



# Behavior of Tubular Hat Structure Under Three Point Bending

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**Abstract:** The paper focuses on the energy absorption capacity of structural materials, the most important in frame design, the structure of the vehicles, scaffolding. Main content include new solution with comparing the general structure cylinder, square tube, top-hat and reverse top-hat. After that, considering and comparing displacement, force in the transformation process and find out the rule of energy that be also the core value of research, a new method to observe these processes.

**Keywords:** Top-Hat, Mean Force, Behavior of Structure

## 1. Introduction

Applications and research results of LS-DYNA software [10] in crashworthiness parts. The term “structural crashworthiness” is used to describe an investigation into the impact performance of a structure when it collides with another object. This type of study is required in order to calculate the forces during a collision, which needed to assess the damage of structures and the survivability of passengers in vehicles, for example. An important aspect of crashworthiness studies deals with impact energy absorption since the main purpose of vehicle crashworthiness is the dissipation of energy in specially designed zones while maintaining a survival space for passengers in stiff zones. Several important technologies have been studied [1-9] to improve the crashworthiness of structures.

This paper focus on bending tubular section which use in car's frame, structures in contractions by using analytical and numerical methods to consider horizontal collision failure shown in Figure 1.

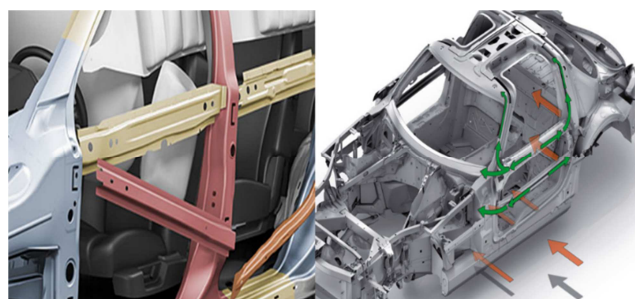


Figure 1. The structures of car frames.

## 2. Theoretical Background

### A. Bending strength

For a rectangular tube in the bending test, bending strength is the highest stress at crashing point. Cross-section of deformation model created moving of hinge lines. This collapse happens when the specimen is bended before it is ruptured like Figure 2.

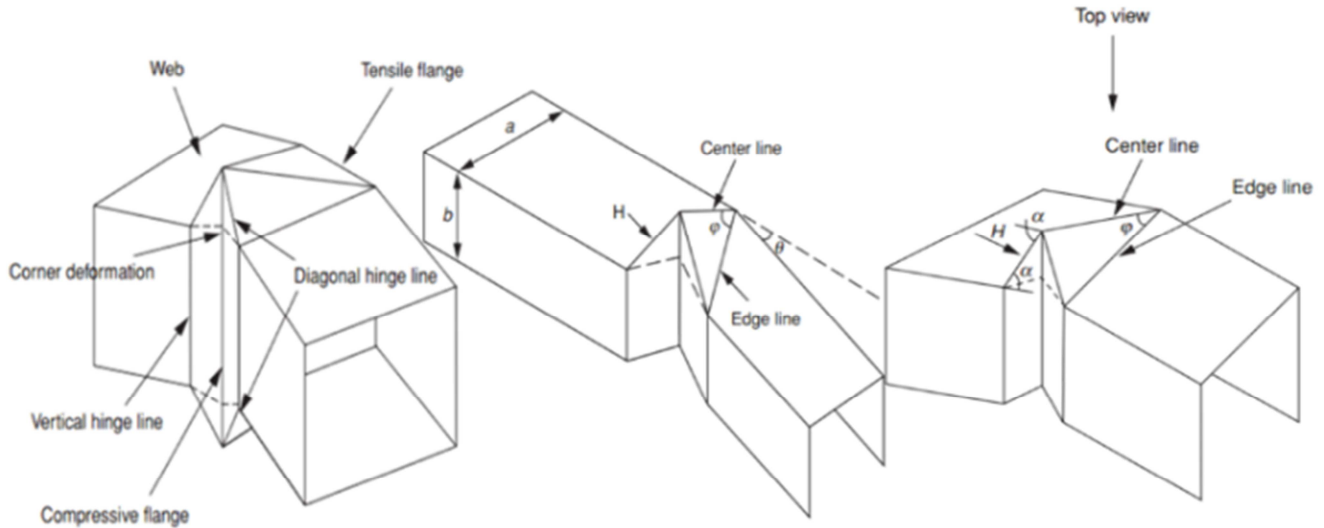


Figure 2. Bending collapse of rectangular and square section tubes [1].

Thus giving the calculated angle equation that depends on displacement  $\delta$  and compressive flange  $2H$ :

$$tg\left(\frac{\theta}{2}\right) = \frac{1}{a}\left(\frac{\delta}{2}\right) = \frac{H(1-\cos\alpha)}{a} \quad (1)$$

The theoretical solution of Y.C Liu and M.L. Day [4] for square tube subjected to bending.

- Mean crushing force

$$P_m = M_0 \left( 4.64 \frac{r}{t} + 2.3 \frac{H}{r} + \frac{3\pi b}{2H} + \frac{\pi^2}{8} \right) \quad (2)$$

- Instantaneous crushing force

$$P(\alpha) = P_m \left( 0.58 + \frac{1}{2\alpha} \right) \quad (3)$$

The value of the compressive flange is  $2H$  and an equivalent value of mean crushing force is:

$$P_m(2H) = \int_0^{2H} P d\delta \quad (4)$$

- Bending resistance moment

$$M(\theta) = P b = b P_m \left( 0.58 + \frac{1}{2\sqrt{\theta}} \left( \frac{H}{b} \right)^{\frac{1}{2}} \right) \quad (5)$$

### B. Material, geometry and meshing

In this study, the wall column material is mild steel RSt37 which was used by S.P. Santosa et al in the studies [7, 8] about foam-filled thin-walled column with mechanical properties: Young's modulus = 200 GPa, initial yield stress  $\sigma_y = 251 \text{ MPa}$ , ultimate stress  $\sigma_u = 339 \text{ MPa}$ , Poisson's ratio  $\nu = 0.3$ , density  $\rho = 7830 \text{ kg/m}^3$ , the power law exponent  $n = 0.12$ . The empirical Cowper-Symonds constants uniaxial constitutive equation  $D = 6844 \text{ s}^{-1}$  and  $p = 3.91$ . The type of material model used to simulate mild steel is Type 24 MAT PIECEWISE LINEAR PLASTICITY, an elasto-plastic material with an arbitrary stress versus strain curve and arbitrary strain rate dependency. The true stress – effective plastic strain curve of

RSt37 steel was verified, the material model used for indenter is Type 20 RIGID with Young's modulus  $E = 200 \text{ GPa}$  and Poisson's ratio  $\nu = 0.3$ .

Square tube in three-point bending was simulated in Santosa's test with the cross section. Similar for the top-hat dimension  $a = 50 \text{ mm}$ ,  $b = 50 \text{ mm}$ ,  $t = 1.5 \text{ mm}$ ,  $L = 460 \text{ mm}$  are given in Figure 3.

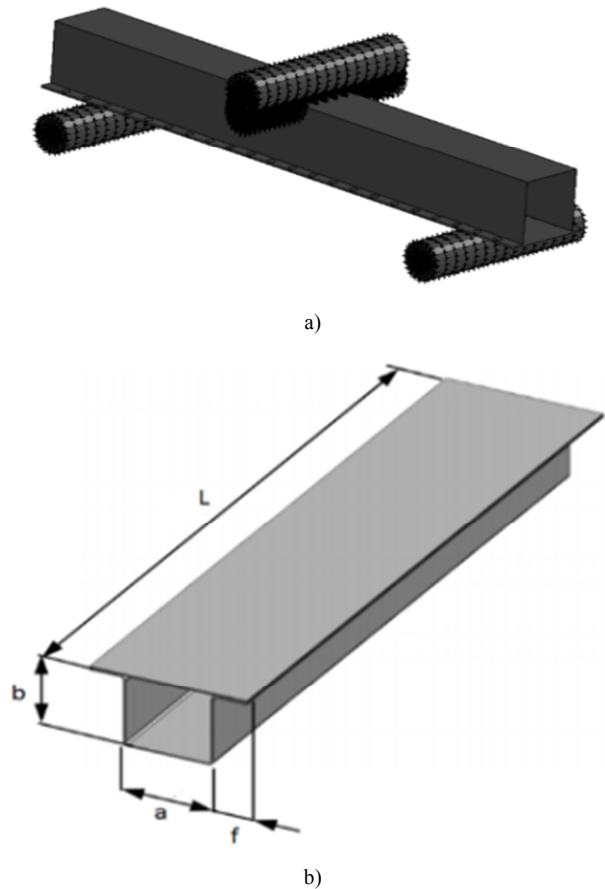


Figure 3. Forward top-hat (a) and reverse top-hat (b) with a same dimension.

The indenter is bounded just allowed to move down in z-axis by setting constraint condition in the translation x, y and the rotation in x, y, z axis. Then, with two supports are imperturbable in the translation / rotation along x, y and z-axis. In addition, the velocity profile constant in 4 m/s when starting bending to the first 50 milliseconds.

In top-hat section, between the flange of the hat section and a plate closing behind, there are many constraint spot-weld, set to make the bond of two structure.

The interaction between shell elements of square tube section and each surface segments of indenter and supports is AUTOMATIC \_ SURFACE \_ TO \_ SURFACE for all surface boundary conditions. In this keyword, “slave ID” is the square tube and the solid cylinders with “master ID” with Coulomb friction coefficients from 0.0 to 0.2 for non-lubricating on experimental surface. This is the friction coefficients (0.3) between the indenter and square tube.

Finally, the AUTOMATIC \_ SINGLE \_ SURFACE was set to simulate “self-contact” of the tube during impact. Because it prevents the elements of the tube passing through the specimen surface during collapse with the automatic re-orientation of the shell element.

However, with top-hat, impact between surfaces of indenter and top-hat section is AUTOMATIC \_ SURFACE \_ TO \_ SURFACE \_ SMOOTH to be sure that it gets more smooth and exactly than original model.

### C. Model verification

The numerical results of specimen analyzed are pressure, stress-strain curve. According to Kamaya Masayuki 's study [11], we can compare with the experimental test from simulation results of author:

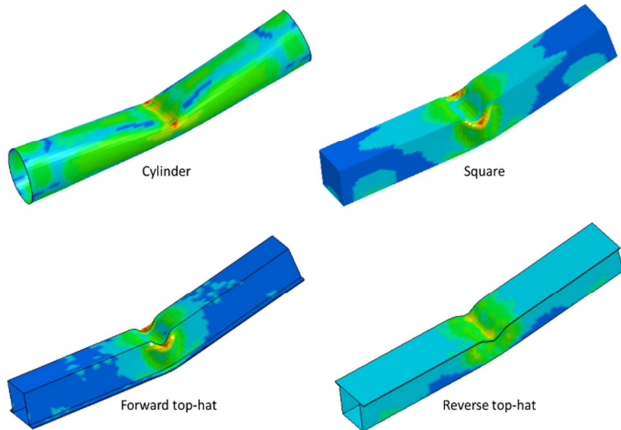


Figure 4. The pressure distribution.

Stress-strain graph of models same the perimeter is divided into two columns for comparison. In general, these curves have the same trend and coincide with materials cures of the manufacturer's offer. Almost these curve give the same value yield stress so enough material properties in computational

models are similar to the real sample that start the simulation.

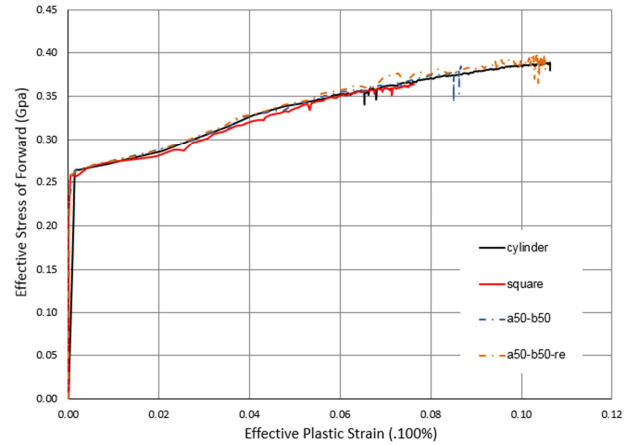


Figure 5. Stress-strain in simulation.

## 3. Results

### A. Displacement and deformation

Shows the differences of geometry to offer behavior of material in displacement between nodes and instantaneous force, also comparing forward top-hat to reverse top-hat. We survey three point: the canter of indenter, one node at the top and one node at the bottom of tube to determine how their differences to comparing the influence of crashing force on structure. The node 1 is almost different from node 2, especially the canter of indenter like Figure 6.

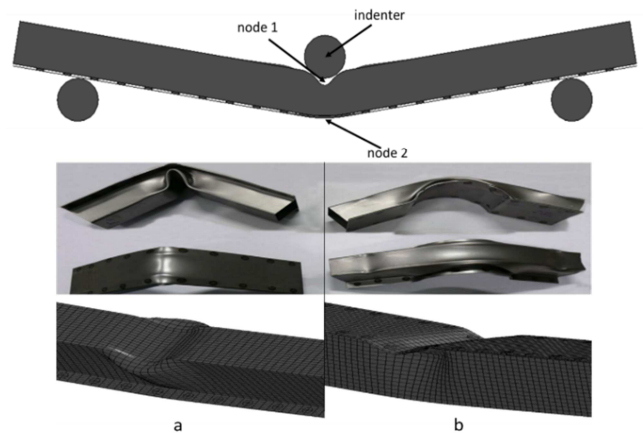


Figure 6. The selected points, the folds of forward top-hat (a), reverse top-hat (b) in fact and in simulation.

Considering two nodes: top and bottom of tube with indenter, these models are mutual compared to review differences.

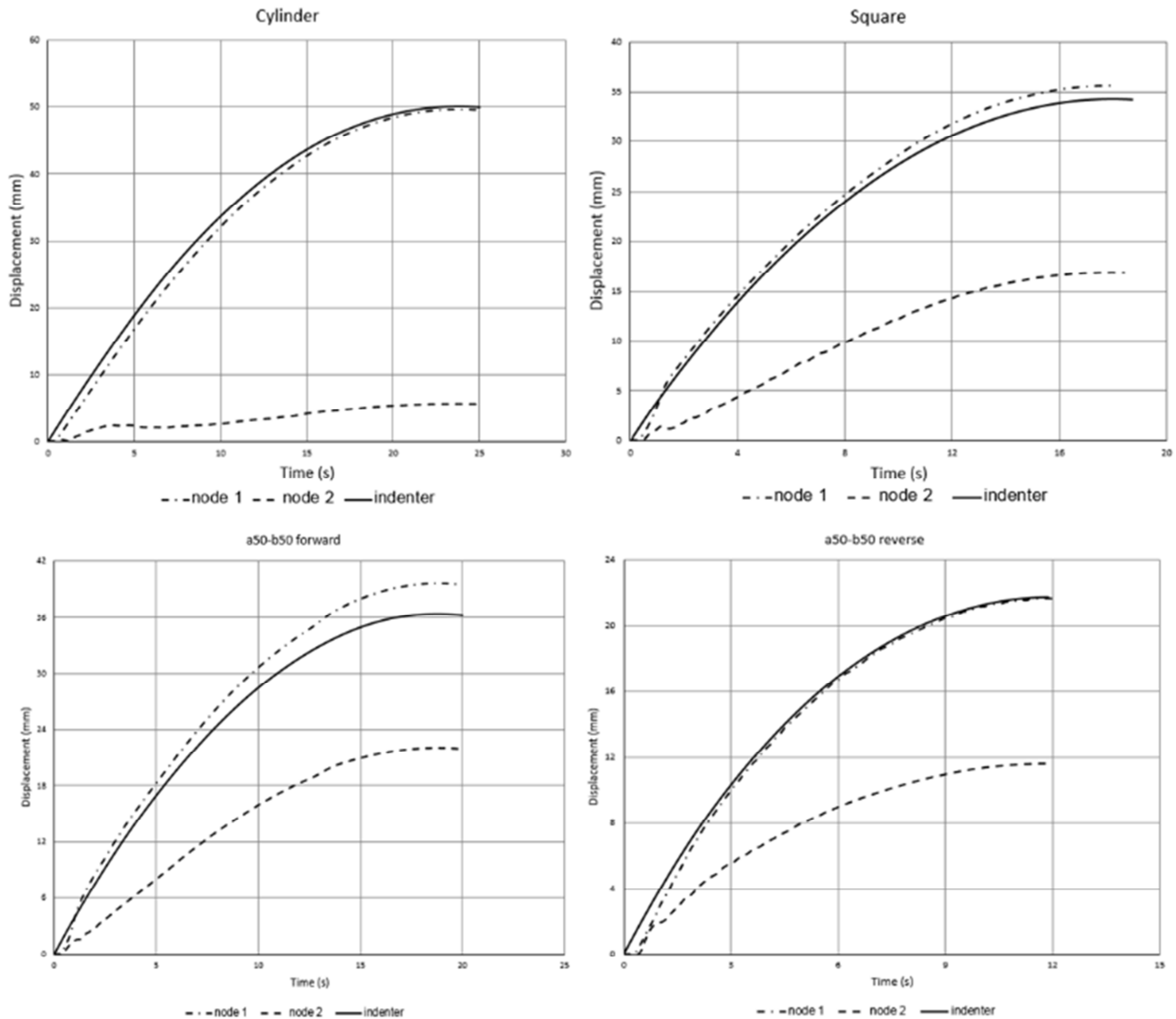


Figure 7. Displacement of cylinder; square tube, forward top-hat and reverse top-hat.

The cylinder tube get the highest displacement at node 1 while the other move more little. With a structure like that, although the bottom side decide to the destruction behind that, especially car frame, but it is just a bit of displacement that is not worry, meanwhile the top surface is hardly destroyed that also deform the surface associated with other structure like car door → cylinder tube is the weakest.

For easy to observer differences, the forward top-hat and square tube are more displacement than indenter, made a space between indenter and top surface of them. In the model a50-b50 reverse, displacement of three point that are lower than the others.

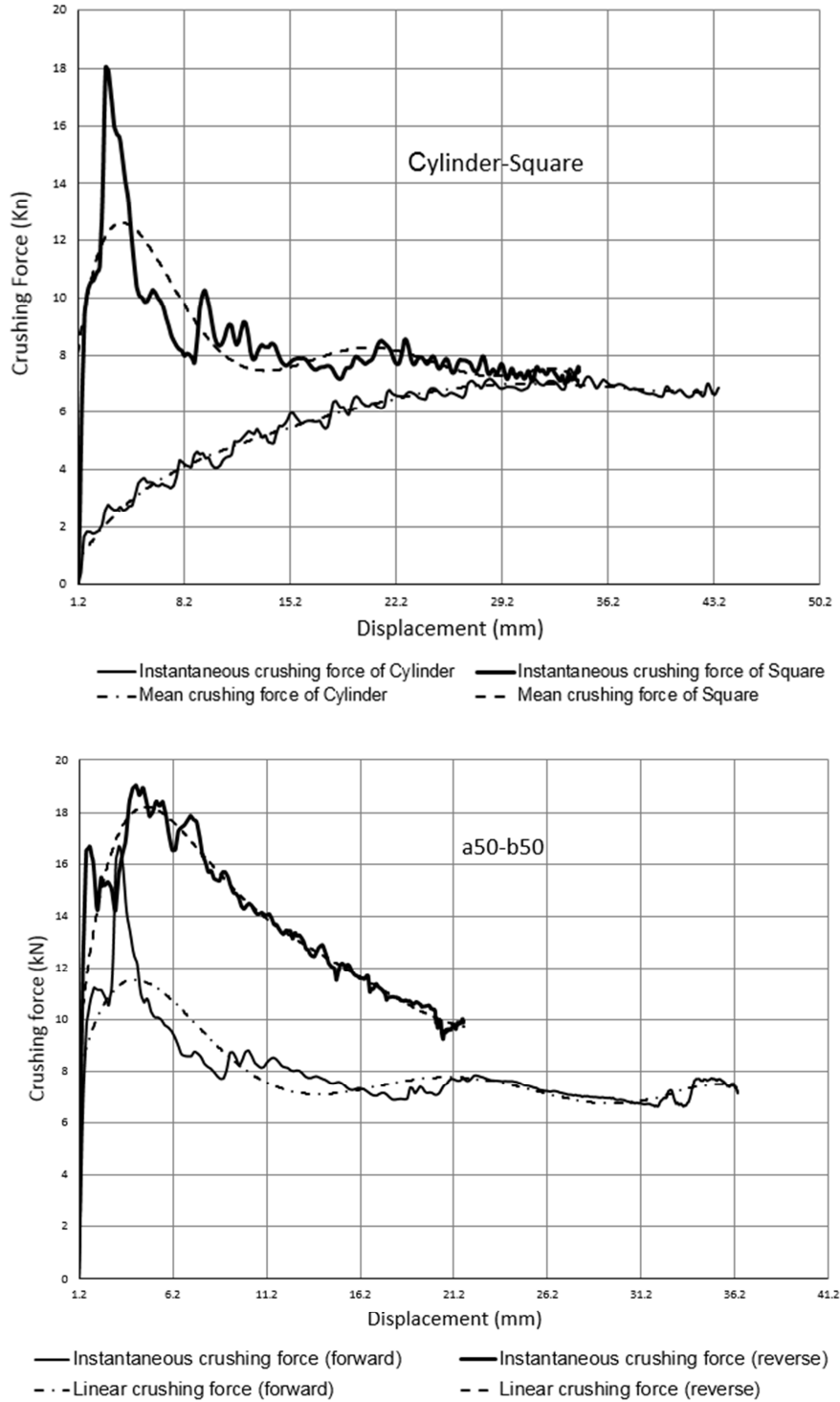
### B. Force and mean crushing force

In fact, there is just a few papers presenting an overview comparison between the shapes of the section of tube, for

example square, cylinder, top-hat, double-hat. Because the collapse ability of each structure are not same. I consider the instantaneous force on the models affecting displacement and deforming in Figure 8.

Since the collision, the results with the cylinder tube can be predicted, beginning from curved surfaces; it is also original folds so do not have any obstacle during destructive process. Instead, square tube, forward top-hat and reverse top-hat lose a large portion of energy to form fold, the curve results is instability especially the first period of the collision.

From Figure 8, instantaneous force impact on reverse top-hat is always higher than forward top-hat and square tube. Next part, we need find out the value of force to finally confirm that reverse top-hat is the best model for this project.



**Figure 8.** Crushing force-displacement diagram of indenter with difference in cylinder and square tube, forward and reverse top-hat.

The initial crushing force gradually increase from cylinder, square, dimension of top-hat, especially reverse top-hat. I must consider the values of mean crushing force, one of the most important factors to determine the effectiveness of structures, the average force throughout models that calculated by theoretical formula:

$$P_m = \int_0^\delta P d\delta \quad (6)$$

**Table 1.** Mean crushing force of models.

| numbers | dimensions | mean force (kN) |
|---------|------------|-----------------|
| 1       | Cylinder   | 4.803           |
| 2       | Square     | 8.270           |
| 3       | a50-b50    | 7.784           |
| 4       | a50-b50-re | 13.007          |

Figure 9 showed behavior of material strength following equations. Comparing with respective model, all of reverse

top-hats are stiffer than forward top-hat. The strong solid line is higher mean crushing force that is reverse top-hat at 13 kN, the minimum point at cylinder (4.8 kN). Then, reverse top-hat offered get more advantage than forward top-hat, we choice it to research behavior of bending collapse when have change in dimension.

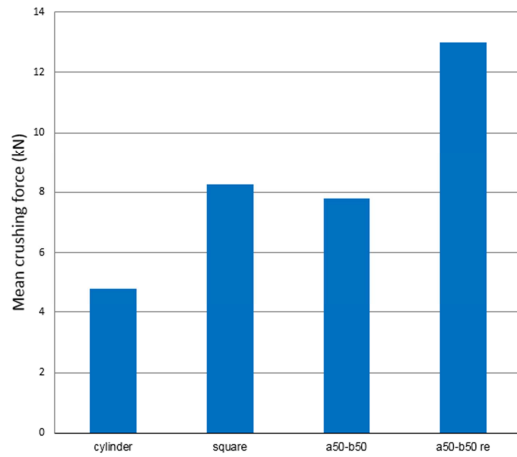


Figure 9. Mean force corresponding to tubes of geometries.

The reverse top-hat model have symmetric dimension, the value reaches the maximum mean crushing force, so we will get it to survey its energy absorption.

Energy exchange process and energy absorption-loss off energy

In zero gravity environment, original energy be transformed from the kinetic of indenter to the internal energy inside tube, almost focus in folds on sheets as top sheet and side sheets, show in Figure 10 (model a50-b50 is chosen when obtained the best results such as displacement, crushing force.).

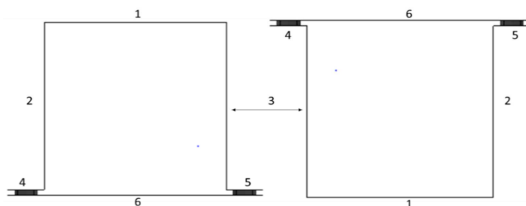


Figure 10. The sreial of sheets in forward model (left) and reverse model (right).

Table 2. Kinetic transformed into internal.

| numbers of sheets | Forward top-hat      |                     |
|-------------------|----------------------|---------------------|
|                   | Internal energy (kJ) | Kinetic energy (kJ) |
| 1                 | 61.911               | 0.441               |
| 2                 | 100.1                | 0.45                |
| 3                 | 100.1                | 0.45                |
| 4                 | 1.246                | 0.068               |
| 5                 | 1.2788               | 0.069               |
| 6                 | 5.512                | 0.481               |
| Total             | 270.1478             | 1.959               |
| Total energy      | 272.1068             |                     |
| Indenter          | 0                    | 283.68              |

Table 3. Kinetic transformed into internal.(cont.)

| numbers of sheets | Reverse top-hat      |                     |
|-------------------|----------------------|---------------------|
|                   | Internal energy (kJ) | Kinetic energy (kJ) |
| 1                 | 24.559               | 0.972               |
| 2                 | 75.504               | 1.289               |
| 3                 | 75.6                 | 1.228               |
| 4                 | 16.401               | 0.177               |
| 5                 | 16.509               | 0.18                |
| 6                 | 51.222               | 1.459               |
| Total             | 259.795              | 5.305               |
| Total energy      | 265.1                |                     |
| Indenter          | 0                    | 283.68              |

The first, simulation model only exist velocity of indenter, the tube and two support same as a free system. When indenter impact to tube, its kinetic energy transforms to tube until it completely stop, the tube also exist internal energy and get the maximum value at stop point.

The second, after the stop point, the tube and indenter is bounced back. Because this is a free system, so have a part of elements in period of plastic stress, it releases energy to return stabilization.

Two flange only have feature that kept constant itself and with surrounding structures.

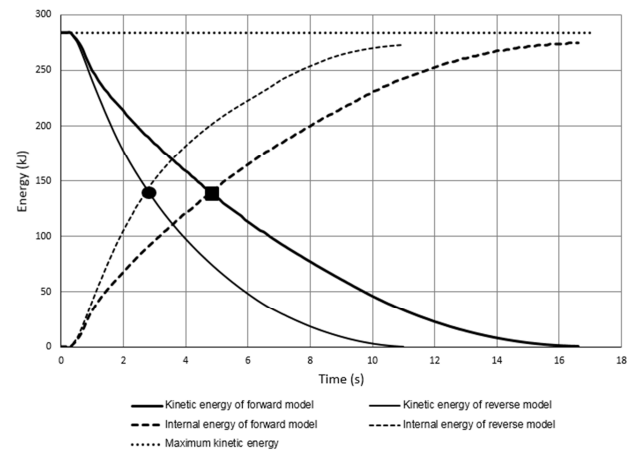


Figure 11. The energy metabolism of forward and reverse top-hat model.

In Figure 11, reverse model need a shorter period to get energy change process than forward model with a cross point at the same energy (140 kJ) and end point of internal energy about 270 kJ. It is so important to determine which more efficient model is. Imagining when the collision, a good energy absorbing structure quickly stop destruction, do not have any the next damage because all of external energy transformed into internal energy of tube. Opposite, in a short time, a model is not absorbed enough external energy, the remaining energy will affect, impact on other part of structure, destroying things around, so it is not worth for a absorption structure.

Maximum internal of two model are a bit of lower than maximum kinetic energy from indenter. According to speculation, some of the energy are transformed into thermal energy by friction between indenter and top surface of tube, the remainder exists as potential energy transform into



kinetic energy at the stop point, creating the elastic force rebound indenter and tube from two supports like Figure 6.

## 4. Conclusion

Simulation models in LS-DYNA achieve high accuracy value, data is verified on bending same as materials properties such as yield stress, ultimate stress, stress-strain curve, young's modulus. Many graphs show displacement, instantaneous force, mean crushing force, the absorbing energy ability of cylinder, square tube and top-hat, therefore, mutual comparing and the results offer the most optimal that is reverse top-hat model a40-b60, it gets the highest mean force and absorption. Offering a new researching method by energy transformation process.

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## Nomenclature

- $a$ : Width of the compression flange or section width  
 $b$ : Depth of the beam cross section or section depth  
 $D$ : Perimeter  
 $E$ : Young's modulus  
 $h$ : Half of the hinge length  
 $H$ : Half – wave length of a folding wave  
 $M_0$ : Moment bending per unit on the perimeter  
 $M_p$ : Fully plastic moment of a section  
 $m_p$ : Fully plastic moment of a unit width of a section wall  
 $P$ : Instantaneous crushing force  
 $P_m$ : Mean crushing force  
 $t$ : Wall thickness

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## Biography



**Hung Anh LY** is a Lecturer in the Department of Aerospace Engineering – Faculty of Transport Engineering at Ho Chi Minh City University of Technology (HCMUT). He received his BEng in Aerospace Engineering from HCMUT in 2005, his MEng in Aeronautics and Astronautics Engineering from Bandung Institute of Technology - Indonesia (ITB) in 2007 and his DEng in Mechanical and Control Engineering from Tokyo Institute of Technology – Japan (Tokyo Tech) in 2012. He stayed at ITB and Tokyo Tech for one month as a researcher in 2012 and 2013. He is a member of the New Car Assessment Program for Southeast Asia (ASEAN NCAP). His main research interests include strength of structure analysis, impact energy absorbing structures and materials.



**Duy Hien Le** was graduated from the Department of Aerospace Engineering, Faculty of Transportation Engineering, Ho Chi Minh City University of Technology (HCMUT), Vietnam. He also received the Bachelor's degree in Aerospace Engineering from HCMUT in April, 2016. His research interests include the areas of structural

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This is the final project that he join from the university under the supervision of Dr. Hung Anh Ly.