Closed Section Steel Tubes Axial Crushing and Energy Absorption Behavior

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***Abstract*— This paper presents the effect of design parameters on crushing behavior and energy absorption of steel tubes used in bus frame manufacturing. Experimental investigations were carried out on different cross sections steel tubes subjected to axial impact load. Experimental tests were repeated on three sets of previously mentioned tubes, dents and holes were added to tubes to evaluate its effect on energy absorbed by those tubes. Experimental results show that adding dents and holes reduce axial force affect tubes, while increasing axial deflection. A finite element model was proposed to simulate experimental tests. Finite element analysis model results show good correlation with the experimental results. More cases were investigated using proposed finite element model. Results show that circular cross section is the best for energy absorption, while square cross section is the worst. Closed sections absorb more impact energy than open section with the same area. Increasing fillet radius for square and rectangular cross sections leads to increase the impact energy absorbed by these tubes.**

Keywords— Impact; absorbed energy; passenger bus; closed section tubes; steel tubes

I. INTRODUCTION

Currently, vehicle safety and alternating power source are the main challenges between vehicle manufacturers. Many researchers investigated and improved active and passive safety systems, to reduce vehicle accident effect on passengers. Self protection for the occupants of passenger cars is based on the principle of stiff occupant cell with strategically positioned deformation zones in combination with restraint systems. [1] The same concept applied on buses and mini-buses frames that are made of space frame steel structure. Steel tubes with various cross sections and dimensions are the main component in bus body building. Tarigopula et al [2], investigated the axial crushing behavior of thin walled high strength steel sections. Quasi-static and dynamic axial crushing tests were performed on thin-walled square tubes and spot welded top-hat sections made of high-strength steel grade DP800. A comparison is made with analytical methods and the response was under-predicted. In addition, numerical simulations of the axial crushing of the thin-walled sections were performed and comparisons with the experimental results were satisfactory. The validated numerical model was used to study the energy absorption capacity of thin walled sections with variations in the yield strength, sheet thickness, flange width and spot-weld spacing. Structural effectiveness differences have been captured through simulations between spot-welded top-hat sections made of mild steel and high-strength steel.

Costas et al [3], investigated the frontal crashworthiness capabilities of carbon-fiber reinforced polymers, glass-fiber reinforced polyamide, polyethylene terephthalate foam and cork conglomerates in combination with cold-formed steel polygonal tubes using quasi-static and dynamic numerical simulation verified with experimental results.
Arameh Eyvazian et al [4], investigated the effect of corrugations on the crushing behavior, energy absorption, and failure mode of circular aluminum tubes. Experimental investigations were carried out on five geometrical types of corrugated and simple tubes, with corrugations different in size and direction, subjected to axial compressive loading.
Sunghak et al [5], investigated the effect of triggering on the energy absorption capacity of axially compressed aluminum tubes. The energy absorption performance of extruded aluminum tubing for space frames was evaluated using computer-simulated compressive tests and quasi-static compressive deformation tests. An experimental deformation test and its simulation were conducted for seven extruded tube specimens on which various types of triggering dents were introduced, and the test data were investigated via observation of deformation mode, maximum repulsive force, and absorbed energy.

D. Al Galib and A. Limam,[6] investigated the comprehensive experimental and numerical study of the crash behavior of circular aluminum tubes undergoing axial compressive loading is performed. Non-linear finite element analyses are carried out to simulate quasi-static and dynamic test conditions. The numerical predicted crushing force and fold formation are found to be in good agreement with the experimental results. A summary of available analytical solutions is presented in order to estimate the mean crushing load and establish a comparison between these analytical loads and the experimental one.
A. Alavi Nia and M. Parsapour, investigated the energy absorption characteristics of multi-cell square tubes. Behavior of simple and multi-cell square tubes with equal cells is studied analytically, experimentally and numerically.[7]

F. Tarlochan, et al, investigated the Enhancement of crashworthiness due to axial and oblique impact forces. Computationally aided design process of a thin wall structure subject to dynamic compression in both axial and oblique directions was investigated.Several different cross sectional shapes of thin walled structures subjected to direct and oblique loads were compared initially to obtain the cross section that fulfills the performance criteria. The selection was based on multi-criteria decision making (MCDM) process. The performance parameters used are the absorbed crash energy, crush force efficiency, ease of manufacture and cost. Once the cross section was selected, the design was further enhanced for better crash performances by investigating the effect of foam filling, increasing the wall thickness and by introducing a trigger mechanism. [8]

Xiaoyun Zhang, et al [9] studied the main energy-absorbing automotive parts design improvement, based on traffic accident analysis.

F. Djamaluddin et al, investigated the Optimization of foam-filled double circular tubes under axial and oblique impact loading conditions. The multi objective optimization of foam-filled tubular tubes under pure axial and oblique impact loadings was presented. In this investigation, the double circular tubes, whose bottom is the boundary condition, while at the top, is the impacted rigid wall; with respect to the axis of the tubes. The optimal crash parameter solutions, namely the minimum peak crushing force and the maximum specific energy absorption, are constructed by the Non-dominated Sorting Genetic Algorithm-II and the Radial Basis Function. Different configurations of structures, such as empty double tube (EET), foam filled empty double tube (FET), and foam filled foam filled double tube (FFT), are identified for their crashworthiness performance indicators.[10]

Axial crushing of tapered circular tubes with graded thickness for axial and oblique loading was studied by many researchers [11, 12]

Improvement of axial impact energy absorption of steel members by applying transverse load during axial impact was also investigated by many researchers [13-15].

Anindya Deb et al, investigated the Performance of Lightweight Materials for Vehicle Interior Trim subject to Low Velocity Impact Perforation [16].

A Comparison of the behaviors of steel section components under axial quasi-static and impact loading was investigated.[17, 18]

Bugelli, E. and Driemeier investigated the axial impact of tubes for vehicle safety tests [19]

In this paper, an impact tester was designed so that steel tubes with square and circular cross sections specimens were subjected to axial impact force. Axial force, deflection of specimen and initial speed of the impact mass were measured. A finite element analysis using ANSYS mechanical was conducted for experimentally tested specimens. Experimental and theoretical results show a good correlation. FEA model was utilized to investigate the effect of shape parameters on impact energy absorption ability of steel tubes.

II. EXPIRMENTAL SETUP

Figure 1 illustrates the impact test rig used in this paper. An impact mass with 45 Kg mass was lifted up to 5.5 m high, and then it triggered to fall down with gravity acceleration (g). Specimen is fully fixed from lower surface, while its upper surface is allowed to move downwards only. Force, axial deflection of specimen was measured, while speed of the impact mass was measured, just before impact.
Force was measured using Honeywell Load cell RGF (EP) model. Axial deflection of the specimen was measured by SHARP GP2Y0A21YK infra-red sensor. A reflector (reflector 1) is used with previous sensor to indicate the distance Vs time relation during impact.
Speed of impact mass was measured by SHARP GP2Y0A02YK0F infra-red sensor. Analog output of this type of sensors is voltage proportional to the measured distance, since speed is the first derivative of distance, so the first derivative of the output signal is the desired speed.

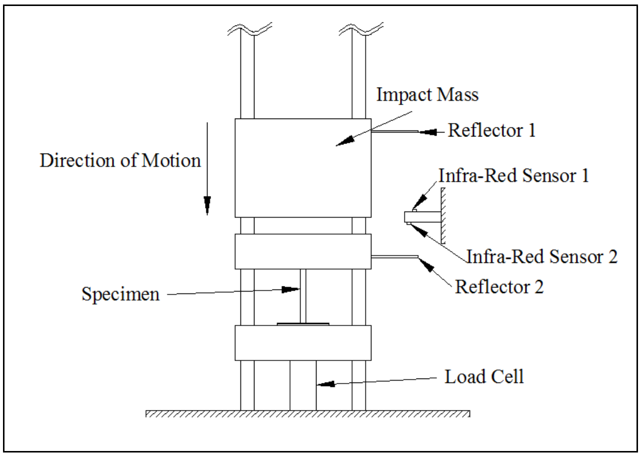

Fig.1 Illustration of test rig used in this investigation

Samples are divided to three repeatable groups, First group are five tubes, second group are the same previous tubes but with a through hole in each tube, last group are the same tube dimensions, materials of group one and two, but with a slot instead of the hole in group two tubes. All tubes lengths are 300 mm, previous length was selected after checking buckling behavior calculations, 300 mm length ensure that no buckling will occur, just crash of specimen. Table 1 summarizes all utilized tubes in this work. Figure 2 shows the shape of a typical specimen, while figure 3 shows the detailed dimensions of hole and slot of group 2 and 3 samples.

Table 1

Code	Cross section shape	Cross section dimension	length	Feature
Group 1				
A1	Rectangular	25X25X2 mm	300 mm	No
A2	Rectangular	37X37X2 mm	300 mm	No
A3	Rectangular	40X40X2 mm	300 mm	No
A4	Circular	25 mm diameterX2 mm	300 mm	No
A5	Circular	50 mm diameter X2 mm	300 mm	No
Group 2				
AH1	Rectangular	25X25X2 mm	300 mm	Φ6 mm hole
AH2	Rectangular	37X37X2 mm	300 mm	Φ6 mm hole
AH3	Rectangular	40X40X2 mm	300 mm	Φ6 mm hole
AH4	Circular	25 mm diameterX2 mm	300 mm	Φ6 mm hole
AH5	Circular	50 mm diameter X2 mm	300 mm	Φ6 mm hole
Group 3				
AS1	Rectangular	25X25X2 mm	300 mm	Slot 3X2 mm
AS2	Rectangular	37X37X2 mm	300 mm	Slot 3X2 mm
AS3	Rectangular	40X40X2 mm	300 mm	Slot 3X2 mm
AS4	Circular	25 mm diameterX2 mm	300 mm	Slot 3X2 mm
AS5	Circular	50 mm diameter X2 mm	300 mm	Slot 3X2 mm

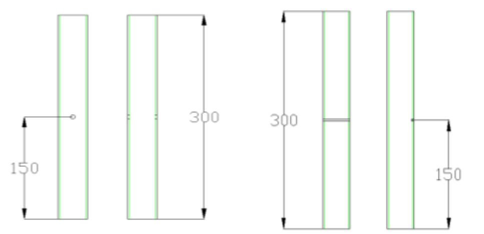

Fig.2 shape and dimensions of features position for specimens used

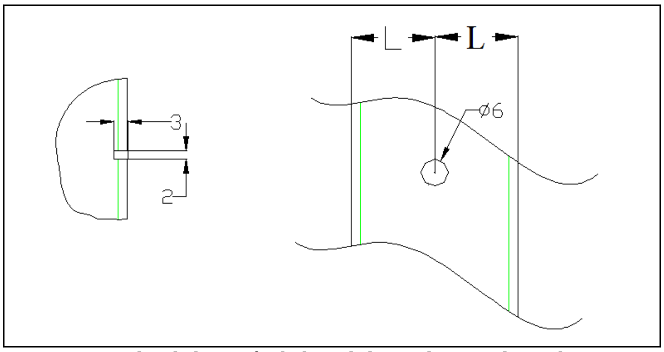

Fig.3 detailed view for hole and slot made in used samples

III. EXPIRMENTAL RESULTS

Impact force, axial deformation, and impact mass speed were measured. Impact mass speed was about 6 m/s. For each specimen, load deflection curves were obtained. Absorbed energy is the integration of the area under load deflection curve. Figures 4 to 8 show load displacement data for five samples

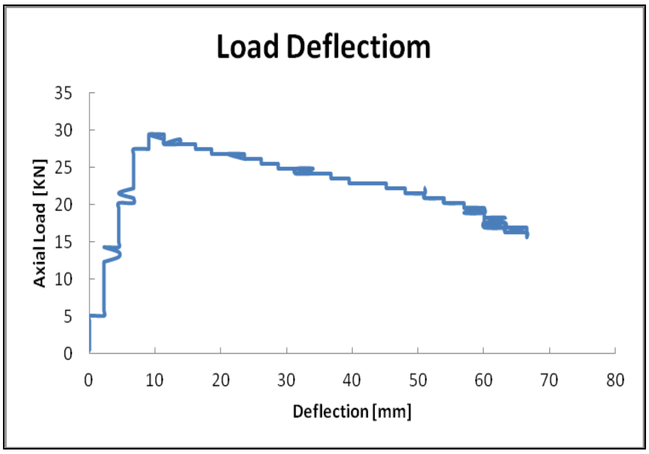

Fig. 4 Load displacement curve for AS1 sample

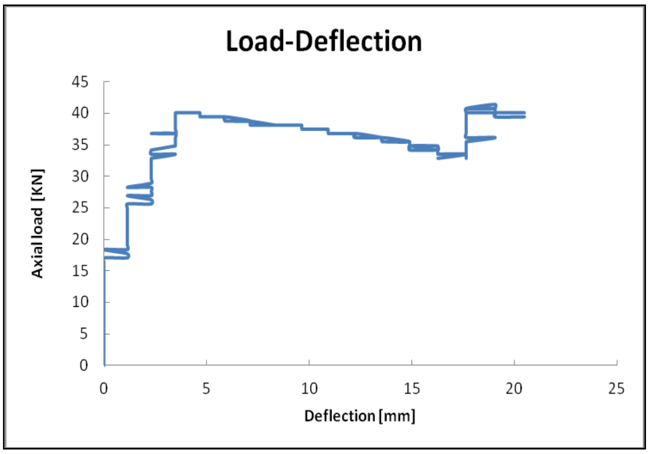

Fig. 5 Load displacement curve for A2 sample

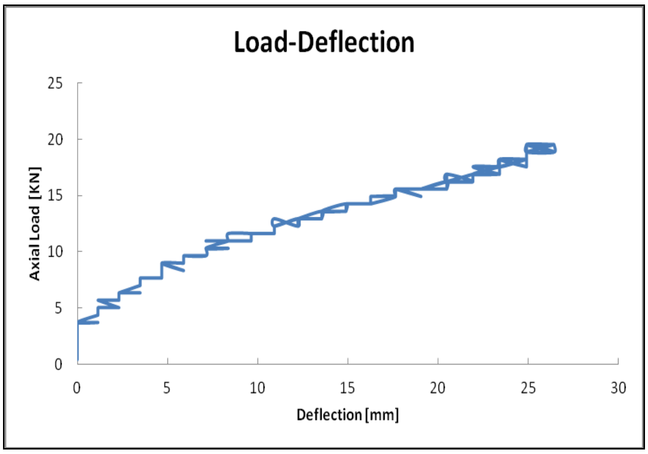

Fig. 6 Load displacement curve for AS3 sample

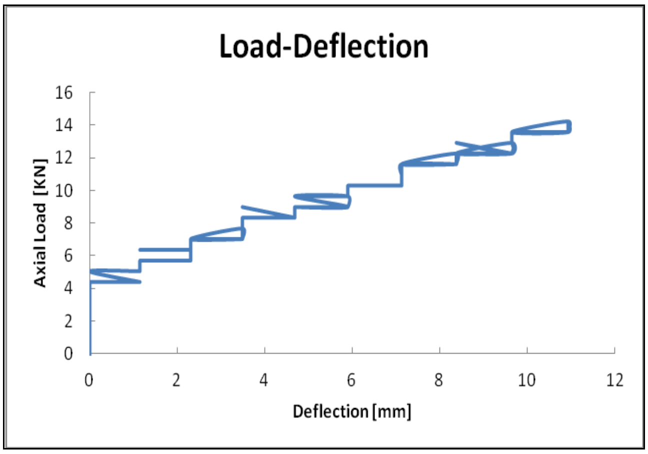

Fig. 7 Load displacement curve for AH4 sample

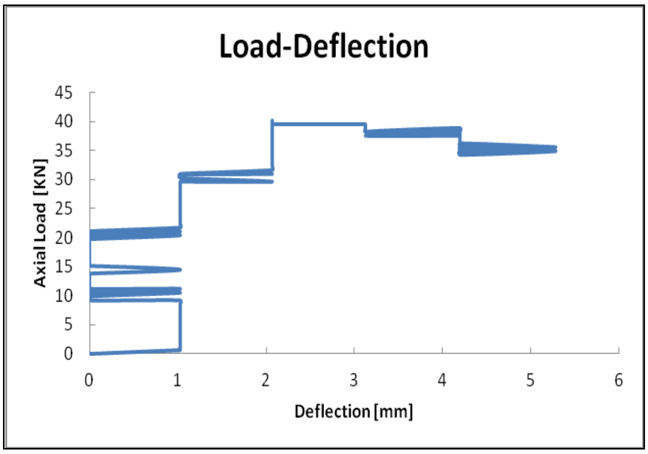

Fig. 8 Load displacement curve for A5 sample

As shown in previous figures, the load deflection curve was conducted, as mentioned before just to be compared with theoretical output in order to validate it. Previous results are logic, as the section cross section increase, the axial load affect it increases, while deflection of the member decreases. A horizontal fluctuation in deflection value was observed, this fluctuation is due to reflector plate vibration during impact.

IV. FINITE ELEMENT ANALYSIS MODEL VALIDATION

In this section, a Finite Element Analysis for previously discussed experimental work was conducted. Load displacement curves for Finite Element Analysis results was obtained and compared with existing experimental results.

A 1:1 scale 3D model with all details and dimensions was made and imported to ANSYS workbench environment. Lower end of specimen are completely fixed. Impactor was given an initial speed of 6-6.5 [m/s] as obtained from experimental data described in previous section. Figure 9 shows the 3D model imported to ANSYS software. Axial force, displacement in Y direction and screen shoots for deformed samples after impact was recorded. Figures 10 to 14 show the experimental vs. theoretical load displacement results. Figure 15 shows a comparison between deformed specimens experimentally and theoretically.

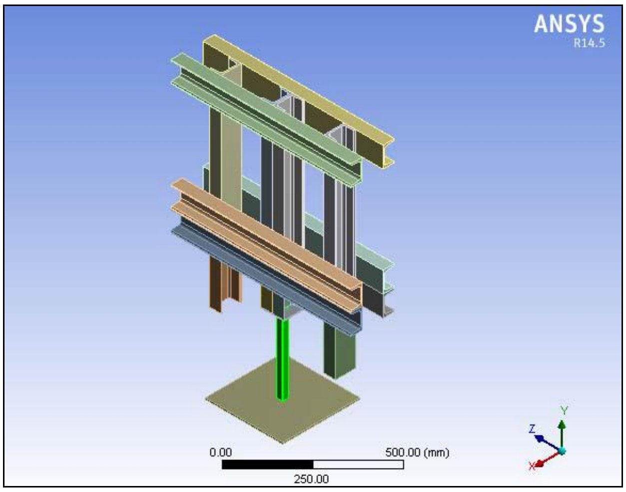

Fig. 9 test rig 3D model imported to ANSYS

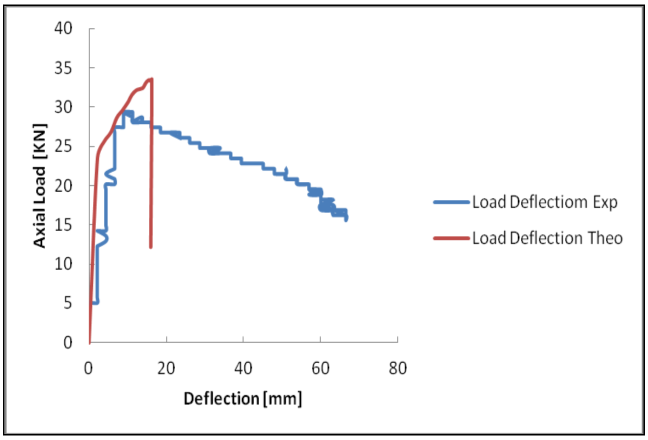

Fig. 10 Load displacement curve for AS1 sample experimentally and theoretically

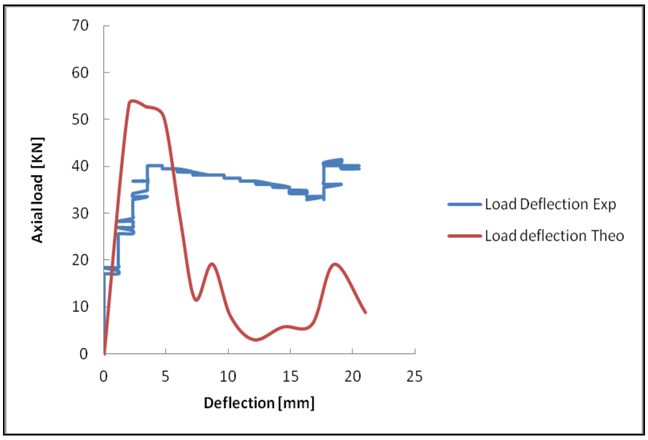

Fig. 11 Load displacement curve for A2 sample experimentally and theoretically

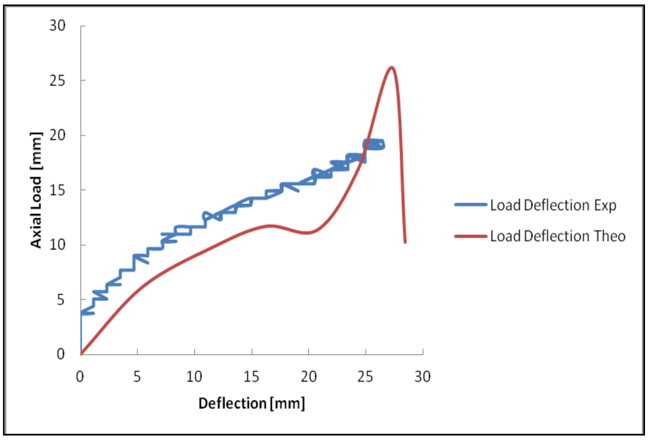

Fig. 12 Load displacement curve for AS3 sample experimentally and theoretically

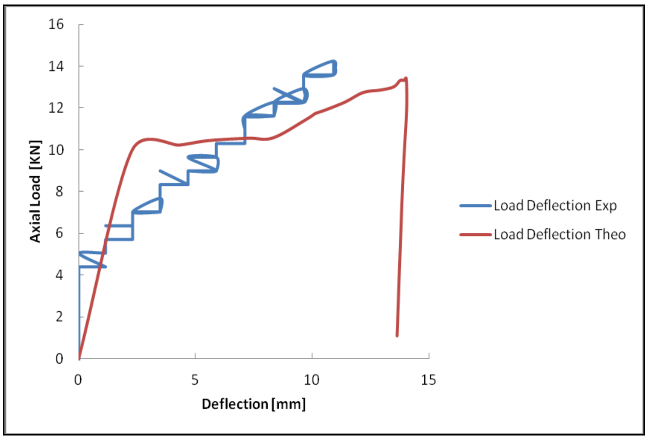

Fig. 13 Load displacement curve for AH4 sample experimentally and theoretically

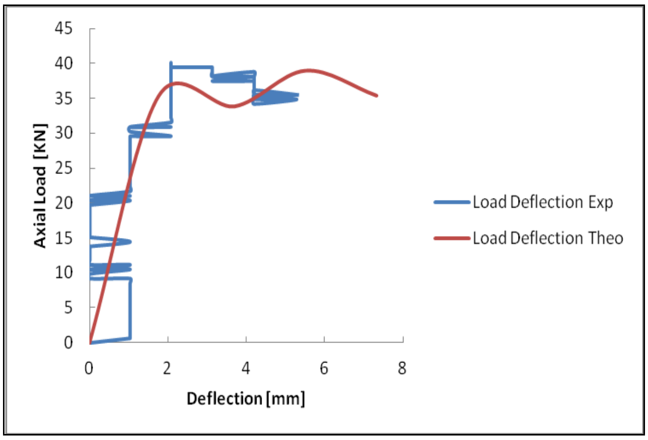

Fig. 14 Load displacement curve for A5 sample experimentally and theoretically

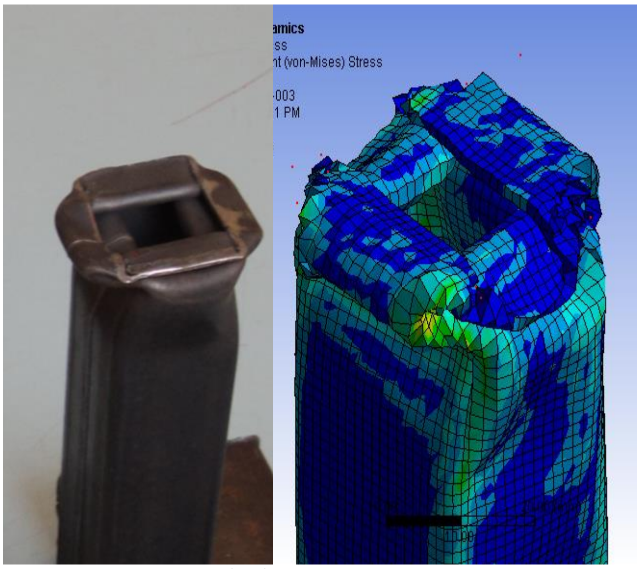

Fig. 15 Isometric view of deformed A3 specimen experimentally and theoretically

As shown in figures, 10 to 14, both experimental and theoretical load displacement curves are common for starting from zero, then load increase with deflection till it reach maximum value, then load decrease as the impactor stop and permanent deformation occurs in specimen. Load fluctuation is due to material yielding properties as plastic folds occur. In other words, when impact start material resets load, so reaction increase till a plastic hinge region exceed its elastic limit, so yield occurs which decrease the axial load , then another cycle of resisting, yielding till the impactor total energy is absorbed by the specimen deformation, this is clear in case of specimens without dents. In case of specimens with hole or slot, there is no flucation in force value, as the dent iniate a plastic hing that lead to large deformation enough to absorb impactor enrgy.

On the other hand, there are some slightly differences between experimental and theoretical curves for peak value and time. As discussed before, for experimental work, utilizing physical and virtual signal filters is essential to overcome noise affecting measurement signal, these filters cause slight change in peak value and time that the peak value achieved. Horizontal flucation in experimental data was discussed in previous. Genrally, peak values for both experimental and theoretical curves are very similar, also maximum deflection values which also match measured permanent samples deformation.

V. EFFECT OF SHAPE PARAMETERS ON ENERGY ABSORPTION ABILITY OF STEEL TUBES

A. Effect of cross section shape on absorbed energy

In this section, effect of cross section on energy absorbed by frame members will be investigated. Three groups of tubes were investigated. Each group consists of three tubes, circular, rectangular and square cross section. All tubes have the same cross section area. Figure 16 shows the main specimen dimensions, Table 2 shows summary of utilized specimens. Figure 17 to 19 shows the load displacement curve for previous mentioned specimens.

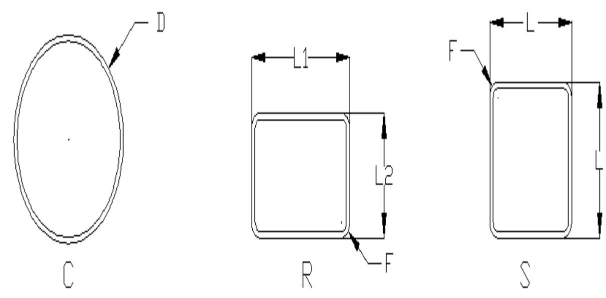

Fig. 16 specimen main dimensions

Table 2

Code	Dimension	Value [mm]	Thickness [mm]	Cross section Area [mm^2]
C1	D	50.5	2	304
R1	L1	50	2	304
	L2	30		
	F	5		
S1	L	40	2	304
	F	5		
C2	D	63	2	384
R2	L1	60	2	384
	L2	40		
	F	5		
S2	L	50	2	384
	F	5		
C3	D	76	2	464
R3	L1	70	2	464
	L2	50		
	F	5		
S3	L	60	2	464
	F	5		

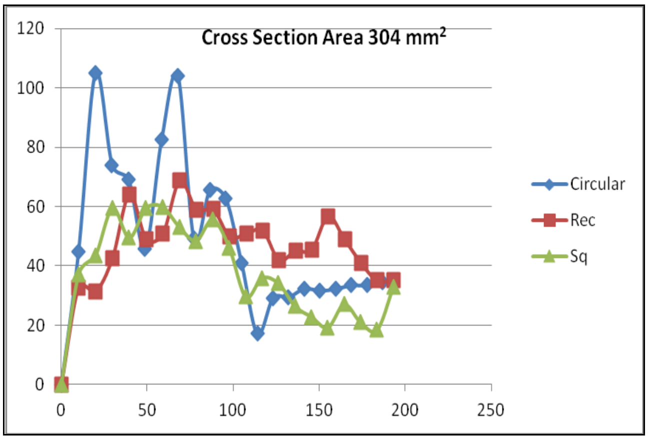

Fig. 17 Load displacement for C1, R1 and S1 specimen

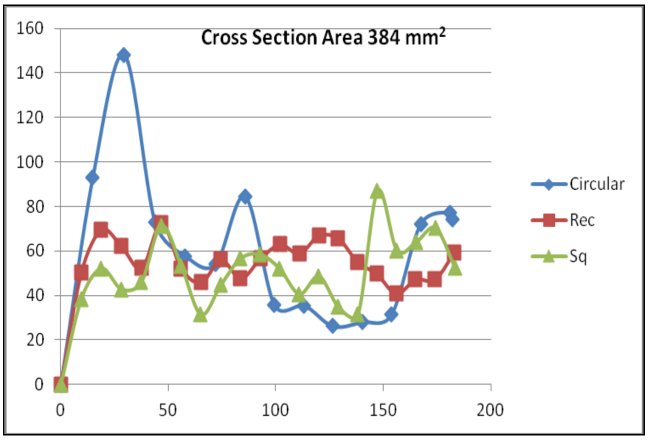

Fig. 18 Load displacement for C2, R2 and S2 specimen

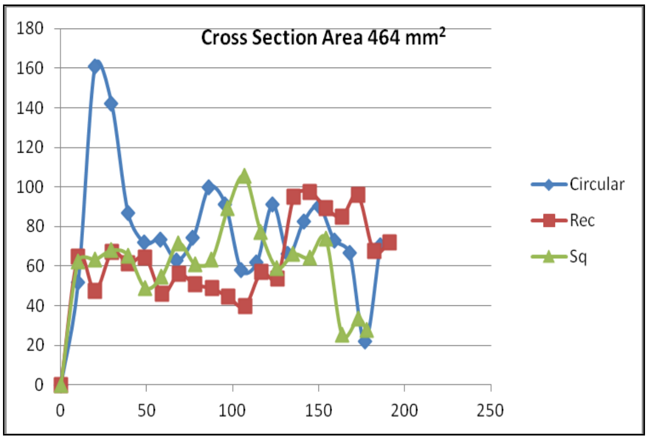

Fig. 19 Load displacement for C3, R3 and S3 specimen

For any cross section area sample, circular tubes absorb maximum value of impact energy, while square cross section absorbs minimum value at the same conditions. In our case, sample was assumed to be fixed at bottom, impacted with solid mass of 350 Kg with initial velocity 10 m/s. for specimens with 304 mm^2 cross sectional area, utilizing circular tubes instead of square tubes increase the value of absorbed energy by this tube by 21.5%, while in case of circular tube instead of rectangular tube, value of absorbed energy increased by 3%. Using rectangular tube instead of square tube increase absorbed impact energy value by 19%. For specimen with 384 mm^2 cross section area, utilizing circular tube instead of rectangular tubes increases the absorbed impact energy by 9%, while in case of replacing square tubes by circular tubes, absorbed energy increased by 16%. Replacing square tubes with rectangular tubes increase the absorbed energy by 7%. In case of 464 mm^2 samples, replacing square tubes by circular tubes increase absorbed energy by 21%, while replacing rectangular tubes with circular one, increase absorbed energy by 1%. Finally replacing square tube with rectangular one improves energy absorption by 20.5%. Figure 20 summarize the effect of using circular, rectangular and square cross sections on value of absorbed impact energy.

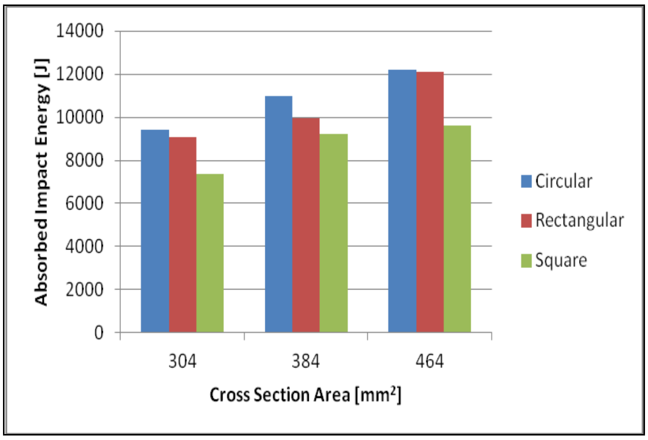

Figure 20 Effect of cross section shape on absorbed energy summary

B. Comparison between open and closed sections

In previous section, comparison between shapes of cross section area was conducted, it was concluded that circular cross section tube was the best from impact energy absorption point of view, while square cross section was the worst. In this section, a comparison between open Vs. closed cross section will be discussed. Figure 21 shows the investigated open sections; they are the same cross section area of R2 and S2 in table 2. Specimen OS1 is equivalent to S2, while OR1 and OR2 are equivalent to R2 with 2 different orientations, all sections are 384 mm^2 area. Figure 22 shows the comparison between absorbed energy value of closed and open sections.

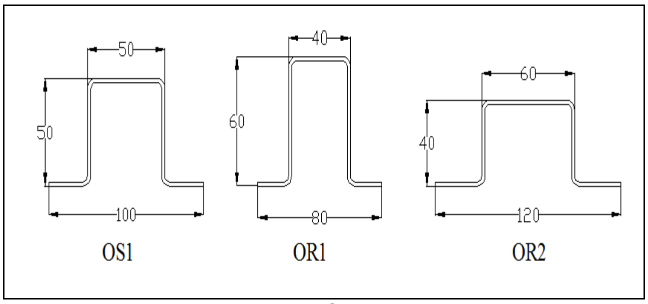

Fig. 21 proposed open sections

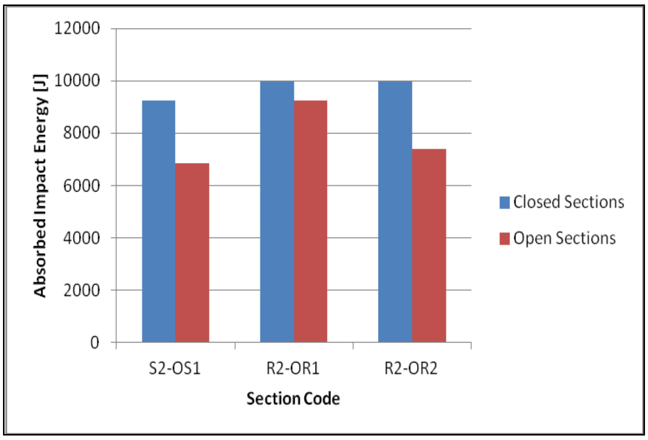

Fig.22 comparison between open and closed section

As shown in figure 22, using open section in case of square tube reduces the absorbed energy by 26%, replacing closed rectangular section with open one, first case is when the open side is the minor side, absorbed energy reduced by 7%., while in case of open side is the major side, energy absorbed reduced by 25.6%. as general conclusion, closed sections is preferred in case of energy absorption applications. More parameters will be investigated in the next section.

C. effect of fillet radius on energy absorption

In this section, the effect of fillet radius value on energy absorption ability will be investigated. As mentioned before in table 2 that the fillet radius F is 5 mm. in this section, the fillet radius F will be 10, 15 and 20 mm for both S2 and R2 sections. Figures 23 and 24 shows the progress of fillet radius change. Table 3 summaries the utilized specimen for this paper. Effect of fillet radius is shown in figures 25 to 30.

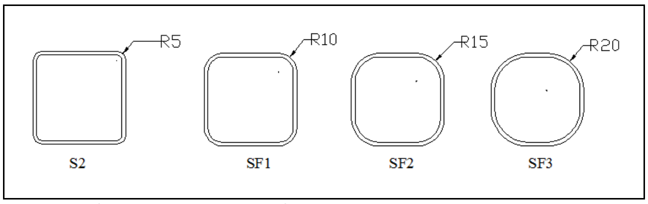

Fig. 23 fillet radius proposed for comparison between square sections

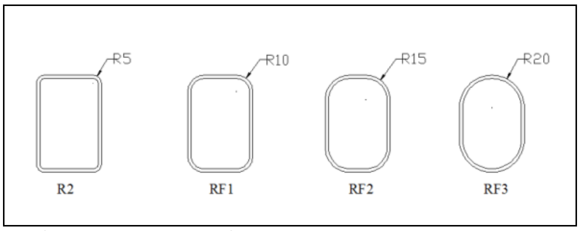

Fig. 24 fillet radius proposed for comparison between rectangular sections

Table 3

Specimen Code	Main Dimensions [mm]	Fillet Radius [mm]
S1	40X40X2	5
SF1	40X40X2	10
SF2	40X40X2	15
S2	50X50X2	5
SF3	50X50X2	10
SF4	50X50X2	15
SF5	50X50X2	20
S3	60X60X2	5
SF6	60X60X2	10
SF7	60X60X2	15
SF8	60X60X2	20
SF9	60X60X2	25
R1	50X30X2	5
RF1	50X30X2	10
RF2	50X30X2	15
R2	60X40X2	5
RF3	60X40X2	10
RF4	60X40X2	15
RF5	60X40X2	20
R3	70X50X2	5
RF6	70X50X2	10
RF7	70X50X2	15
RF8	70X50X2	20
RF9	70X50X2	25

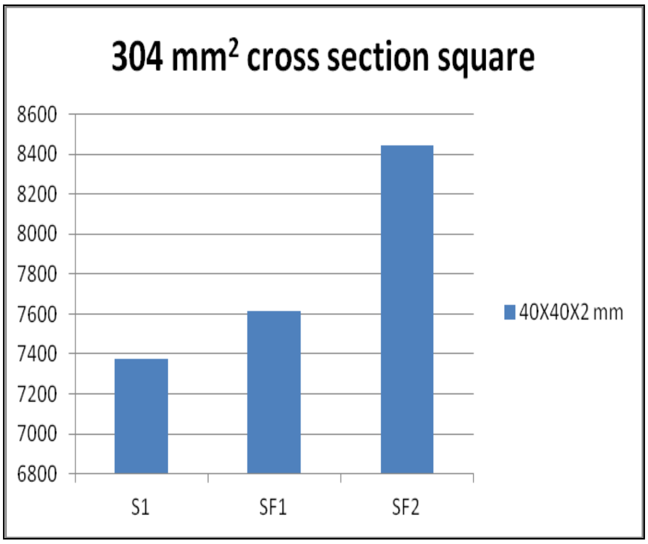

Fig.25 Effect of fillet radius on absorbed energy for 40X40 tubes

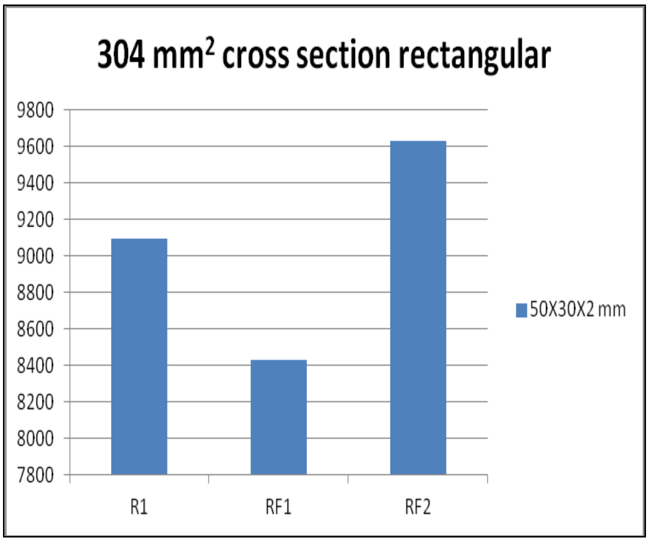

Fig.26 Effect of fillet radius on absorbed energy for 50X30 tubes

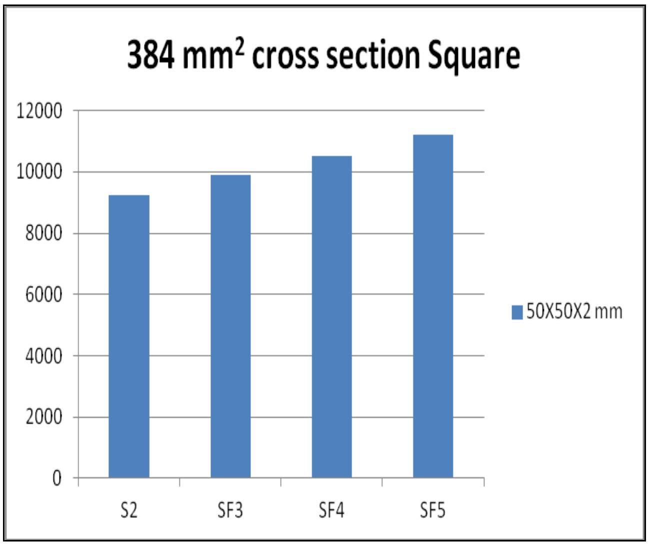

Fig.27 Effect of fillet radius on absorbed energy for 50X50 tubes

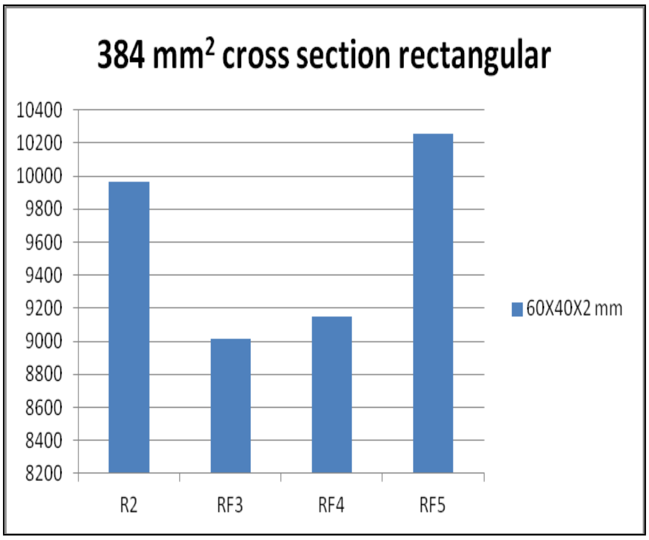

Fig.28 Effect of fillet radius on absorbed energy for 60X40 tubes

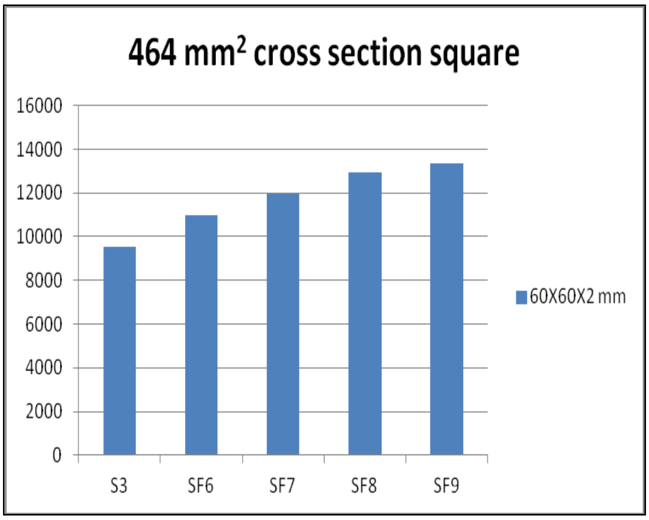

Fig.29 Effect of fillet radius on absorbed energy for 60X60 tubes

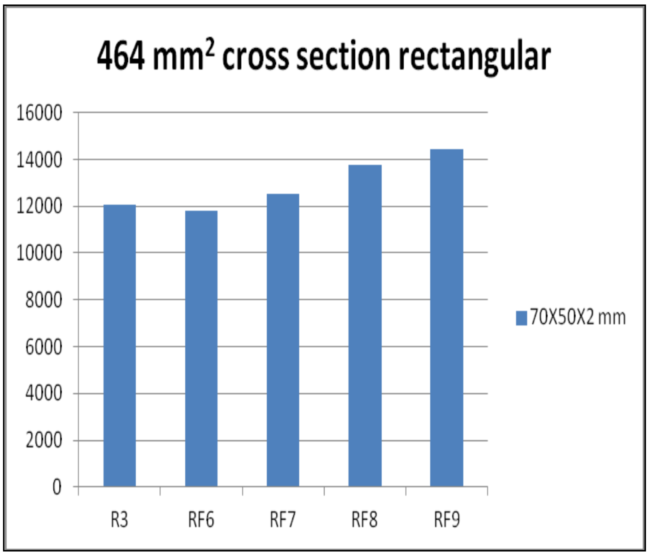

Fig.30 Effect of fillet radius on absorbed energy for 70X50 tubes

As shown in previous figures, 25 to 30, tube fillet radius has a significant effect on absorbed impact energy by these tubes for both square and rectangular cross section. The same tests were conducted on all tubes dimensions utilized before so that the effect of radius is confirmed. For square cross section, increasing the fillet radius leads to increase of absorbed amount of impact energy, figures 25, 27 and 29. While in case of rectangular cross section, leads to sudden decrease in amount of absorbed impact energy, then the absorbed energy value increased as fillet radius increase, finally significant increase when fillet radius is the same cross section radius, figure 28 RF5 specimen. In this case specimen is composed of circular shape with two straight sides. This configuration absorbs the maximum amount of impact energy. It must be noted that there is a limit to increase the fillet radius as maximum radius can achieved is the rectangular cross section radius. All values were compared with the original 5 [mm] filleted specimen

For 40X40 sections, when fillet radius increased to 10 [mm], absorbed energy increased by 3 %, while when radius increased to 15 [mm], absorbed energy increased to 14%. For 50X50 section, increasing fillet radius to 10 [mm] leads to increase in absorbed energy by 7%, for radii 15 and 20 [mm] absorbed energy increased by 14% , 21% respectively. For 60X60 section, changing fillet radius from 5 [mm] to 10,15,20 and 25 [mm] increase the absorbed impact energy by 15%, 25%, 35% and 40% respectively. Variation in previous percentage is due to the capability of each specimen to absorb impact energy.

On the other hand, for 50X30 sections, replacing fillet radius from 5 [mm] to 10 [mm] decreased the absorbed energy by 7%, while when radius became 15 [mm] absorbed energy increased by 6%. For 60X40 sections, replacing 5 [mm] fillet radius by 10 and 15 [mm] decreased the amount of absorbed energy by 10.5% and 9% while replacing the fillet radius from 5 [mm] to 20 [mm] increased the amount of absorbed energy by 3%. Finally shifting from 5 [mm] to 10 [mm] fillet radius leads to decrease the amount of absorbed energy by 2%, while when it replaced by 15,20 and 25 [mm], absorbed energy increased by 4%, 13% and 19% respectively.

VI. SUMMARY

In this paper, behavior of closed section tubes subjected to impact load was investigated experimentally and theoretically. Previous tubes were investigated as it utilized in passenger coaches body manufacturing, and the aim of this paper to recommend solutions to enhance accident impact energy absorption by the bus frame. Load displacement history for impacted tubes was obtained experimentally; a finite element model was introduced and validated. Theoretical results show good correlation with experimental results, which is an indication that proposed finite element method can be utilized for further investigations and comparisons. A set of specimens were tested using finite element analysis, results show that circular cross section is the best form point of view of absorbed amount of impact energy, while square cross section tubes are the worst. Also results shows that closed sections can absorb impact energy better than open section. Finally, the effect of corner fillet of square and rectangular cross section on amount of impact energy absorbed was investigated. Results show that, for square cross section, increasing fillet radius leads to increase in the amount of absorbed energy, while in rectangular cross section increasing fillet radius leads to decrease in absorbed amount of energy, but when fillet radius achieve rectangular cross section value, amount of absorbed energy increased significantly.

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