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NUMERICAL DYNAMIC AXIAL CRUSHING OF BI-TUBULAR METALLIC CYLINDRICAL TUBES WITH STIFFENERS

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Abstract. *Thin walled multi-cell columns are highly efficient in energy absorption under axial crushing loads. In this study, the dynamic axial crushing of bi-tubular metallic cylindrical tubes is numerically studied. Proposed bi-tubular tubes are unique in the feature as the inner tube is conical in shape and outer tube is circular, along with stiffeners in between these tubes. The inner tube conical angle named as β is varied from zero to 5 degrees and its sensitivity in energy absorption is studied. In total six configurations with varying β from 0 to 5 with 1 degree increment in each configuration are studied. Deformation modes, specific energy absorption and crushing efficiency are discussed and a generic contribution of β is proposed for such configurations.*
Keywords: Bi-tubular, Dynamic crushing, Numerical modeling, Specific energy absorption, Stiffener, Conical

1. **Introduction.** Multi-cell thin walled tubes are highly under research focus due to the increasing demand for safety and energy absorption in aerospace and automotive structures. They can be used as an energy absorber in the energy-absorbing devices such as vehicle structural components (front rails and low rails of the passenger car) [1,2], train buffers [3,4] and helicopter subfloors [5]. An ideal energy absorber should resist impact loads without causing a complete instant failure, and dissipate impact energy with controllable deformation [6].

Metal columns with varying cross-sections like circular [7,8], square and hexagonal [9,10] are studied for their energy absorption capabilities theoretically, numerically and experimentally under axial impact loadings. These tubes could be deformed in different modes of deformation such as an axisymmetric (concertina) mode, non-symmetric (diamond) mode, mixed mode or global Euler buckling mode [11]. Numerical and experimental studies of dynamic axial impact response of different configurations of multi-cell columns showed that the crash force efficiency of the middle ribs (MR) multi-cell columns was the highest because it had the highest number of interaction between the inner and outer walls [12].

X. Zhang et al. [16] studied the energy absorption characteristics of tapered circular tubes experimentally and numerically. The tapered circular tubes with graded thickness showed higher energy absorption efficiency as compared to straight circular tubes. They also proposed a novel analytical model to determine the mean crushing force of tapered and circular tubes. Conical tubes are a relatively new area of research. Researcher's investigations showed that thin-walled conical tubes achieve different crushing modes based on their length and cross-section dimensions under crushing load. Energy dissipation rate is concentrated over relatively narrow zones and energy absorption is usually by progressive buckling of tubes walls. Recently, a newly developed foam filled bi-tubular configuration is studied under dynamic axial and oblique loading in which the outer tube is kept circular while the inner tube is conical in shape [13]. Crashworthiness simulation showed a higher energy absorption in this configuration as compared to earlier bi-tubular designs. Numerical and experimental energy absorption studies for tapered multi-celled tubes revealed that the increase of the taper angle, the wall thickness and the number of cells in the cross section would enhance the crashworthiness capacity of the structure [14].

The stability of tube crushing with progressive folding is critical for higher energy absorption. A combination of circular and conical tubes may serve the purpose by providing larger diameter at one end. In this study, a new configuration of multi-cell thin walled bi-tubular configuration with joining stiffeners in between two tubes is presented. The outer tube is circular while inner tube is conical in shape with varying angles with vertical reference of outer tube. Six configurations are named as SCβ-n where SC stands for straight-conical and β-n is the inner conical tube reference angle which varies from 0 to 5 degrees. A finite element analysis of all of the proposed configurations is performed in SIMULIA ABAQUS Software Explicit Dynamics. The complete work is presented in five sections. Section 2 describes the proposed configurations, Section 3 shows the finite element modeling adopted in the study, Section 4 highlights some of the energy absorption indicators and Section 5 concludes the work in the form of conclusion.

2. **Proposed Configurations.** A new all metal bi-tubular configuration with outer tube of diameter D_0, length L and thickness t_0 is joined with an inner conical tube of diameter at reference bottom face D_i-bottom, length L and thickness $t_i = t_0$ using stiffeners along the radial directions of length L is proposed in this study as shown in Figure 1. The conical tube angle is called β and has a value of 0 to 5 degrees in each configuration simultaneously, defining the name of each configuration as SCβ-0, SCβ-1 to SCβ-5 as shown in Figure 2. Thickness of the stiffeners is circumferentially controlled in a manner to keep the mass value same in all configurations.

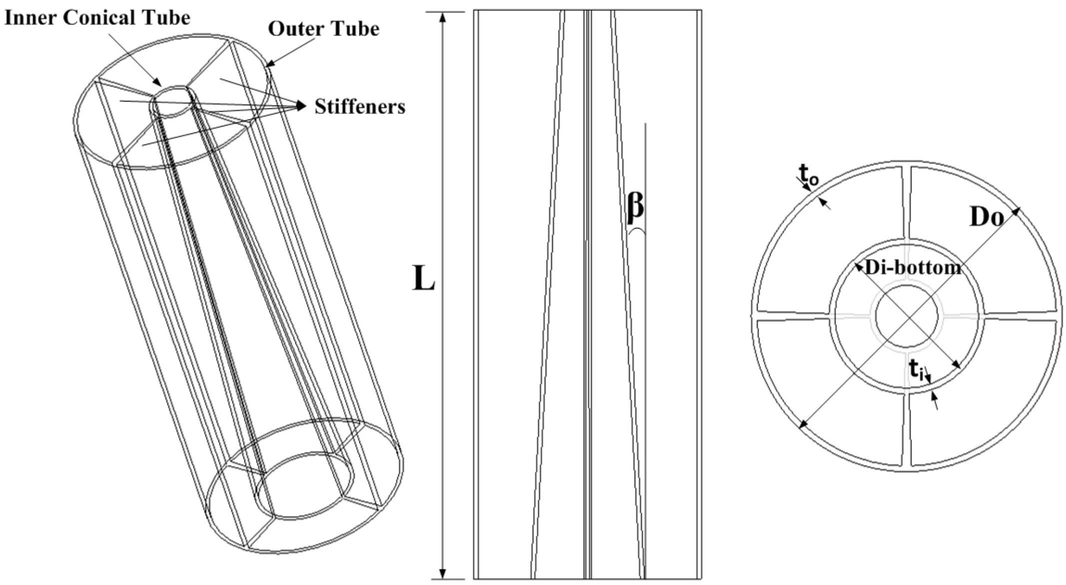

Figure 1. Schematic drawing of the proposed configuration

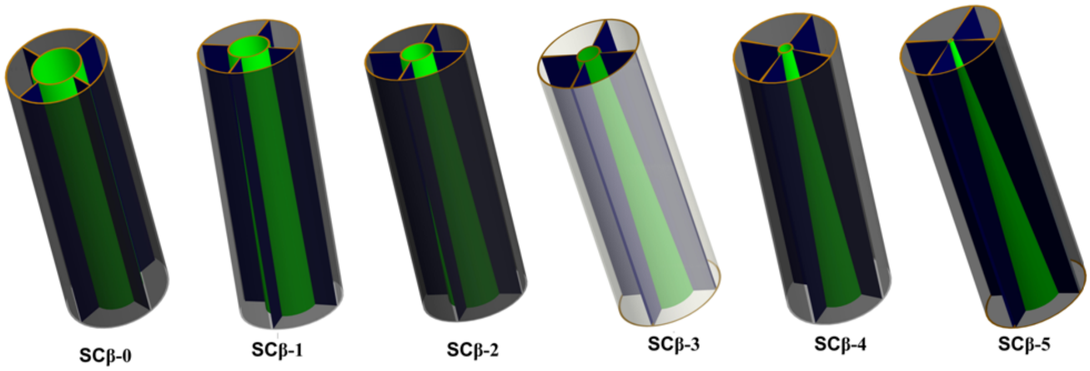

Figure 2. All SCβ-n configurations

3. Finite Element Modeling.

3.1. **Mesh and boundary conditions.** The dynamic explicit finite element package ABAQUSTM is employed in this study to find out the crushing behavior and energy absorption of bi-tubular multi-cell proposed configurations under axial dynamic loading. As shown in Figure 3(a), the proposed configurations are impacted by a moving plate with velocity V of 10m/s in a way that it faces the lower diameter of the inner conical tube. The other face is constrained in all directions of freedom using a rigid plate.

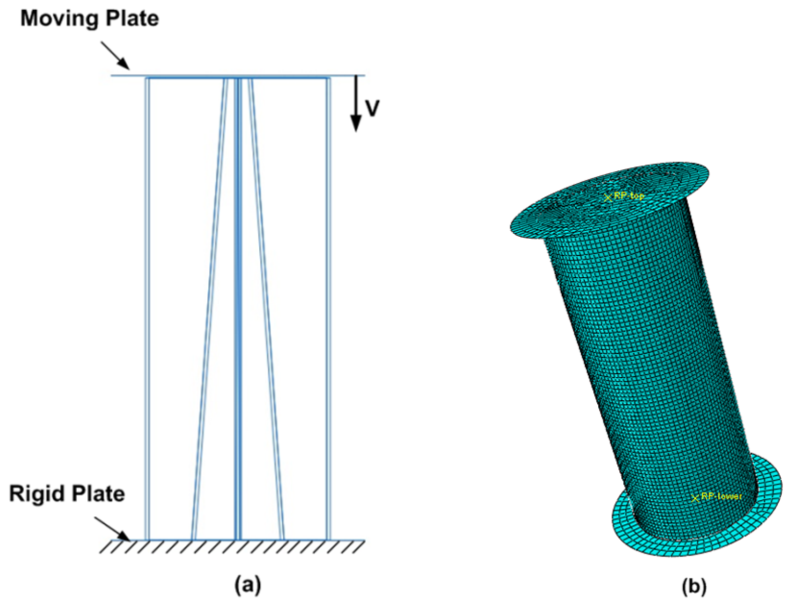

Figure 3. Boundary conditions (a); model mesh (b)

In the FE model, the solid C3D8R element is used for tube configurations, which is an 8-node linear brick element with reduced integration and hourglass control. The top and bottom plate is meshed using discrete rigid element. The top plate has an impact mass of 50Kgs. After mesh convergence studies, an element size of 2.5mm is found feasible and adopted in this study for all of the configurations. The FE model mesh is shown in Figure 3(b). The contact between the top rigid plate and the tube is modeled as general explicit contact with tangential behavior being frictional using frictional coefficient of 0.2 and normal behavior being hard contact. The contact between the lower plate and tube was defined as tie contact and to avoid the interpenetration while folding of the tube, a self-contact is also defined for all of the elements of the configuration.

The load, material configurations and boundary conditions are identical for all of the configurations.

3.2. **Material properties.** The proposed configurations are all metal configuration, in which tube's material is extruded aluminum AA 6060 T4 [15], whose properties are tabulated in Table 1. The tensile stress-strain curve is shown in Figure 4.

Table 1. Material properties of AA 6060 T4

Material Property	Value
Youns's Modulus [GPa]	68.21
Yield Strength [MPa]	80
Ultimate Strength [MPa]	173
Ultimate Elongation [%]	17.4
Poissson's Ratio	0.3

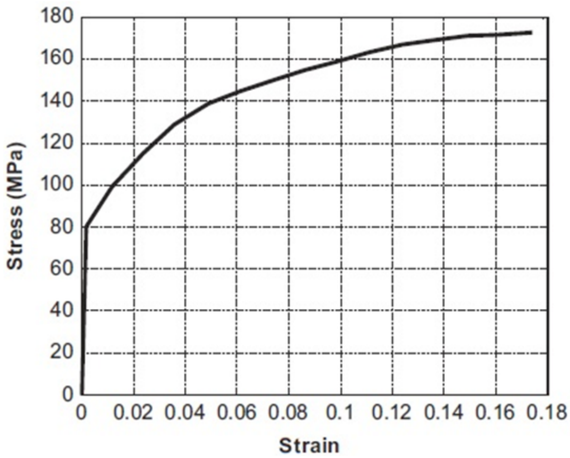

Figure 4. Tensile stress-strain curve of AA 6060 T4 [15]

In FE model, the material behavior for the tube system is based on an elastic-plastic material model with Von-mises isotropic plasticity algorithm with piecewise linear plastic hardening. In the FE model, failure criteria based on plastic strain and plastic thinning have been adopted with ultimate value of each being 0.174 and 0.2, respectively. The strain rate effect is neglected in the finite element modeling as the aluminum alloy is strain rate insensitive.

4. **Numerical Results and Discussion.**

4.1. **Energy absorption indicators.** Some energy absorption indicators necessary to describe the crushing capability and energy absorption characteristics are listed in this section.

The mean crushing force MCF is defined as:

$$MCF = EA/x \tag{1}$$

where EA is the absorbed energy and x is the crushing displacement. An ideal energy absorber has a mean crushing force which is constant and not fluctuating.

The specific energy absorption (SEA) is defined as:

$$SEA = EA/m \tag{2}$$

where m is the mass of the tube system.

The crush force efficiency (CFE), which is an indicator to characterize the load consistency of an energy absorber, is defined as:

$$CFE = MCF/PCF \tag{3}$$

where PCF is the peak crushing force. For an ideal energy absorber, the CFE is 100%.

4.2. **Validation of finite element modeling.** Experimental published results of X. Zhang et al. (2015) are selected for validation of the current numerical model adopted in this study. The validation was conducted by keeping the structural geometry, material properties and the boundary conditions exactly the same as those in the mentioned studies. The force displacement curve of present numerical study is compared with experimental work of X. Zhang et al. in Figure 5 and a close agreement was found between experimental and present numerical study. The mean crushing force of current study was found to be 36.5KN while experimental value is 39.2KN and it shows a small difference of 7% only. Hence it is evident from the validation study that the current methodology may be used for the numerical simulation as the validation process is validated for mentioned experiments.

4.3. **Deformation modes.** Deformation patterns of the entire configurations considered in this study are depicted in Figure 6. All the tubes deformed in concertina or diamond mode which is the desirable modes of deformation for better energy absorption. The deformation starts from the crushing/top end and goes down to the fixed side. However, the deformation starts from the crushing end in SCβ-1 configuration but after few lobes formed, crushing from the bottom end was also observed. SCβ-2 shows the same deformation pattern as observed in the case of SCβ-1 but the crushing process is smoother than

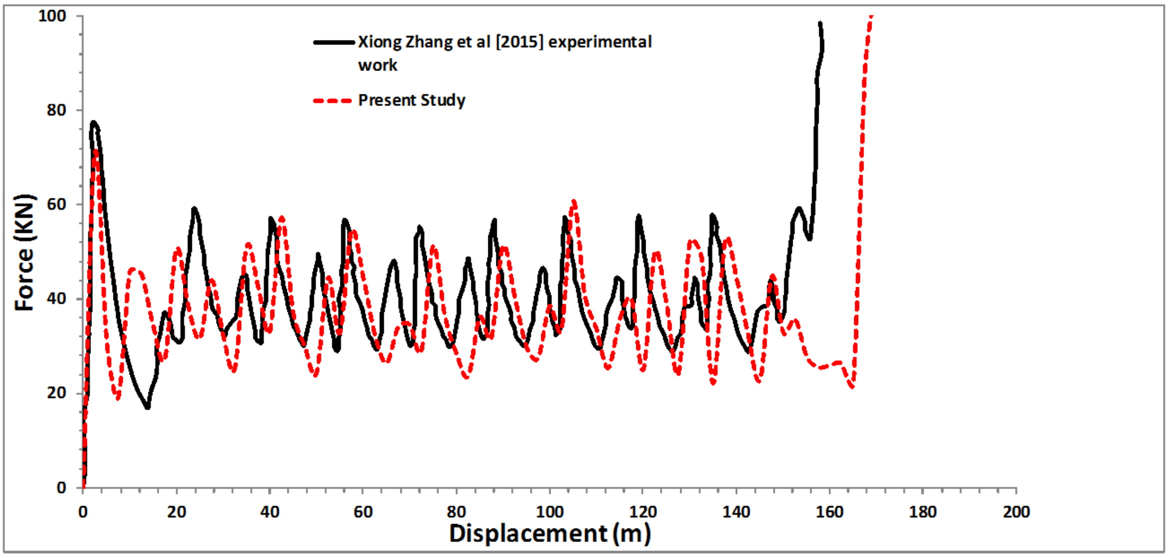

FIGURE 5. Force displacement curves (Validation of the current study with X. Zhang et al. [16])

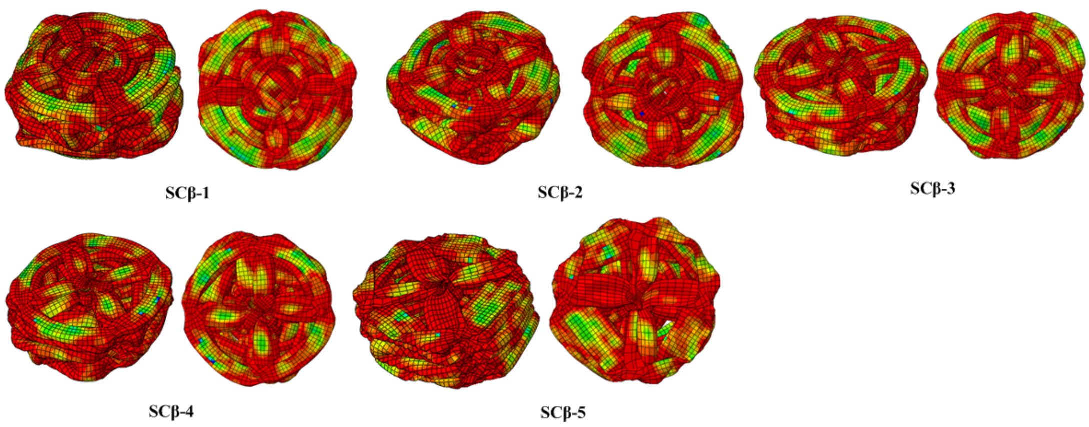

FIGURE 6. Deformation modes for all of the configurations

the former, which is one of the reasons for better energy absorption of SCβ-2. For the case of SCβ-3, deformation starts from the crushing end and goes down towards the other side. In this case, a drop in initial peak force is observed and also more abrupt fluctuation around the mean crushing force. SCβ-4 and SCβ-5 configurations show almost the same crushing behavior as that of SCβ-3 but a decrease in the initial peak force compared to the previous case and also an abrupt fluctuation was observed around the mean crushing force.

4.4. **Energy absorption indicators.** The load-displacement curves for all of the proposed configurations are shown in Figure 7. The mass is kept same in all configurations and a comparison in between the energy absorption indicators from Equations (1) to (3) are tabulated in Table 2. These parameters are calculated from the load-displacement curves. It is clear from Table 2 that EA, SEA, MCF and CFE increase as β increases from 0 to 2 degrees in SCβ-0 to SCβ-2 configurations, and then a decline in all indicated parameters is observed after further increase in β from 3 to 5 degrees in SCβ-3 to SCβ-5 configurations. However, compared with the standard configuration for this study SCβ-0, the EA, SEA, MCF and CFE is higher in configurations SCβ-1 to SCβ-3 while SCβ-4 has almost similar parameters as of SCβ-0. The results are the lowest in configuration SCβ-5. When the loads applied on cylinder, it resists up till critical buckling load is achieved. This load under impact cannot be avoided for a specific cylindrical configuration but can be delayed and distributed by inserting conical angle in internal tube. Energy absorption in configurations SCβ-1 to SCβ-4 is 9.5%, 10.6%, 6.72% and 1.8% higher respectively as compared to SCβ-0 while it is 18.5% low in SCβ-5. Crush force efficiency is the highest in SCβ-2 following SCβ-1 while in all other configurations it is almost the same as SCβ-0.

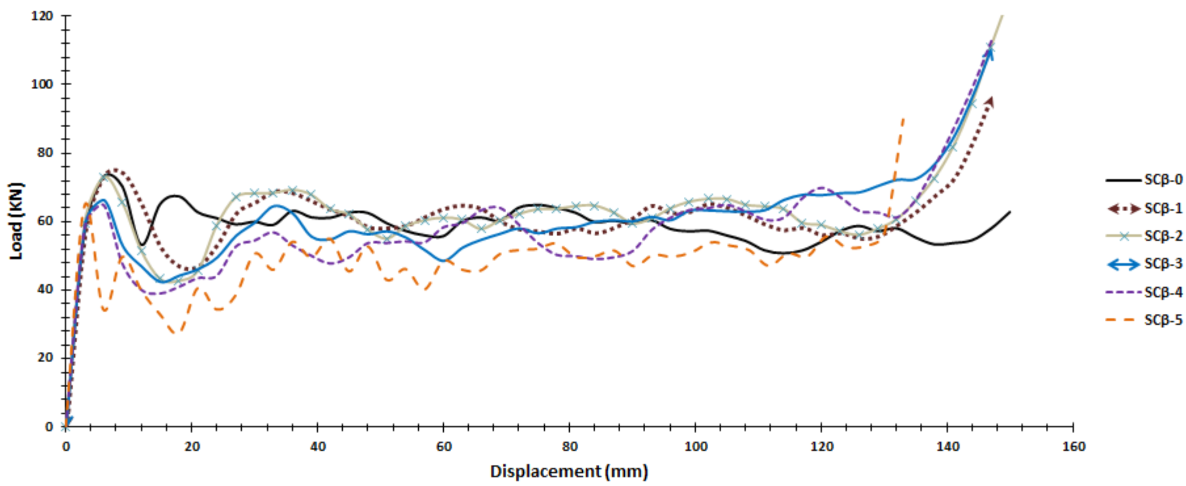

FIGURE 7. Load displacement curves for all of the proposed configurations

TABLE 2. Energy absorption indicators' results

Configuration	EA (KJ)	SEA (KJ/Kg)	PCF (KN)	MCF (KN)	CFE
SCβ-0	7503.10	21.75	71.43	53.51	0.75
SCβ-1	8216.07	22.31	74.30	59.51	0.80
SCβ-2	8299.75	22.54	73.04	60.16	0.82
SCβ-3	8007.79	21.74	76.80	58.01	0.76
SCβ-4	7638.35	20.74	76.38	55.28	0.72
SCβ-5	6111.97	16.60	64.77	47.00	0.73

5. **Conclusion.** Bi-tubular multi-celled tubes energy absorption response can be enhanced by making inner tube conical. In this study, a bi-tubular multi-cell system with straight tubes is kept as a reference and then different configurations are proposed making inner tube conical with angle (β) varying from 1 to 5 degrees. It is shown that this parameter is sensitive to energy absorption. A maximum of 10.6% energy absorption enhancement is obtained in SCβ-2 with CFE value of 0.82. This increase is due to the contribution of distributing axial crushing load into different components introducing radial and tangential load components. There is a limit for this contribution after which radial loads give a pre-mature bending along with buckling load as shown in SCβ-5 in which an 18.5% energy absorption loss is recorded. Hence, β can be used as energy absorption parameter in bi-tubular multi-cell tube systems.

The effectiveness of β proposed in this work can be extended for the proposed tubes with an inversion under axial loading along with determination of buckling loads with varying values of β.

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