strain curve into true stress-plastic data points for steel in FE model. Fig.3 shows the true static true stress strain curve for mild steel. TABLE 2 shows the input data points for steel in FE model.

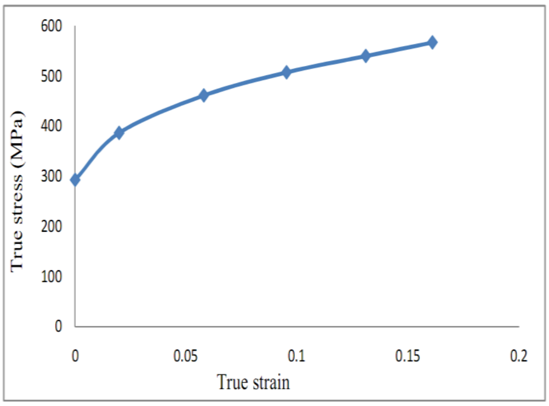


Fig.3 True static true stress strain curve for mild steel

TABLE 2
True stress-plastic data points for steel in FE model

σ_t (MPa)	293	386.586	461.36	507.5	540.0	567.15
ε_p	0	0.0198	0.058	0.0953	0.131	0.161

III. FINITE ELEMENT ANALYSIS:

Software used for analysis is LS-DYNA which is processing software. LS-DYNA is a nonlinear dynamic structure analysis program developed by Livermore Software Technology Corp. (LSTC) in the USA.

A. *Modeling and meshing:*

The rectangular tube and the rigid plate are modeled with 2D shell elements in HYPERMESH software as shown in Fig.4. Model consists of two parts the tube and the rigid surface representing the crushing surface. Upper rigid plate can carry the relatively large mass element which represent the striker and generates the impact loading of the tube. Rigid plate strikes on larger side of crush tube i.e.110mm under oblique loading condition. A coefficient of friction μ=0.1 is considered between rigid plate and tube also same value incorporates between the tube surfaces. The element size used is 5mm x 5mm as is used by Nagel [4]. For both the components, no. of integration points is used as 5 and element type used is Belytschko Tsay shell. The number of nods and elements are 3864 and 3757.

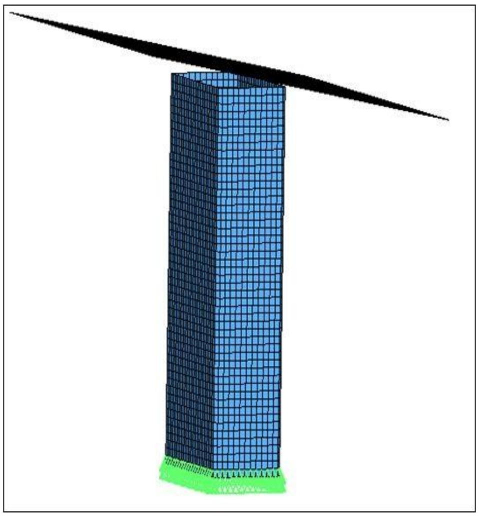


Fig.4 Meshed model of rectangular tube

B. Boundary conditions & Load conditions

Boundary condition: The tube is constrained at the bottom in all translational and rotational directions as in Fig.4.

Load condition: The Rigid plate is given prescribed velocity of 10m/s and 15m/s in vertically downward direction.

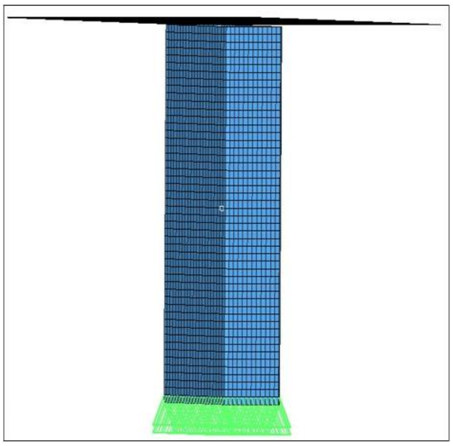
IV. RESULTS AND DISCUSSION

A. RESULTS OF IMPACT VELOCITY 10m/s AND LOADING ANGLES 0 TO 30^0 WITH IMPACT MASS 125kg:

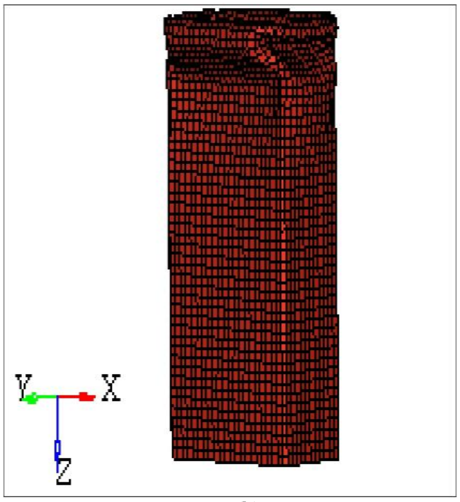
Oblique loading is carried out on the rectangular crush tube with impact mass 125kg. For dynamic oblique loading both inertia effect and strain rate hardening effect is considered. According to Nagel [4] there is no significant change in the load-deflection response as the mass of impact increases, the only difference observed is an increase in maximum deflection associated with the increased impact energy of tube and loading rigid body as the impact mass increases.

a) LOADING ANGLE 0^0:

Following Fig.5 shows the rectangular crush tube with load angle 0^0 with velocity 10m/s i.e. 36km/hr and impact mass of rigid plate is 125kg.



(a)



(b)

Fig.5 Crush tube under load angle 0^0
(a) Loading condition (b) Deformed shape

Energy absorption:

Fig.6 shows the load vs deflection curve of crush tube. Tube is not fully deformed due to strain rate hardening and inertia effect. 6133J is the energy absorbed by the crush tube. Material becomes hard so that maximum force required for the first folding. Peak load is 369.55KN and deformation of crush tube is 38.26mm.

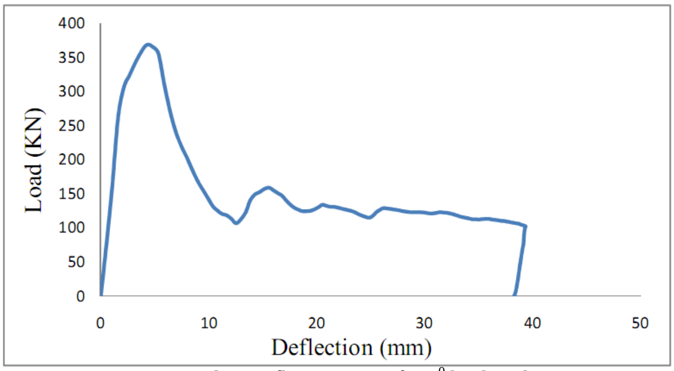


Fig.6 Load vs Deflection curve for 0^0 load angle

Mean crush load:

Mean crush load is 160.25KN. Following Fig.7 shows the mean load vs deflection of rectangular crush tube.

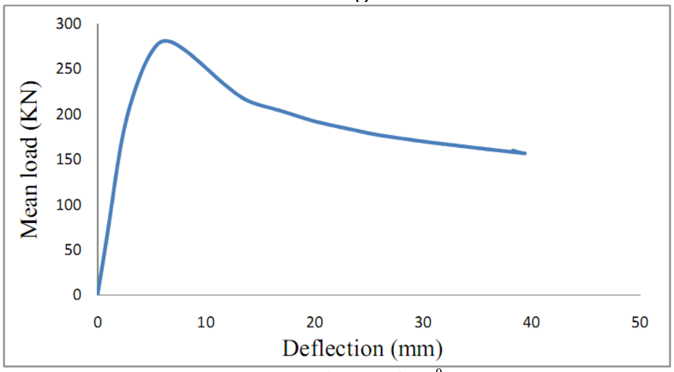
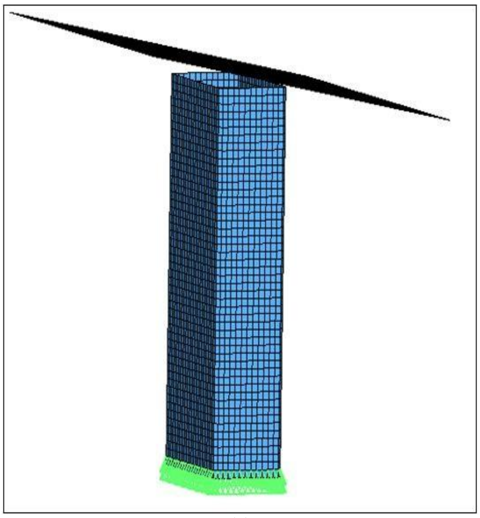


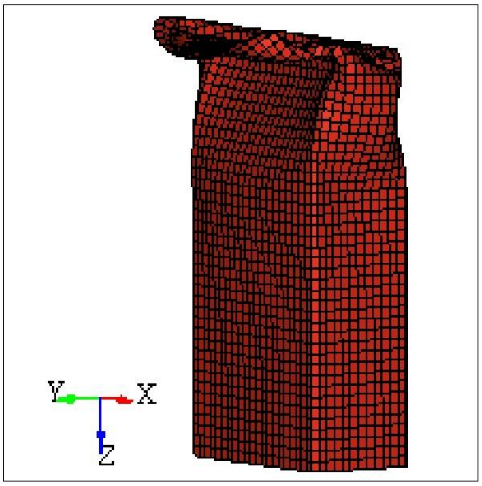
Fig.7 Mean load vs Deflection for 0^0 load angle

b) LOADING ANGLE 10^0:

Fig.8 shows the loading condition and deformed shape of crush tube. Folding pattern is not symmetrical about vertical axis of crush tube.



(a)



(b)
Fig.8 Crush tube under load angle 10^0
(a) Loading condition (b) Deformed shape

Energy absorption:

Under 10^0 loading angle 6155.38J is the energy absorbed by the crush tube with deflection 56.86mm and peak load is 151.45KN. Peak load decreased as load angle increase. Deflection is high as compared to 0^0 load angle. Fig.9 shows the load vs deflection curve of crush tube.

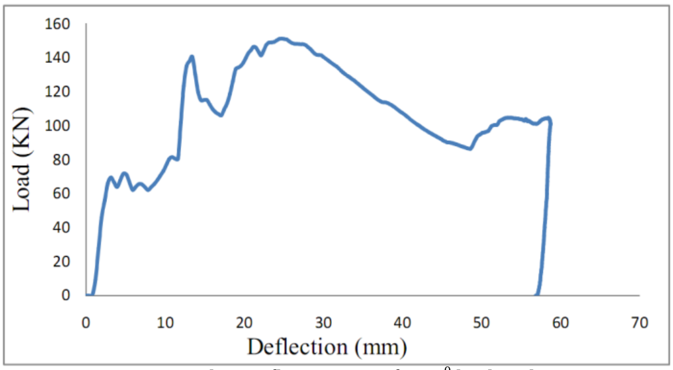


Fig.9 Load vs Deflection curve for 10^0 load angle

Mean crush load:

Here mean load is 108.24KN which is less than mean load of 0^0 load angle. Fig.10 shows the mean load vs deflection of rectangular crush tube.

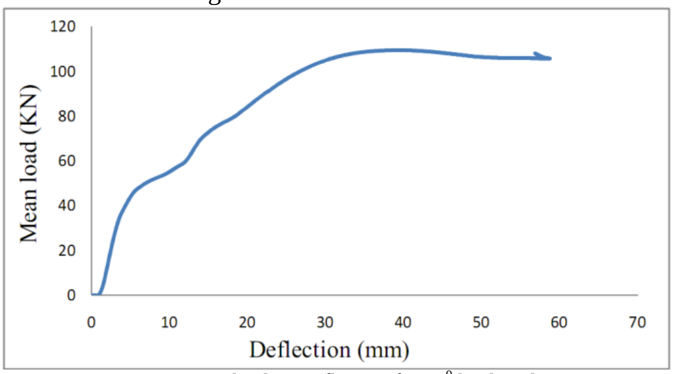


Fig.10 Mean load vs Deflection for 10^0 load angle

c) LOADING ANGLE 20^0:

Fig.11 shows the deformed shape of crush tube. Less peak force required for deformation of tube under oblique loading. Tube deform like Euler's buckling mode. There is no contribution of middle portion of the tube for energy absorption.

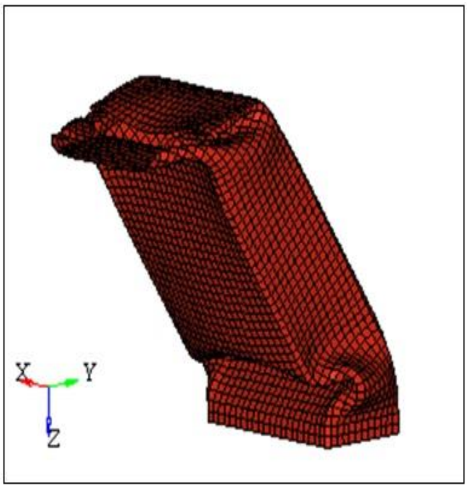


Fig.11 Deformed shape of crush tube under load angle 20^0

Energy absorption:

Under 20^0 loading angle 6410.084J is the energy absorbed by the crush tube with deflection 115.38mm and peak load is 120.65KN. Deflection is high as compared to previous load angles. Fig.12 shows the load vs deflection curve of crush tube.

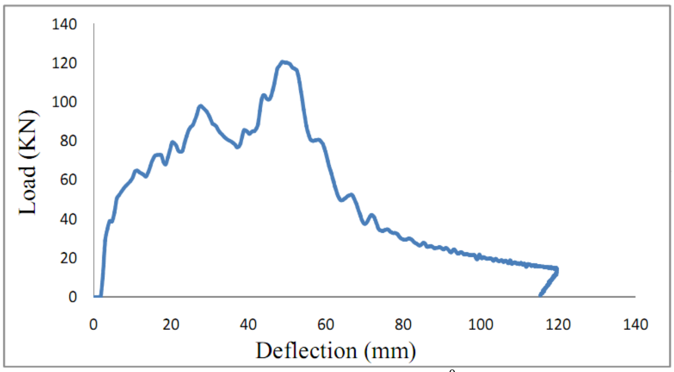


Fig.12 Load vs Deflection curve for 20^0 load angle

Mean crush load:

Fig.13 shows the mean load vs deflection of rectangular crush tube. Mean load is 55.55KN.

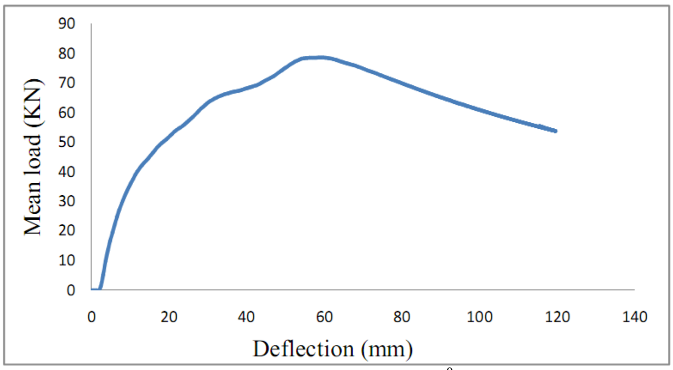


Fig.13 Mean load vs Deflection for 20^0 load angle

d) LOADING ANGLE 30^0:

When tube goes in global bending collapse mode instead of progressive collapse mode then load transferred to the occupants of vehicle and there are chances of injury to the passengers. As compared to all other loading conditions energy absorption is very less in this loading angle. From following Fig.14 deformation of crush tube it is observed that there is no progressive folding patterns are created at the top of tube

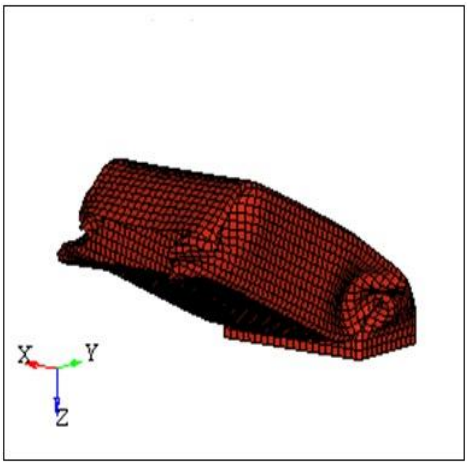


Fig.14 Deformed shape of crush tube under load angle 30^0

Energy absorption:

Under 30^0 loading angle 5302.64J is the energy absorbed by the crush tube with deflection 166mm and peak load is 77.18KN. Peak load is low as compared to other loading angles. Here 66% is the deformation length of total length of column is considered. Fig.15 shows the load vs deflection curve of crush tube.

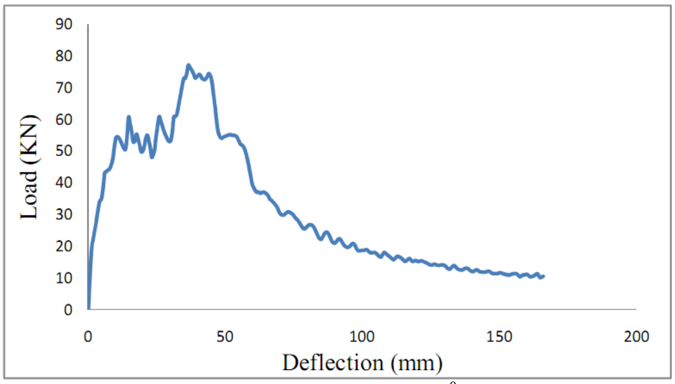


Fig.15 Load vs Deflection curve for 30^0 load angle

Mean crush load:

Fig.16 shows the mean load vs deflection of rectangular crush tube. Mean load is 31.91KN. Mean load is also decreases in this type of loading. The mean crushing load is calculated when the end of column moves 2/3 of column length, before column jams itself [3].

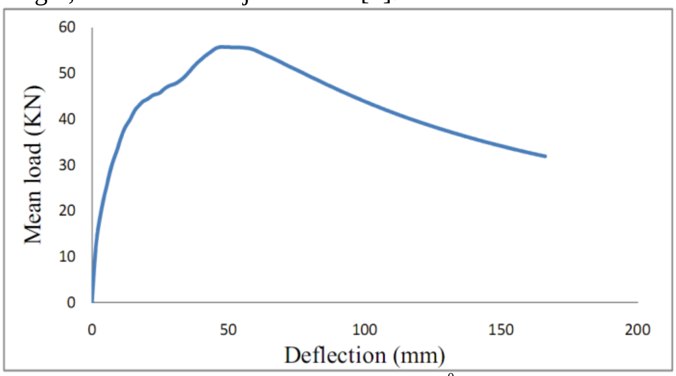


Fig.16 Mean load vs Deflection for 30^0 load angle

DISCUSSION:

Following TABLE 3 shows the comparison of results between peak load, mean loads and crush force efficiency of 10m/s impact velocity.

TABLE 3

COMPARISON OF RESULTS FOR OBLIQUE LOADING WITH 10m/s IMPACT VELOCITY

Angle	Energy absorption (J)	Mean load (KN)	Reduction in mean load (%) compared with axial loading	Peak load (KN)	C.F.E %
0	6133	160.25	-	369.55	43.36
10	6155.38	108.24	32.46	151.45	71.46
20	6410.084	55.55	65.34	120.65	46
30	5302.64	31.91	80.09	77.18	41.34

Following Fig.17 shows the mean load vs load angle which is drawn from above mean load values for different load angles. From graph it is observed that mean load decreases as impact load angle increases. As mean load high then energy absorption capacity of crush tube becomes high. If mean load decreases then capacity of energy absorption decreases.

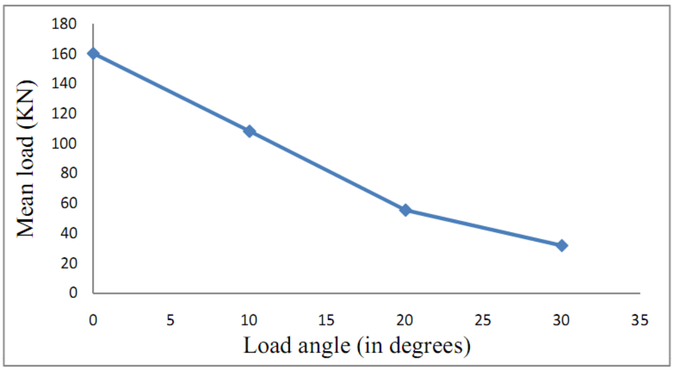


Fig.17 Mean load vs Load angle for 10m/s

Fig.18 shows the peak load vs load angle. Peak load decreases as loading angle increases. For 0^0 load angle peak load is high so maximum force required for deflection of tube. For 30^0 load angle peak load is very less as compared to other loading angles, this happens because tube goes in global bending collapse mode instead of progressive collapse mode.

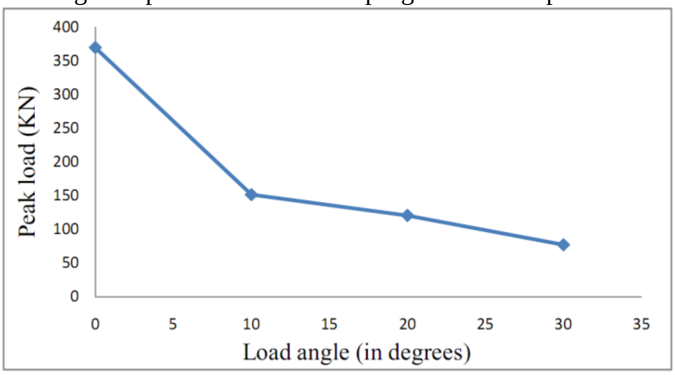


Fig.18 Peak load vs load angle for 10m/s

Crush force efficiency is defined as it is the ratio of mean crushing force divided by maximum crushing load [6]. Maximum the crush force efficiency for energy absorbers used in crash worthiness design when the protection of occupants is a priority. From following Fig.19 crush force efficiency is high for 10^0 load angle.

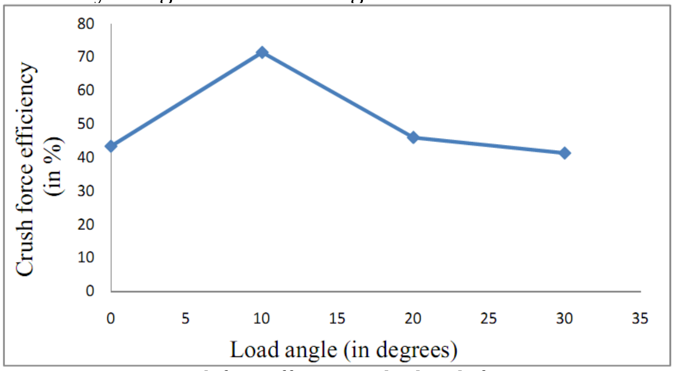


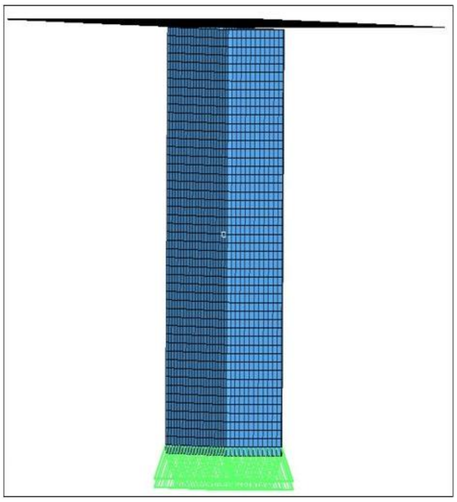
Fig.19 Crush force efficiency vs load angle for 10m/s

B. RESULTS OF IMPACT VELOCITY 15m/s AND LOADING ANGLES 0 TO 30^0 WITH IMPACT MASS 125kg:

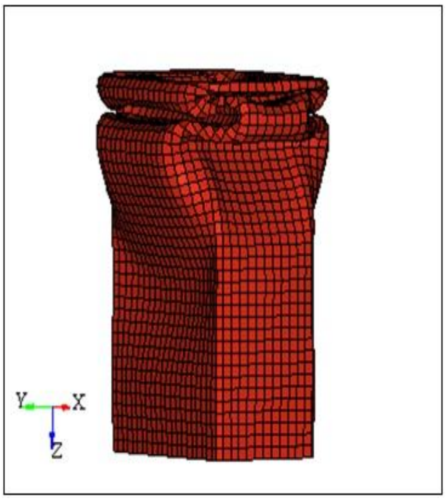
When accidents occur at 54km/hr it is dangerous to the occupants of vehicle. Impact velocity significantly influences the maximum crush energy. Tube absorbs more impact energy at higher velocity. The mode of deformation of the structure under dynamic loading may be significantly different from the quasi-static mode on account of 'inertia forces' developed within the structure by the rapid acceleration which parts of it experience during the impact. Strain rate enhance the energy absorption. This chapter has examined the energy absorption response of straight rectangular tube under oblique loading, in which the angle of applied load is varied from 0^0 to 30^0 to the longitudinal axis.

a) LOADING ANGLE 0^0:

Fig.20 shows the crush tube under load angle 0^0. When load applied on the crush tube at higher velocity then maximum peak force also required for deflection of tube. For 0^0 loading tube deform axially. Due to strain rate hardening and inertia effect tube becomes strong so that less deformation occurs.



(a)



(b)

Fig.20 Crush tube under load angle 0^0
(a) Loading condition (b) Deformed shape

Energy absorption:

Under 0^0 loading angle 13851.46J is the energy absorbed by the crush tube with deflection 93.79mm and peak load is 387.92KN. Maximum force required for first folding. Fig.21 shows the load vs deflection curve of crush tube.

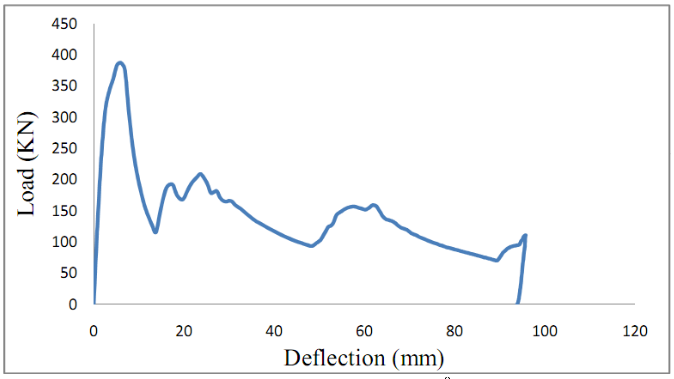


Fig.21 Load vs Deflection curve for 0^0 load angle

Mean crush load:

Mean load indicates the energy absorption capacity of crush tube. Mean load under 0^0 load angle is 147.67KN. Fig.22 shows the mean load vs deflection for 0^0 load angle

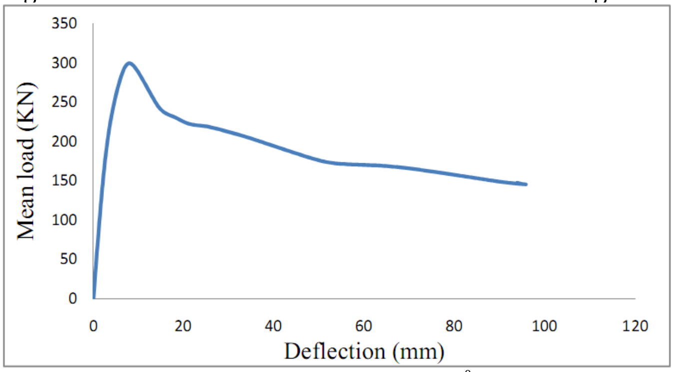
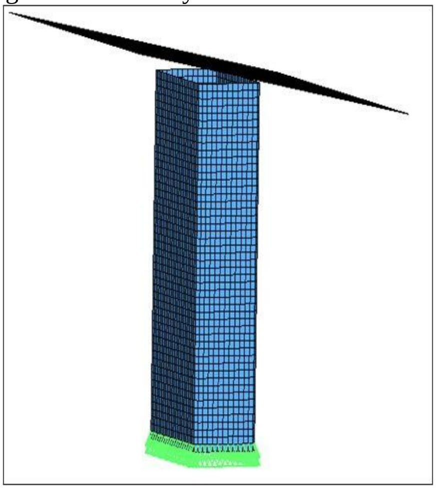


Fig.22 Mean load vs Deflection for 0^0 load angle

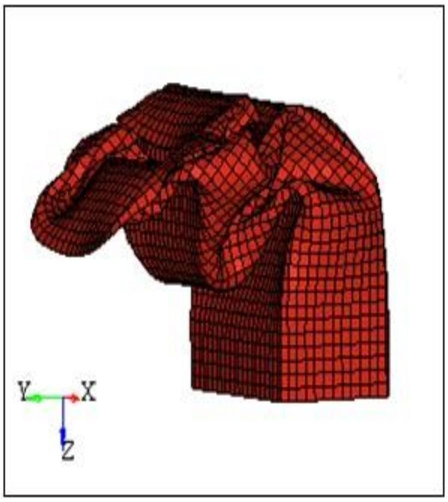
b) LOADING ANGLE 10^0:

As load angle increases from 0^0 to 10^0 then deformation of crush tube is not symmetrical about vertical axis of crush tube. Deformation of crush tube is under global buckling mode.

Following Fig.23 shows the crush tube under load angle 10^0. Folding of tube is not synchronous fashion.



(a)



(b)

Fig.23 Crush tube under load angle 10^0
(a) Loading condition (b) Deformed shape

Energy absorption:

Under 10^0 loading angle 13655.66J is the energy absorbed by the crush tube with deflection 166.147mm and peak load is 167.57KN. Peak load is less as compared to 0^0 load angle. Less peak load under oblique loading indicates that tube goes in global buckling mode. Deformation is high as compared to 0^0 load angle. Fig.24 shows the load vs deflection curve of crush tube.

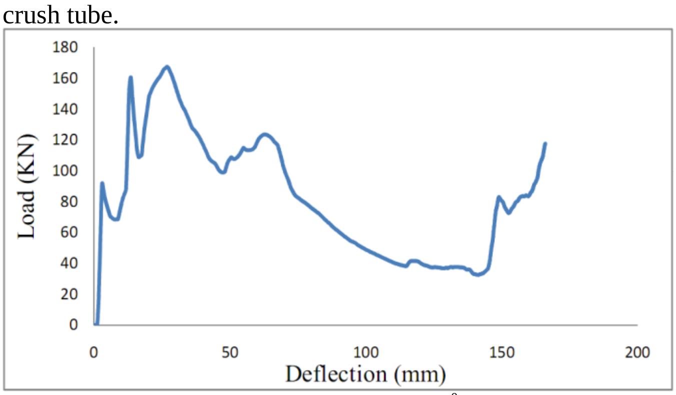


Fig.24 Load vs Deflection curve for 10^0 load angle

Mean crush load:

Fig.25 shows the mean load vs deflection of rectangular crush tube. Mean load is 82.19KN.

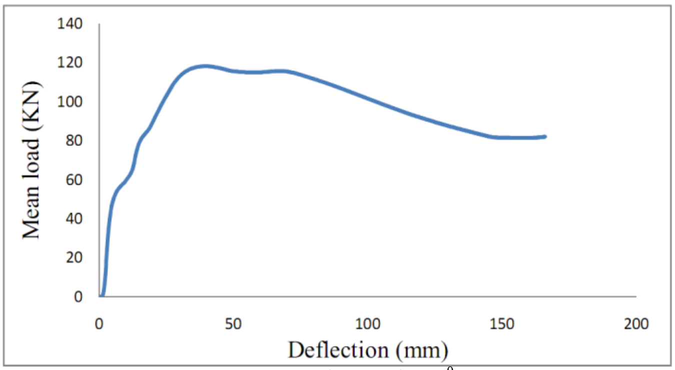


Fig.25 Mean load vs Deflection for 10^0 load angle

c) LOADING ANGLE 20^0:

Fig.26 shows the loading condition and deformed shape of crush tube. Less peak force required for deformation of tube under oblique loading. Tube deform like Euler's buckling mode.

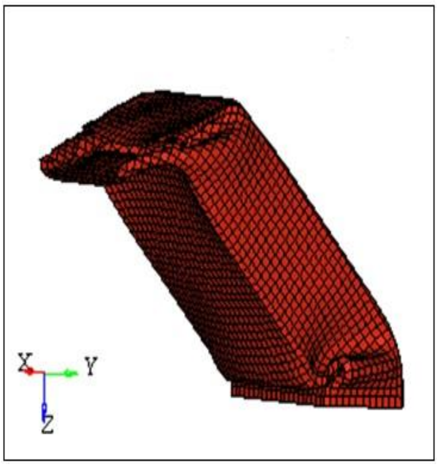


Fig.26 Deformed shape of crush tube under load angle 20^0

Energy absorption:

Under 20^0 loading angle 9100.796J is the energy absorbed by the crush tube with deflection 166.61mm and peak load is 148.326KN. Peak load is less as compared to 10^0 load angle. Here energy absorption decreases than 10^0 load angle. Fig.27 shows the load vs deflection curve of crush tube.

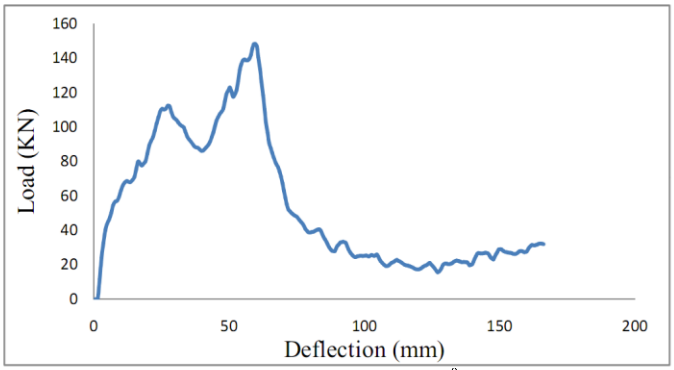


Fig.27 Load vs Deflection curve for 20^0 load angle

Mean crush load:

Fig.28 shows the mean load vs deflection of rectangular crush tube. Mean load is 54.68KN. Mean load is also decreases in this type of loading as compared to previous loadings.

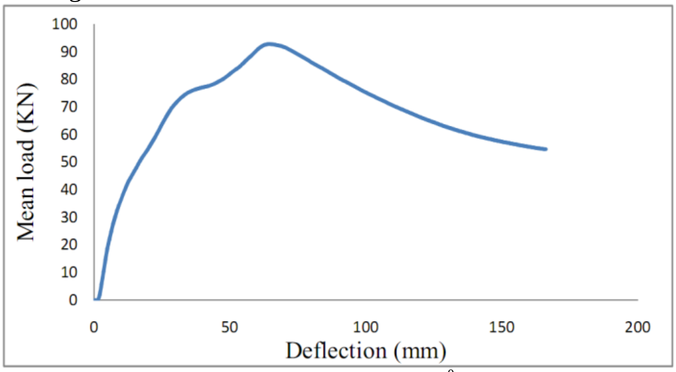


Fig.28 Mean load vs Deflection for 20^0 load angle

d) LOADING ANGLE 30^0:

Under high loading angle with high velocity then tube goes in global bending collapse mode instead of progressive mode so that it is dangerous to the passengers. From following Fig.29 it is clear that there is no synchronous folding pattern crated.

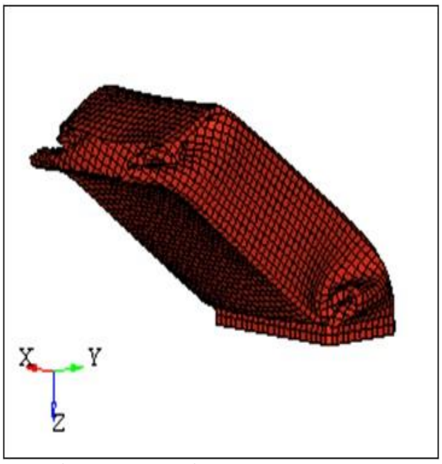


Fig.29 Deformed shape of crush tube under load angle 30^0

Energy absorption:

Under 30^0 loading angle 5974.408J is the energy absorbed by the crush tube with deflection 166.23mm and peak load is 88.16KN. Peak load is less as compared to 20^0 load angle. Here energy absorption decreases than 20^0 load angle. Fig.30 shows the load vs deflection curve of crush tube.

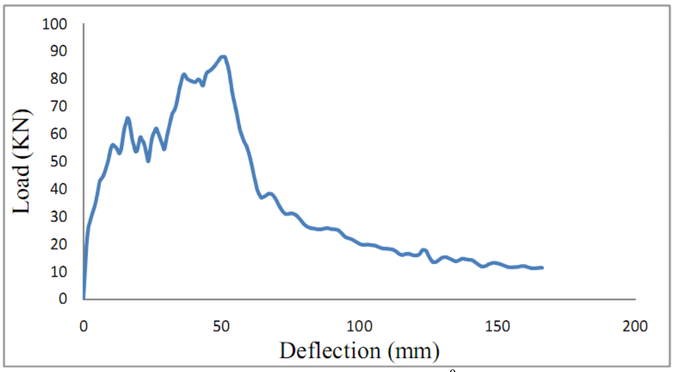


Fig.30 Load vs Deflection curve for 30^0 load angle

Mean crush load:

Fig.31 shows the mean load vs deflection of rectangular crush tube. Mean load is 35.90KN.

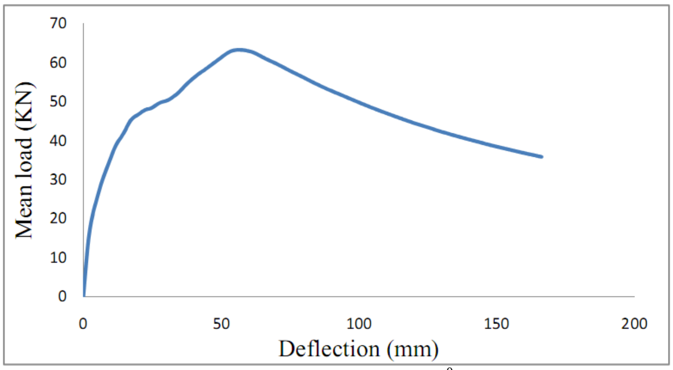


Fig.31 Mean load vs Deflection for 30^0 load angle

DISCUSSION:

Following TABLE 4 shows the comparison of results between peak load, mean loads and crush force efficiency of 15m/s impact velocity.

TABLE 4

COMPARISON OF RESULTS FOR OBLIQUE LOADING WITH 15m/s IMPACT VELOCITY

Angle	Energy absorption (J)	Mean load (KN)	Reduction in mean load (%) compared with axial loading	Peak load (KN)	C.F.E %
0	13851.46	147.67	-	387.92	38
10	13655.66	82.19	44.35	167.57	49
20	9100.796	54.68	62.98	148.326	36.86
30	5974.408	35.90	75.7	88.16	40.72

Following Fig.32 shows the mean load vs load angle which is drawn from above mean load values for different load angles. From graph it is observed that mean load decreases as impact load angle increases. As mean load high then energy absorption capacity of crush tube becomes high. If mean load decreases then capacity of energy absorption decreases.

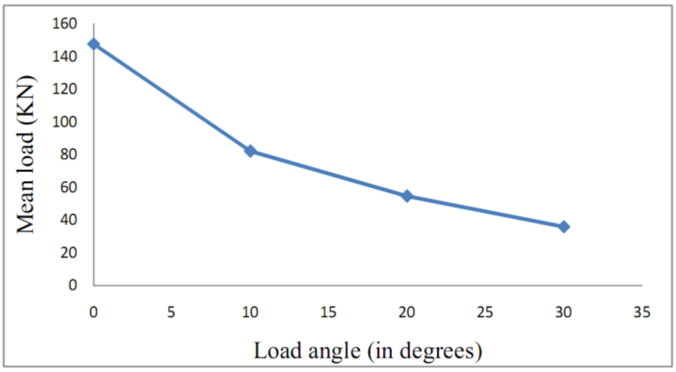


Fig.32 Mean load vs Impact angle15m/s

Fig.33 shows the peak load vs load angle. Peak load decreases as loading angle increases. For 0^0 load angle peak load is high so maximum force required for deflection of tube. For 30^0 load angle peak load is very less as compared to other loading angles, this happens because tube goes in global bending collapse mode instead of progressive collapse mode.

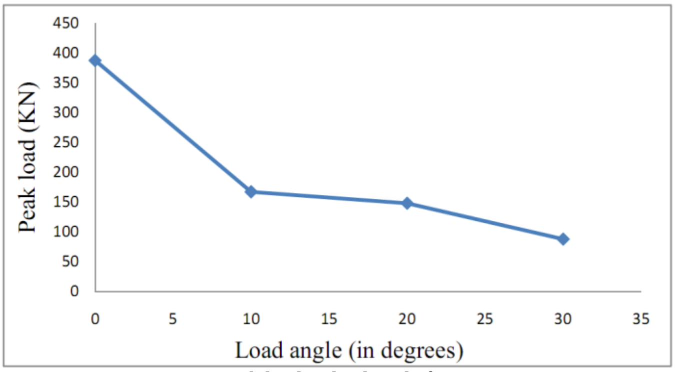


Fig.33 Peak load vs load angle for 15m/s

From following Fig.34 crush force efficiency is high for 10^0 load angle.

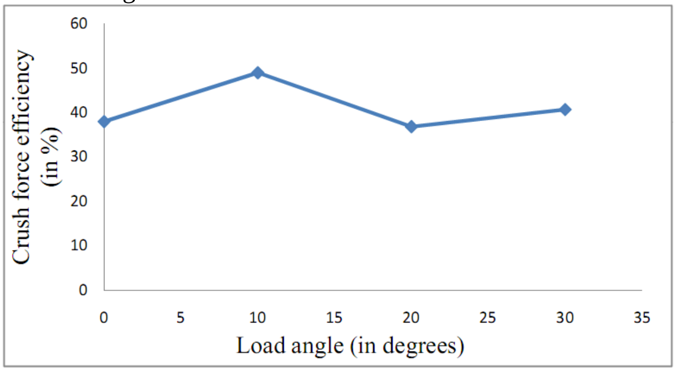


Fig.34 Crush force efficiency vs load angle for 10m/s

V. CONCLUSION

From above dynamic analysis of rectangular tube under oblique loading following conclusions are drawn.

- Energy absorption decreases with increasing load angle.
- As load angle increases peak load decreases.
- As load angle increases mean load also decreases.
- Deformation of tube in dynamic axial loading is less as compared to quasi-static axial loading. This is due to strain hardening.
- With increasing impact velocity peak load and deflection of crush tube also increases.

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