Effect of Triggers on Energy Absorption Capacity of Rectangular Tubes during Oblique Loading

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***Abstract*—Energy absorption devices are used in all vehicles and moving parts such as road vehicle, railway couches, aircraft, ships, lifts and machinery. The aim is to minimize injury to people and to confine the damage to properties. Most of the frames in modern vehicles are made from thin-walled sections. Crashworthiness studies devote a great deal of attention to the behavior of thin-walled structures, which have been widely used as load bearing structures as well as energy absorbers. One of the types of energy absorber is crash box which absorbs kinetic energy of 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. It is meshed with Belytschko Tsay shell element with 5 mm element size. Quasi-static analysis is carried out in this work for axial loading. Mean crushing load is taken as a parameter for validation of the results. Effect of Oblique loading on rectangular tube without triggers and with triggers is studied. For preprocessing and post processing HYPERWORKS is used. LS-DYNA software is used as the processor. The energy absorbing capability of obliquely loaded rectangular tube for 15 m/s is studied with different loading angles. The collapse behavior of tube is investigated at loading angles from 0^o to 30^o in the steps of 5^o. Energy absorption, Mean load, Peak load, CFE, deflection and deformation of rectangular tube for different load angles are observed.**

***Keywords*—Energy Absorption, Oblique Loading, Triggers.**

I. INTRODUCTION

Today, automobiles are one of the most important transportation devices in our lives. The greatest demand facing the automotive industry has been to provide safer vehicles with light weight materials at minimum cost. To this end, over the past several decades increasing focus has been paid to the use of impact energy absorbers, devices designed to dissipate energy during an impact event and hence protect the structure and occupants under consideration. Thin-walled columns have a high energy absorption capability and therefore have played an important role in vehicle crashes.

Energy absorbers are often part of the car structure to protect passengers and structure itself during impact. One type of energy absorber is the crash box or crush tubes or energy absorbing tubes, which is connected to the bumpers, situated in the front and rear end of the body structure. The crash box is designed to absorb energy at low speed impacts. Its purpose is to control the initial kinetic energy during impact and at the same time avoids permanent deformations in the rest of the car body by keeping the force levels sufficiently low and to decrease the shock transferred to the occupants, where the progressive plastic buckling lobes are generated.

Types of loading are (a) Axial loading (b) Oblique loading (c) Lateral loading

Oblique loading: Figure 1 shows the oblique loading of the column. ϴ is the oblique angle between the axis of the column and applied force.

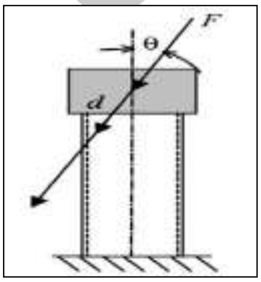


Figure 1: Oblique loading of column [5]

During an actual crash event the crash box will be subjected to either pure axial or bending collapse but rather the combination of two modes. If the crash box experiences global bending instead of axial crushing then energy absorption will be lower and both moments and axial forces will be transferred to the rest of the structure.

Triggers: Triggers or buckling initiators are nothing but cuts or the weak areas created on the object. Accurate use of triggers cause collapse transition from global bending to progressive buckling and decrease the peak force and increase crush force efficiency. Types of triggers are (a) Bead initiator (b) Diamond notch (c) Spheres (d) Plastic fold (e) Smaller thickness (f) Circular notch (g) Circular holes (h) Oval holes (i) Hole type rectangular shape

Terminology Used:

Peak load (P_{max}):

Peak load, is the maximum force during loading process and often occurs at the initial stage of loading when the first folding happens. It is in N or KN.

Mean crushing load (P_{mean}):

Mean load is an appropriate criterion to find the energy absorption capacity of an absorber. It is obtained by dividing the measured absorbed energy to the total crushing distance.

$$P_{mean} = (1/\delta) \int P \, d\delta$$

In this equation, $\int P \, d\delta$ is the area below the force displacement curve and δ is the total crushing distance. The greater the P_{mean}, the more energy is absorbed. It is in N or KN.

Crush force efficiency (CFE):

Crush force efficiency is defined as it is the ratio of mean crushing force to maximum crushing load.

$$\text{Crush force efficiency (CFE)} = P_{mean} / P_{max}$$

This is a very important parameter to evaluate the performance of the structure during the crushing process. For ideal energy absorber CFE=1.If we introduce triggers on the side walls of the crush tube then it increases the crush force efficiency and helps to decrease the maximum peak load. It is expressed in %.

Energy absorption (E_{abs}):

The area under the Load vs. Deflection curve shows the amount of energy absorbed during impact. It is in J.

II. LITERATURE REVIEW

Gregory Nagel [6] analyzed the impact and energy absorption response of tapered and non-tapered (straight) rectangular tubes for axial and oblique loading under his thesis. The results showed that the mean load and energy absorption of both straight and tapered rectangular tubes decrease significantly as the angle of applied load increases also tapered rectangular tube gives more energy absorption in oblique loading.

Je-Seung Park et al. [3] analyzed the collapse behavior of square, rectangular and thin-walled column under oblique loading. Also parameters like thickness, width and length of the square column were studied. In the oblique collapse of rectangular column, the mean crushing load is expressed in terms of mechanical properties, geometrical parameters and oblique load angle. They concluded that the critical load angle indicates the location of transition region and it can be increased in tapered column or column with initiators and should be applied only at the front of the column.

A.Alavi Nia et al. [10] studied about the effect of collapse initiators on energy absorption of square tubes under oblique quasi-static loading by experimentally and numerically. The location and position of initiators was also studied. They concluded that by using initiators the mechanical behavior was from general to progressive buckling resulting in considerable energy absorption. In order to reduce the peak load the initiators should be located at near top of the tube and the highest initiator at the first contact side.

Javad Marzbanrad et al. [9] compared the different cross sections of the tube. They simulated the theory about the axial crushing of steel and aluminium tubes subjected to impact dynamic axial loading. Verification was done through comparison with some experimental results. They studied effect of width and thickness also. They found that the amount of energy absorption per weight of steel tube was about 4.5 times greater than the aluminium tube for all three sections. Also they observed that the amount of energy absorption will be greater with increasing the thickness for smaller section tubes.

X.W.Zhang et al. [7] studied the effect of buckling initiator on the square tube under axial loading experimentally and numerically. Prior to the buckling initiator high peak forces were obtained which caused serious injury or damage to the people. The results showed that by installing the buckling initiator. The objective of reducing the initial buckling force can be achieved with very little effects on the subsequent progressive crushing mode and the excellent energy absorption capacity of the square tube.

III. ESTIMATION OF MEAN LOAD FOR QUASI-STATIC ANALYSIS

A) Mean Load:

The quasi-static mean load (P_m) for rectangular tube is obtained using the expression proposed by W. Abramowicz and N.Jones [1]. The equation used for the validation of analysis of rectangular tube are strictly speaking only applicable to square tubes, however it has been found to produce reasonable results for rectangular tube [2]. Here the perimeter of rectangular & square tube should be same. Also it is used by other researchers for rectangular tube. Mean load is an appropriate criterion to find the energy absorption capacity of an absorber.

$P_m / M_o = 52.22 \times (c/h)^{1/3}$

Here,

c= side lengths of tube = (110+60)/2 =85 mm &

h= thickness of tube = 2.5 mm

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

$M_o = (\sigma_0 \times h^2)/4$ ……………… Here σ_0 is yield stress of the material

Thus,

$\sigma_0 = (\sigma_{0\,yield}) = 293.8$ MPa

$M_o = (293.8 \times h^2)/4$

$= (293.8 \times (2.5)^2)/4$

= 459 MPa
$P_m / M_o = 52.22 \times (c/h)^{1/3}$
$P_m = 459 \times 52.22 \times (85/2.5)^{1/3}$
$P_m = 77650.190$ N =77.65 KN
Mean load for Quasi-static loading = 77.65 KN

B) Finite Element analysis:

1) Preprocessing: Preprocessing involves modeling, meshing, load condition and boundary conditions. The rectangular tube and the rigid plate are modeled with 2D shell elements using HYPERWORKS software. Figure 2 shows model of the tube for quasi-static loading. The element size used is 5mm x 5mm as used by Nagel [6] .The tube is constrained at the bottom in all translational and rotational directions. For both the components, no. of integration points is used as 5 and element type used is Belytschko Tsay shell. The Rigid plate is given prescribed velocity of 10mm per minute in vertically downward direction of rectangular tube. For quasi-static analysis no mass is considered for plate. A fillet of 3mm is used at the corners of the model. Material used for the tube is mild steel of length=250 mm, width=60mm and height=110mm. Thickness of the tube is 2.5 mm. Number of elements=3760 and number of nodes=3873 are generated.

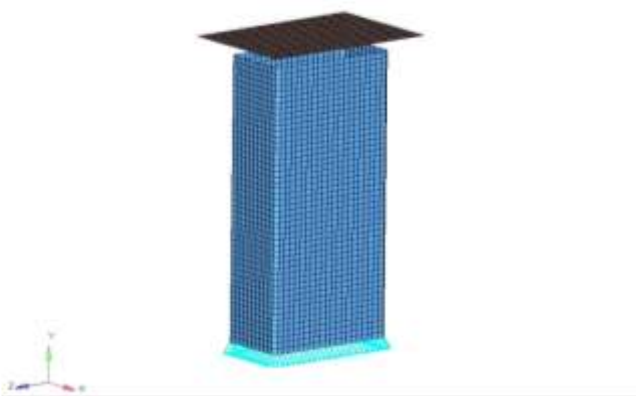


Figure 2: Model of the tube for quasi-static loading

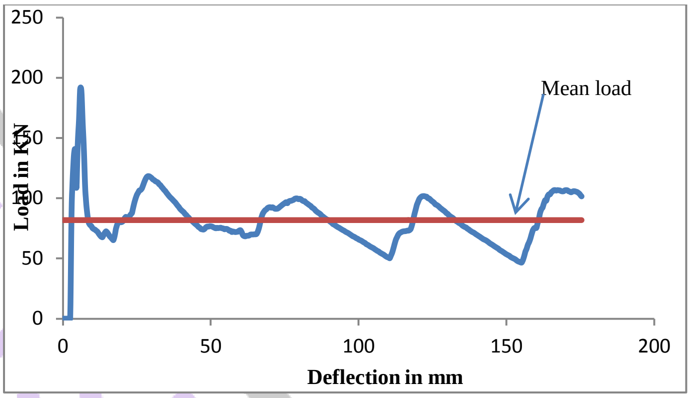


Figure 3: Load vs. Deflection curve of quasi-static analysis

2) Processing: The next step after preprocessing is processing and it is carried out using LS-DYNA software.

3) Post processing: The third step of analysis is post-processing. Various results are obtained from this post-processing step. Load vs. Deflection curve is one of the outputs as shown in Fig.3. From the data points load-deflection curve is obtained. Area under the curve is the energy absorbed by the tube which is determined using Microsoft Excel software. The energy absorbed by the tube under quasi-static impact loading is 14358.04 J, peak load is 191.996 KN, Mean load is 81.83 with the CFE=42.62%.It is observed that for quasi-static loading the tube gets deformed in regular pattern.

Comparison of Results: Analytical solution of square tube is validated with F.E.A. of rectangular tube and it gives reasonably good results. Table 1 indicates the comparison of analytical results and F.E.A. results of mean load values for quasi-static loading.

Table 1: Comparison of Mean Load Values

Type of Analysis	Mean Load		
Quasi-static	Analytical (for square tube) KN	F.E.A. (for rectangular tube) KN	Difference %
	77.65	81.83	4.18

IV. ENERGY ABSORPTION OF TUBE WITHOUT TRIGGERS

Model consists of two parts the tube and the rigid surface representing the crushing surface. The rectangular tube without triggers and the rigid plate is modeled with 2D shell elements. For dynamic Oblique loading both inertia effect and strain rate hardening effect is considered. The element size used is 5mm x 5 mm [6]. The tube is constrained at the bottom in all translational and rotational directions. For both the components, no. of integration points is used as 5 and Belytschko Tsay shell type of element is used. Mass of the plate is 125kgs. A coefficient of μ=0.1 is considered between rigid plate and tube also same value incorporates between the tube surfaces. The Rigid plate is given initial velocity of 15m/s in vertically downward direction of rectangular tube. The rigid plate is inclined at various loading angles from 0^o to 30^o in the steps of 5^o. Figure 4 shows model of tube without triggers with the impacting plane at the larger side of the tube. No. of Elements and No. of Nodes are 3757 and 3864 are generated.

From the data points obtained load deflection curves for tube without triggers for different loading angles is plotted as shown in the Fig. 5. It is observed that as the load angle increases the peak load decreases and at the end it remains constant. Deflection of the tube is restricted up to 70% of the total length of the tube. There is very large reduction in peak load from 0^o to 5^o.

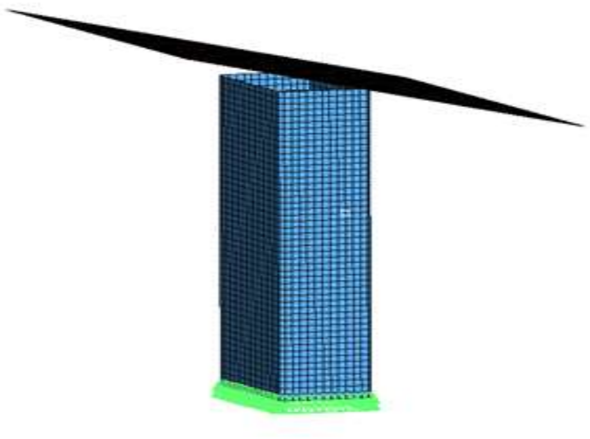


Figure 4: Model of tube without triggers

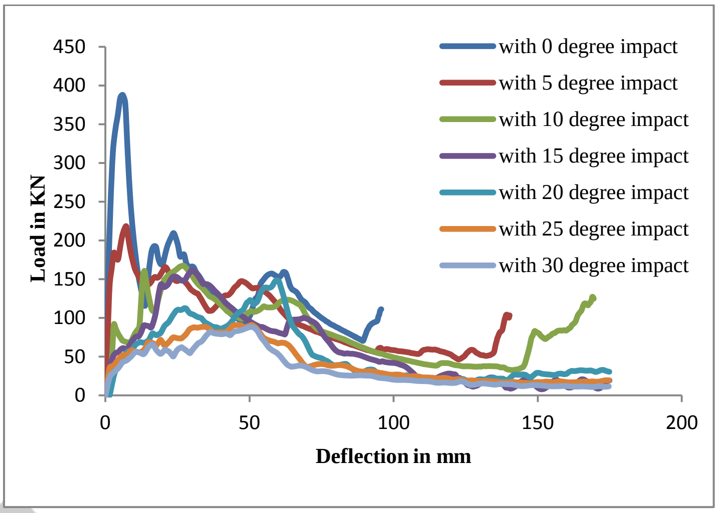


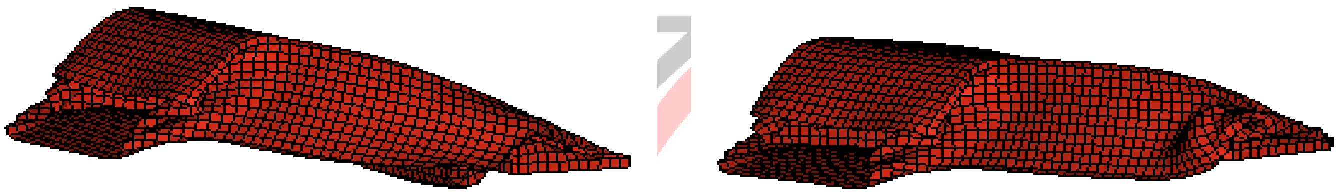
Figure 5: Load vs. Deflection curve for tube without triggers

The table 2 shows the results of tube without triggers for peak load, mean load, CFE at the various loading angles and its deflection in mm.

Table 2: Results of tube without triggers

Angle	Energy absorbed(J)	Mean load (KN)	Peak load (KN)	CFE (%)	Deflection (mm)
0^o	13940.97	145.64	387.92	37.54	95.72
5^o	14004.02	99.84	217.94	45.81	140.27
10^o	14052.39	82.93	167.57	49.49	169.44
15^o	10542.86	60.27	162.09	37.18	174.92
20^o	9374.173	53.61	148.33	36.14	174.85
25^o	7374.099	42.20	91.03	46.36	174.74
30^o	6069.41	34.75	88.17	39.14	174.67

Figure 6 shows the deformed shapes of the tube without triggers for 25^0 & 30^0 loading angle. Tube is not fully deformed due to strain rate hardening and inertia effect. It is observed that very less part of the tube is folded for higher angles of impact.



For 25° For 30°

Figure 6: Deformed Shapes of the tube without triggers for 25^o & 30^o

V. ENERGY ABSORPTION OF TUBE WITH TRIGGERS

Triggers or the weak areas are provided for the tube in order to make the progressive folding of the tube instead of global bending leading to increase of energy absorption of the tube. The dimensions and the material are same as for the tube without trigger. The tube with triggers and the rigid plate is modeled using 2D shell element. The element size is used as 5mm x 5mm [6]. No. of integration points is used as 5 and Belytschko Tsay shell type of element is used for both tube as well as plate. The tube is constrained at the bottom for both rotational as well as translational motion. Initial velocity is given as 15 m/s to the plate in vertically downward direction. Mass applied to the plate is 125 kg. Number of elements and nodes generated are 3715 and 3864 respectively. Figure 7 shows model of the tube with triggers.The position and location of the triggers for the tube is as shown in the Fig. 8.

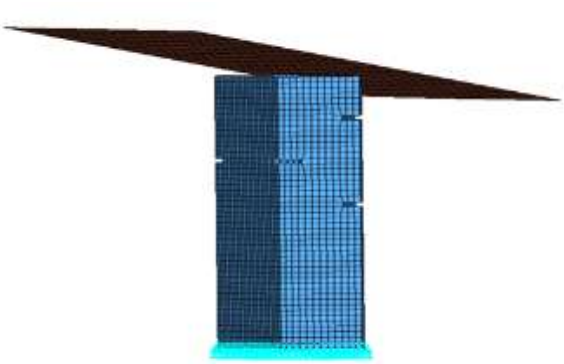


Figure 7: Model of the tube with triggers

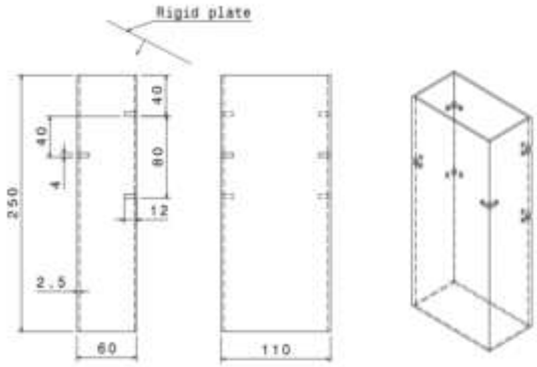


Figure 8: Position of the triggers in the model

From the data points obtained load deflection curves for different loading angles is plotted for the tube with triggers as shown in the Fig. 9.

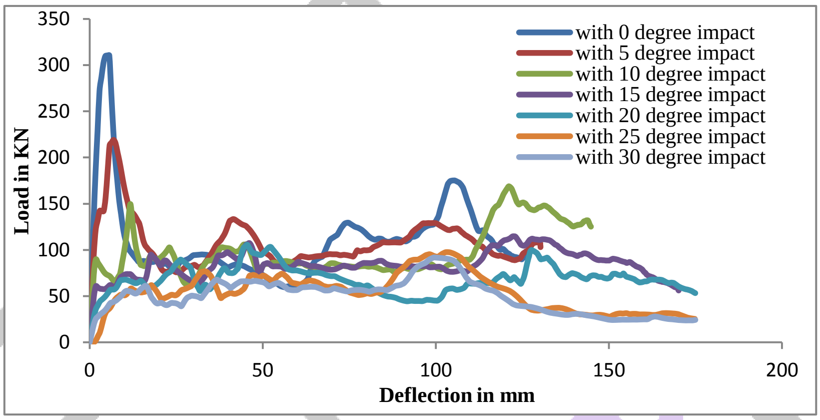


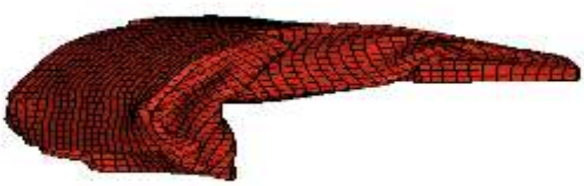
Figure 9: Load vs. Deflection curve for tube with triggers for various loading angles.

It is observed that as the load angle increases the peak load decreases and at the end for 25^o and 30^o it remains constant. Deflection of the tube is restricted up to 70% of the total length of the tube. There is very large reduction in peak load for increasing load angles. Table 3 shows the results of tube with triggers for peak load, mean load, CFE at the various loading angles and its deflection in mm.

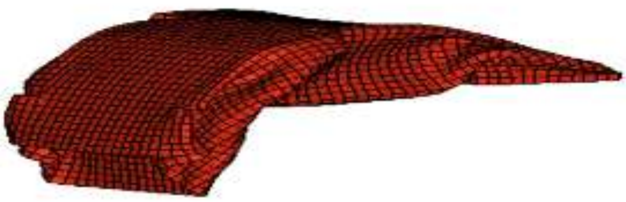
Table 3: Results of tube with triggers

Angle	Energy absorbed(J)	Mean load (KN)	Peak load (KN)	CFE (%)	Deflection (mm)
0^o	14000.04	110.33	310.46	35.53	126.89
5^o	14040.81	107.82	219.04	49.22	130.22
10^o	14158.19	97.78	149.68	65.32	144.79
15^o	14349.53	84.35	107.47	78.48	170.12
20^o	11947.01	68.29	105.65	64.64	174.93
25^o	9491.497	54.29	97.54	55.66	174.82
30^o	8735.867	49.93	91.88	54.34	174.95

Figure 10 shows the deformed shapes of the tube with triggers for 25^o & 30^o. It is observed that in deformed shapes of tube with triggers more portion of the tube is folded as compared with the tube without triggers leading to increase in energy absorption capacity of the tube.



For 25^o



For 30^o

Figure 10: Deformed Shapes of the tube with triggers for 25^o & 30^o

VI. COMPARISON OF ENERGY ABSORPTION BY TUBE WITH TRIGGERS AND WITHOUT TRIGGERS

Table 2 & 3 shows the results of tube without and with triggers. By comparing the mean load, peak load & CFE of tube without and with triggers we obtain the following conclusions.

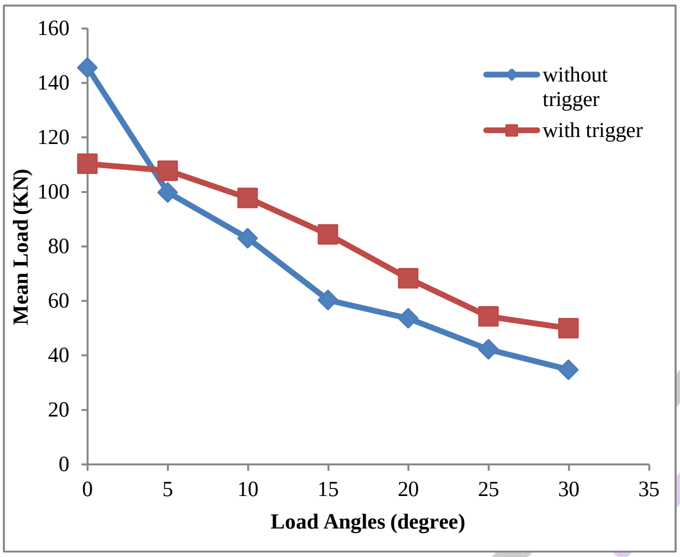


Figure 11: Mean load vs. Load angles for tube without and with triggers

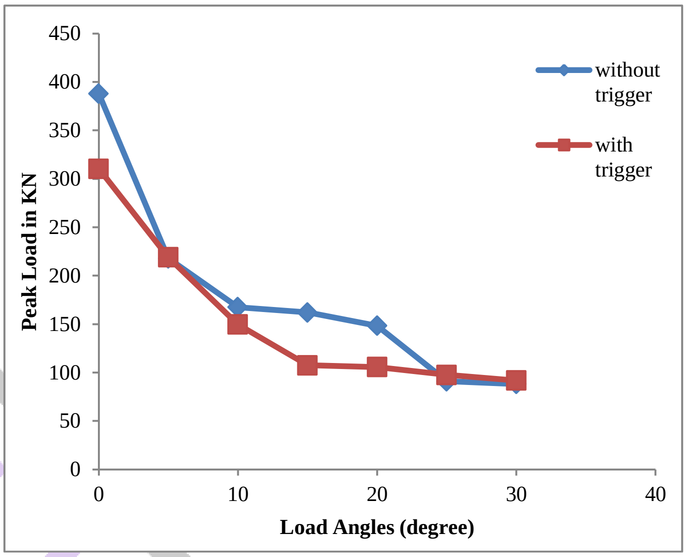


Figure 12: Peak load vs. Load angles for tube without and with triggers

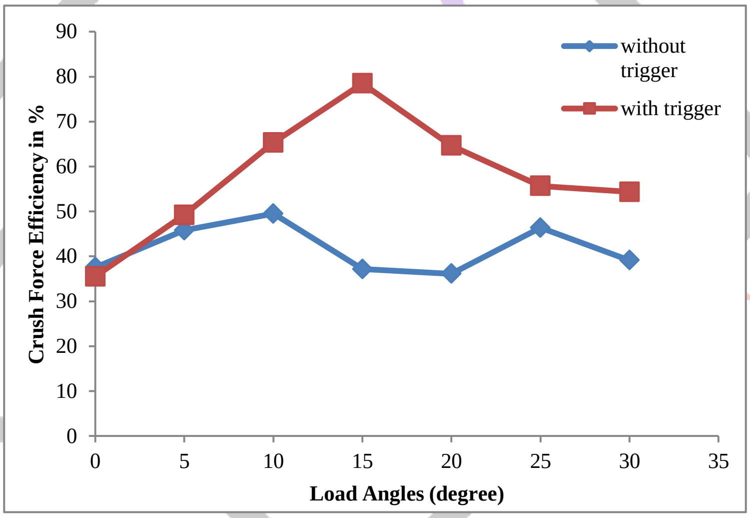


Figure 13: Crush Force Efficiency vs. Load angles for tube without and with triggers

Figure 11 shows mean load vs. load angles for tube without and with triggers and it is observed that for the tube without triggers the mean load decreases as load angle increases and there is more reduction in mean load at 5^o load angle. For the tube with triggers there is very little decrease in mean load at the start and there is reduction of peak load as compared to tube without triggers.

Figure 12 shows peak load vs. load angles for tube without and with triggers and it is observed that for the tube without triggers peak load decreases as loading angle increases and there is more reduction in peak load for 5^o loading angle. For the tube with triggers there is more decrease in peak load as compared to the tube without triggers and for tube with triggers at 15^o loading angle there is more reduction in peak load.

Figure 13 shows crush force efficiency vs. load angles for tube without and with triggers and it is observed that for the tube without triggers crush force efficiency is high for 10^o load angle and it is low at 0^o loading angle also it nearly remains constant between 15^o to 20^o loading angle. While for tube with triggers Crush force efficiency is high for 15^o load angle and it is low at 0^o loading angle also it nearly remains constant between 25^o to 30^o loading angle.

VII. CONCLUSIONS

- During Oblique loading energy absorption is less.
- By using triggers energy absorption can be increased during oblique loading.
- In case of axial impact loading, tube with triggers absorbs less energy as compared to tube without triggers.
- As angle of impact increases peak force decreases.
- Crush force efficiency increases or decreases because of different rate of decreasing mean load and peak load.

VIII. ACKNOWLEDGMENT

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