Energy absorption, deformation and crushing behavior of bi-metallic tubes with different cross-sectional shapes under axial loading

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Abstract- Thin walled tubes because of their lightweight, economic manufacturing and efficient energy absorption characteristics are widely used in safety applications contemporaneously many researchers have investigated the behavior of thin-walled metallic tubes with the different cross section under identical test conditions for assessing its effectiveness in crashworthiness. This paper presents the deformation and energy absorption characteristics of bi-tubular tubes along with several different cross-sectional shapes whose base was set as the boundary condition whereas in reference to the axis of the tubes the load was applied at the opposite end with the help of a rigid wall. The analogy of double-walled tubes with different cross-section alters the deformation modes substantially and resulted in significant increase in the energy absorption capacity over bi- metallic tubes as an effect of stress wave propagation. The overall results divulge that the proposed geometry can be a good alternative due to stabilized deformation mode in safety applications such as a locomotive, automotive industries.

Keyword: Bi-metallic tubes; crashworthiness; cross-section; energy absorption

1. Introduction

The preferment in technology has led to automobiles being able to hit the 300mph milestone with ease contemporaneously increasing the probability of casualty. Keeping in mind for the occupant safety in recent decades a lot of research has been done to improve the crashworthiness characteristics of structures. Hollow tubes are the conventional tubes for energy absorption systems under various loading conditions. Quasi-static axial loading is preferred for finding the effectiveness of any structure. One of the methods of improving the crushing behavior of metallic tubes is by changing their cross-section as energy absorption of bodies depends on their shapes. It is not always preferable to increase the amount of energy absorbed rather a reduction in peak force is also desired for the safety of both the occupant and vehicles. The rendition of the tubular structure is exclusively dependent on either material or the cross-sectional shape. The behavior of metallic tubes under axial loading with different cross-sectional shapes such as circular, rectangular, multi-corner metal columns, hexagonal, polygonal and star-shaped had been studied both theoretically and experimentally for finding the behavior in terms of peak forces modes of buckling and energy absorbing characteristics [1-2]. Z. Fan concluded both experimentally and theoretically that the value of peak force changes accordingly with the variation in a number of corners [3]. Previous research shows that introduction of corrugation perpendicular to the axis of tube results in significant increase in buckling load along with the energy absorption capacity and crushing force efficiency [4-6]. It was also found that the crushing behavior can be stabilized by combining the geometries of the tubular structures [7]. Goel MD compared the behavior of concentric bi-tubular and tri-tubular empty and foam filled deformations in terms of deformation modes and energy absorptions. It was found that bi-tubular and tri -tubular structure was far ahead in terms of energy absorption and crushing behavior pattern [8]. In this research, the effectiveness of the bi-tubular structures under quasi-static axial loading in terms of energy absorption and peak force with different cross-sections, namely circular, rectangular, square, hexagonal and octagonal shapes is presented. The analysis is simulated using non-linear finite element analysis

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Nomenclature

C	Circular	E	Octagonal
S	Square	N	None
R	Rectangular	O	Outer periphery
H	Hexagonal	I	Inner periphery

software ABAQUS/Explicit. A comparative analysis is carried out to demonstrate the optimal design of bi tubular structures with different cross-sectional shapes.

2. Numerical modeling

2.1 Material model

Low carbon steel ASTM A36 and aluminum alloy AA6060 were used for modeling single, bi-walled tubes. The material properties for A36 steel were taken from the tensile test data performed by Z. Fan et al [3] whilst aluminum properties are taken from the experimental testing data provided by Kumar AP et al [7].

Table 1. Parameters for A36 steel and AA6060 alloy.

Specimen	Density (kg/m^3)	E (GPa)	Poisson's Ratio
ASTM A36	7800	210	0.3
AA6060 T4	2700	71	0.33

2.2 Finite element model

The finite element simulation was carried out using ABAQUS/Explicit non-linear element code. The C3D8R element was used to model the tubes whilst the two restraining rigid plates were modeled using a 4 -node 3-D bilinear rigid quadrilateral elements. A total of ten tubular configurations were modeled with single and bi-tubular structures with different cross-sectional shapes combinations were simulated. Primarily the outer tube was kept as circular and diversification was racked up by altering the inner tube and then the antipodal profiles were made by keeping the inner tube circular and varying outer tubular cross section. Throughout the simulation, in all the alteration the mesh size was kept constant. All degree of freedom of the bottom plate was fixed. Quasi-static axial displacement was given to the upper plate to crush the tubes to half of its length. All the analysis was performed by keeping the step time stable at 70 ms. For simulating the contact interaction between the bi-metallic tubes and the two plates general contact algorithm was used with a coefficient of friction of value 0.2.

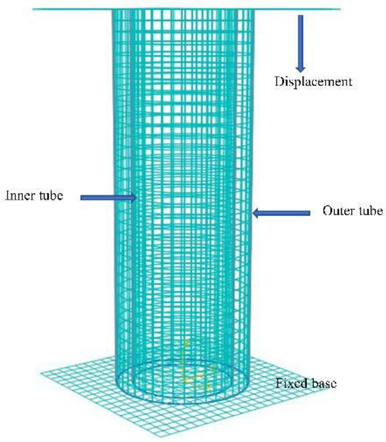
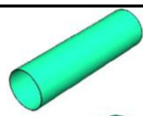
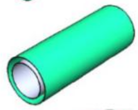
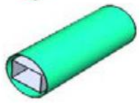
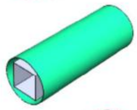
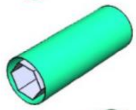
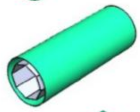
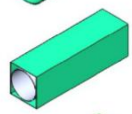
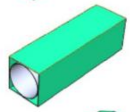
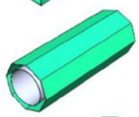
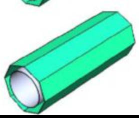


Figure 1 Finite element model of specimen COCI

Table 2. Dimensions and profile of tubes under study.

	Perimeter(mm)		Length	ThickNess(mm)		
Specimen ID	Outer tube	Inner tube	(mm)	Outer tube	Inner tube	Profile
CONI	400	-	350	1	-	
COCI	400	300	350	1.00	1.00	
CORI	400	300	350	1.00	1.00	
COSI	400	300	350	1.00	1.00	
COHI	400	300	350	1.00	1.00	
COEI	400	300	350	1.00	1.00	
ROCI	400	300	350	1.00	1.00	
SOCI	400	300	350	1.00	1.00	
HOCI	400	300	350	1.00	1.00	
EOCI	400	300	350	1.00	1.00	

3. Results and discussion

3.1 CONI:

In the specimen testing of the CONI model, The values recorded were the lowest as compared to any other geometry probably because of the fact that it is a single-celledthin-walledmember while the other specimens were multi-walled. Due to their multi-wallednature, they have shown appreciable results in terms of the testing parameters. The peak force was recorded at about 10 mm deformation with a value of 104.706 kN.The average crush force was found to be at 56.030 kN and the energy absorbed was about 11.765 kJ, which was least among all the geometries.

3.2 COCI:

The COCI specimen performed much better than the simple circular tube model and showed a 28.28% increase in the value of Peak force which was found around 125mm of deformation. The value of peak force was recorded to be about 134.916 kN. A similar rising trend was found in case of the values of average crushing force and energy absorbed values which were found to be 79.109 kN and 16.611 kJ respectively. The energy absorption capacity increased by about 1.4 times when compared to the CONI model.

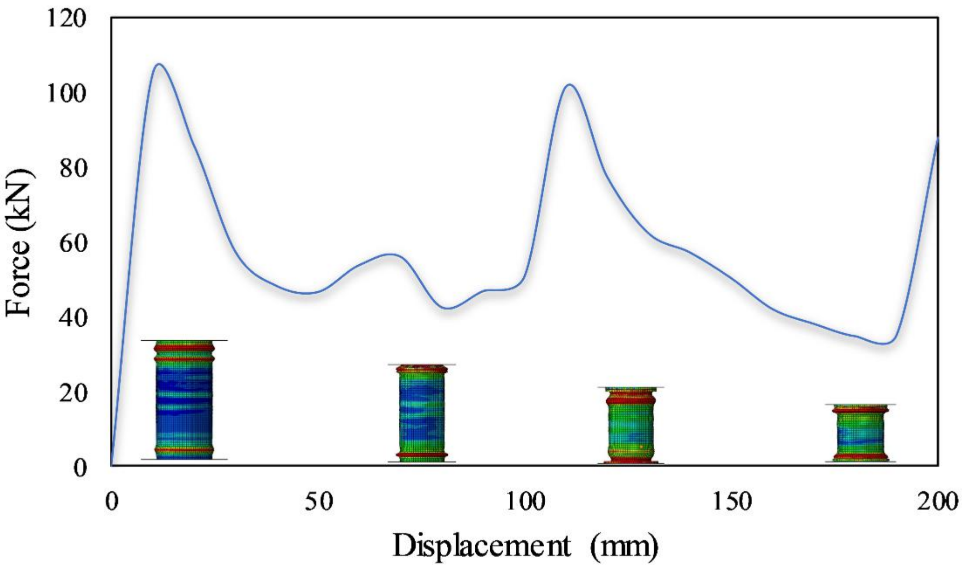


Figure 2. Force vs. displacement curve for specimen CONI

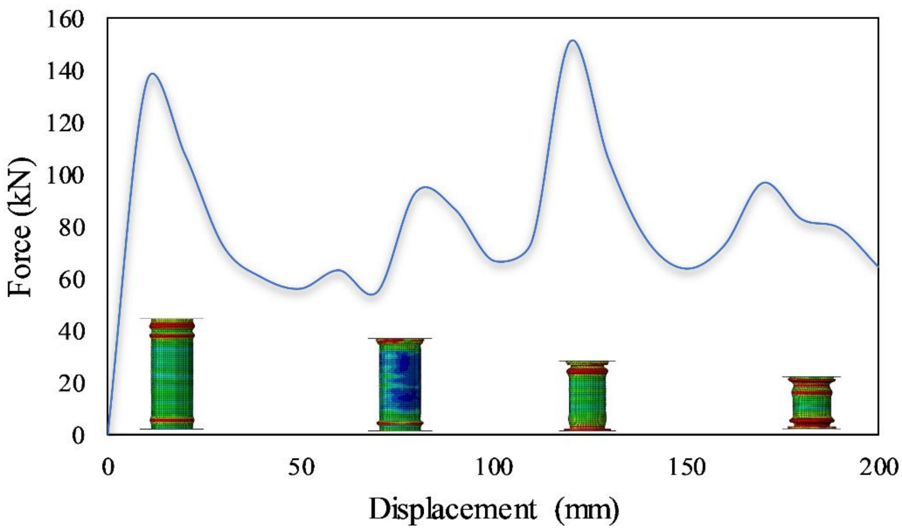


Figure 3. Force vs. displacement curve for specimen COCI

3.3CORI:

The results of the CORI and COCI models were quite similar and comparable but in referenceto CONI models, there was a remarkable difference. The CORI models gave better results for the average crush values and the and energy absorbed values than the COCI models while the value of peak force decline negligibly when compared to the COCI section. The energy absorbed values were about 1.45 times the energy absorbed values in the CONI models also this value of 17.170 kJ was the highest among the specimens having a circle as the outer shell. The value of average crush force was about 81.77 kN. The value of peak force was recorded after 110 mm of deformation.

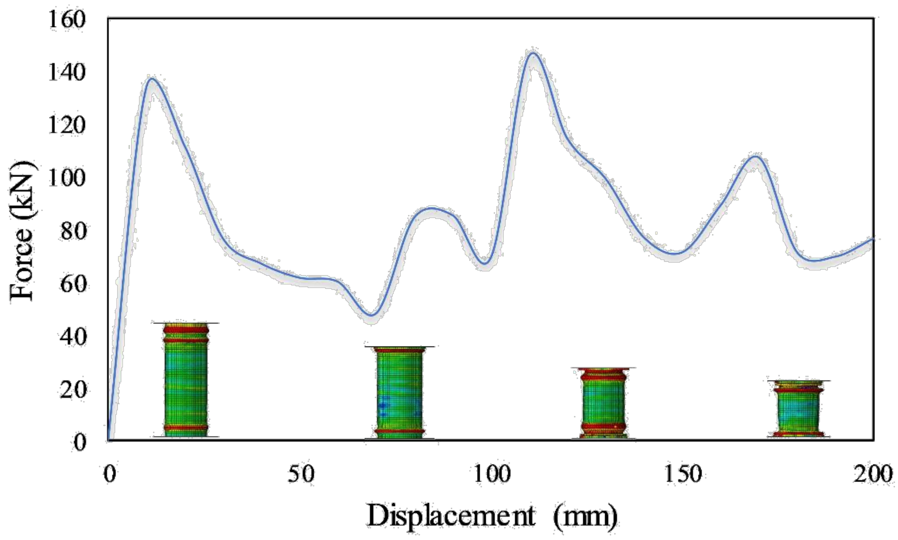


Figure 4.Force vs. displacement curve for specimen CORI

3.4*COSI*:

The CORI and the COSI models were quite contemporary in their performances the values of the Peak force, average crush force and energy absorbed of the above mention model were having hardly a difference of 0.16%. Thus, it can be said that the results obtained by the variation of inner wall as rectangle and square revealed similar results. But In accordance with the CONI models, the peak force increased by about 27.90% having a value of 133.921 kN. The values of average crush force and the energy absorbed also got increased in similar proportion.

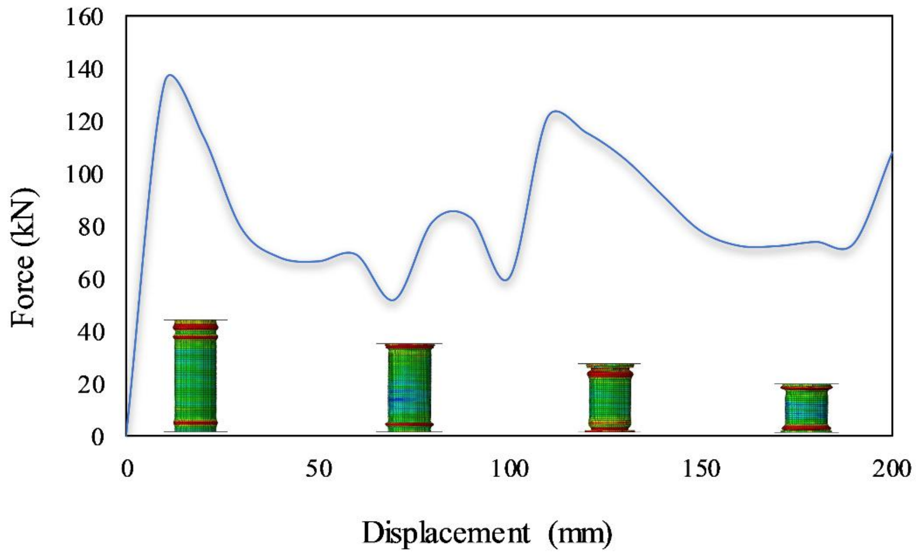


Figure 5. Force vs. displacement curve *for specimen COSI*

3.5*COHI*:

Among all the models that had the circular section at the outer core the value of peak force was highest for the COHI model and showed a 1.30-fold increase in comparison to CONI model. But the values of average crush force and the energy absorbed were lower when compared to the CORI, COSI and COCI models. The value of average crush force was noted as 78.170 kN, and similarly, the value of energy absorbed was found to be 16.414 kJ. The value of peak force was found to be around 120mm of deformation of the model.

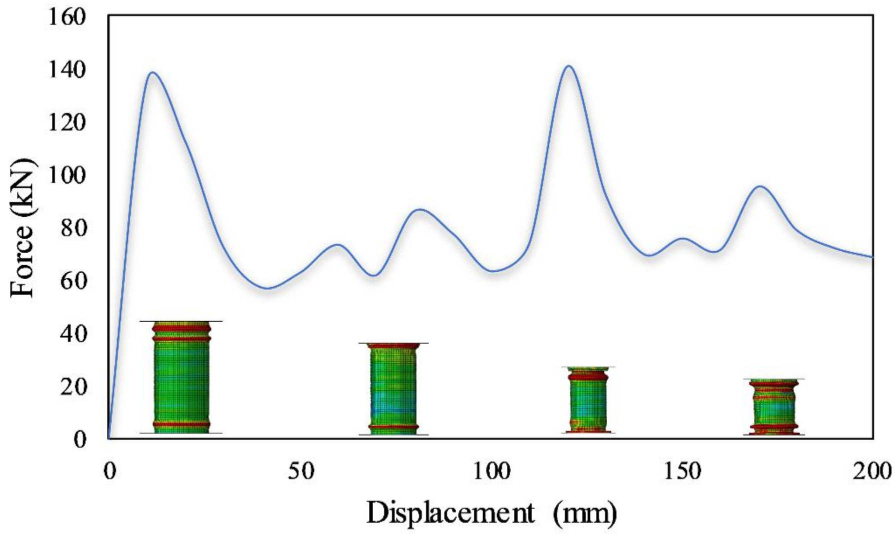


Figure 6. Force vs. displacement curve for specimen COHI

3.6*COEI*:

In this module, the value of peak force was greater than the value of CONI but it was lower than any other value, alternatively, it can be stated that the second highest value of peak force was recorded in the COHI section. A similar situation was observed with the average crush values and the energy absorbed values, the values were greater than the CONI model results and were lower when compared to any other specimen.135.196 kN, 78.170 kN, 16.414 kJ, were the value noted for the peak energy absorption, average crush force and energy absorbed respectively.

3.7*ROCI*:

The peak force for the ROCI was found at about 75 mm of deformation and the value so observed as 138.344 kN. It showed a 32 % increase in the value of peak force when compared to the CONI model. The values of crush force and the energy absorbed showed even better results by registering an 85% increase in the above-mentioned values. The value of average crush force and the energy absorbed were recorded as 103.892 kN and 21.815 kJ respectively. Thus it can be said that the geometries with a polygon as outer shell gave much better values than the specimens having a circle as their outer periphery.

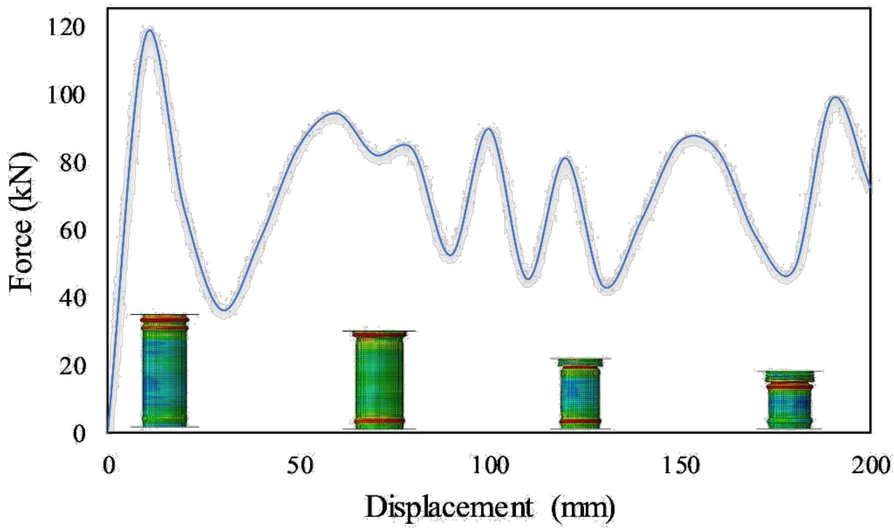


Figure 7. Force vs. displacement curve for specimen COEI

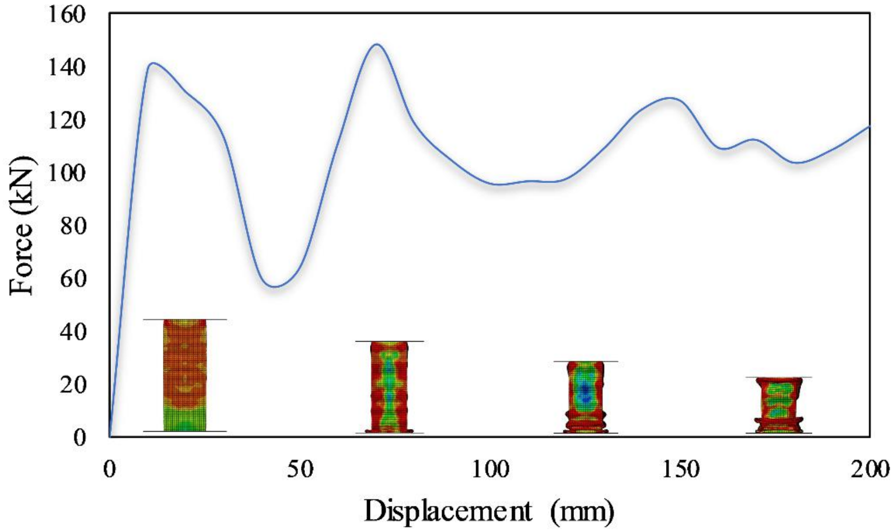


Figure 8. Force vs. displacement curve for specimen ROCI

3.8 SOCI:

Among all the above numerical simulation specimen the best results were obtained in the SOCI geometry the values of peak force, average crush force and the energy absorbed was recorded in this specimen the values of crush force and the energy absorbed increased by 94% in reference to the CONI model and the value of peak force showed 1.32 times increase in comparison to the CONI model. The value of peak force was recorded at instance before the 200mm deformation of the specimen.

3.9 *HOCI*:

The values of the HOCI model was slightly less than the SOCI model but it was quite comparable with the ROCI. The peak force was recorded as 138.570 kN, the crush force as the 100.975 kN while the value of energy absorbed was 21.203 kJ. The values may be slightly lower than the SOCI model but it appreciably good when we consider the geometries with outer shell as a circle.

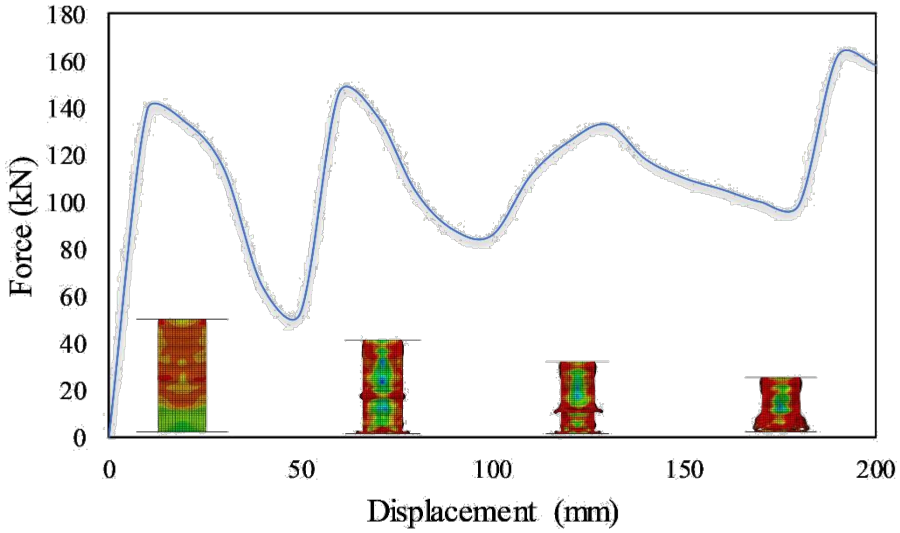


Figure 9. Force vs. displacement curve for specimen SOCI

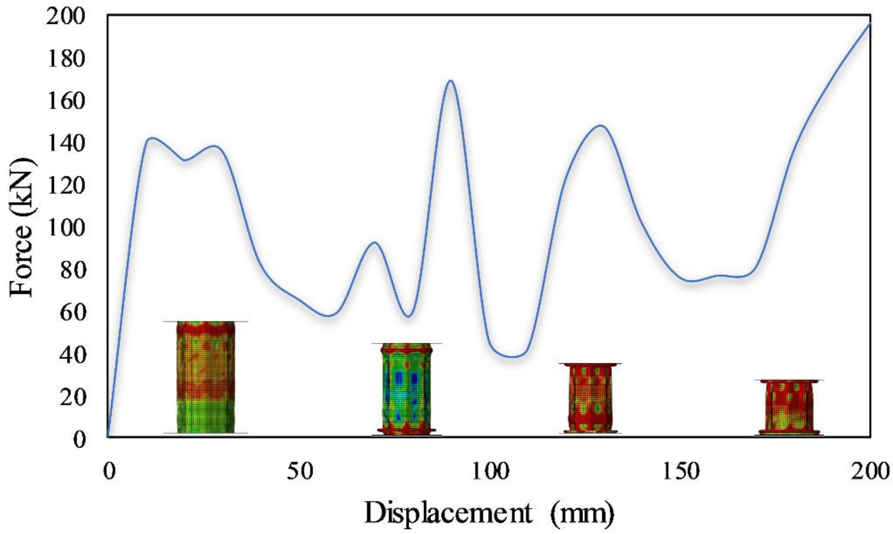


Figure 10. Force vs. displacement curve for specimen HOCI

3.10 *EOCI*:

The values of the EOCI were quite similar to the values of the SOCI, that is to say, that the values so noted were having appreciably high values in terms of peak force, average crush force and energy absorbed. This model outperformed the other models.

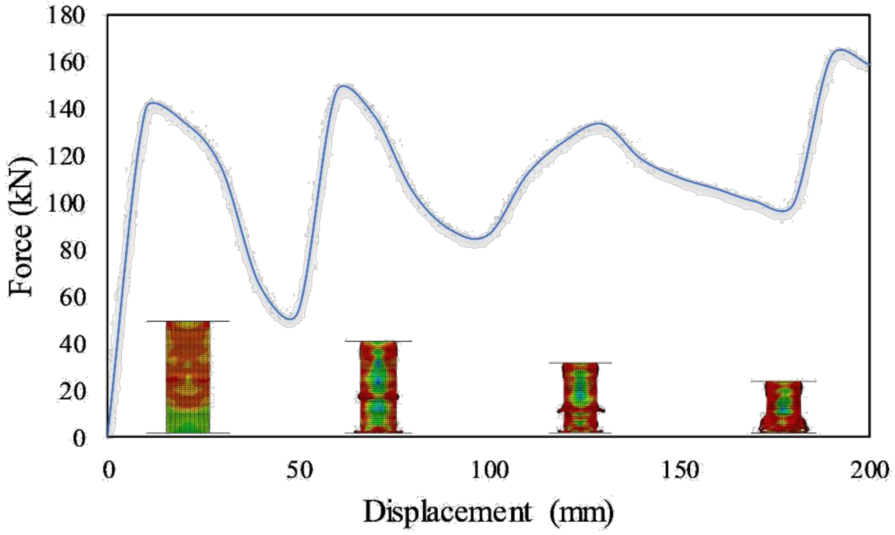


Figure 11. Force vs. displacement curve for specimen EOCI

A comparison of peak force values of the various specimen is presented in Figure 12.

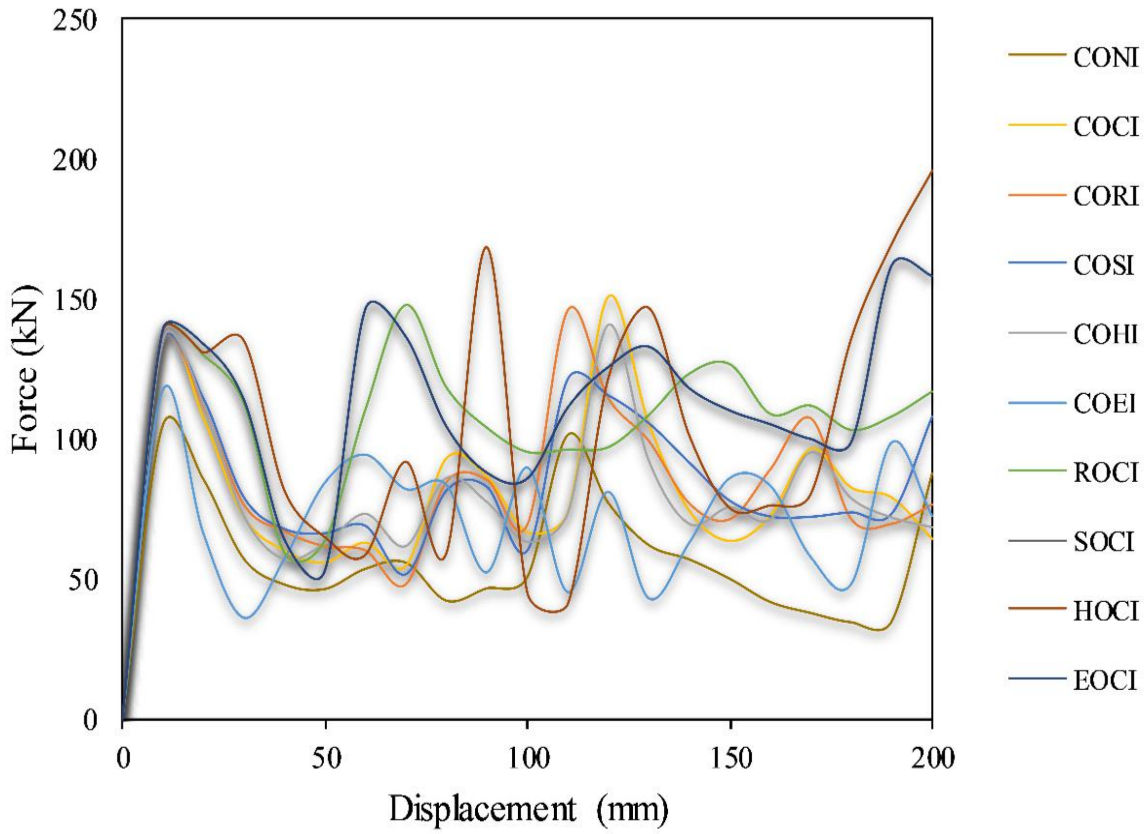


Figure 12. Force vs. displacement curve for all specimens

Table 3. Summary of results of different profiles (stroke: 200 mm)

Specimen	Peak force (kN)	Average crush force (kN)	Energy (kJ)
CONI	104.706	56.030	11.765
COCI	134.916	79.109	16.611
CORI	133.630	81.77	17.170
COSI	133.921	81.651	17.145

COHI	135.196	78.170	16.414
COEI	117.052	68.591	14.402
ROCI	138.344	103.892	21.815
SOCI	138.938	108.876	22.862
HOCI	138.570	100.975	21.203
EOCI	138.938	108.876	22.862

4. Conclusion

The main aim of the paper was to analyze the different cross sections of the bimetallic tubes on the basis of the parameters like Energy absorption, deformation and crushingbehavior, On the basis of the numerical simulations the results of the mentioned geometries can be summarized as follows:

- It can be said that the values of peak force, average crush force, and energy absorption does vary in accordance with the number of sides.
- In some cases, like HOCI, COCI, ROCI, EOCI, SOCI, etc. The peak force values are not found at the starting of the crushing, rather it happens at a much later stage, this phenomenon happens due to the densification of the material.
- Geometries having polygon as the outer shell revealed better results than the geometries having the circular shells as their outer shell. In reference to the test parameters, i.e. peak force, average crush values, and energy absorbed.
- The minimum values of the crushing force and energy absorbed were found in the CONI model, because of the absence of an inner wall.
- The maximum Values of the simulation results were found for the geometries having polygon cross section at the outer shell and that too with a maximum number of sides.

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