Effect of Thin-walled Tube Geometry on Its Crashworthiness Performance

Anton Kuznetcov, Igor Telichev, Christine Q. Wu
University of Manitoba, Canada

Abstract

The present paper deals with the numerical analysis supporting the crashworthiness design of a thin-walled tube. The thickness and wall shape were parametrically changed to study their effect on the tube performance under the axial impact. Different tube geometries were evaluated based on the common crashworthiness criteria to identify the effective designs which provide the efficient energy absorption and low peak force. The applicability of selected criteria for crashworthiness design was discussed. The observations obtained in the parametric study can be used to improve the crash behavior of energy-absorbing structures.

1 Introduction

For a modern passenger vehicle the ability of the structure to protect its occupants during the impact is one of the main performance indicators strictly controlled by the government regulations. The structural design for crashworthiness is a challenging engineering problem requiring the careful tradeoff between structure's static strength, stiffness, and ability to absorb the energy during the impact in a controlled and efficient manner. Today in a passenger car, the energy absorption during a collision is mainly provided by the thin-walled tubular members such as front rails and crashboxes.

The optimal design of the thin-walled energy absorbers has received a lot of attention in recent years. Many researches have performed the parametric studies on a crashbox geometry and material in order to improve its performance for different loading conditions.

Under axial loading a thin-walled tube can exhibit two main deformation modes: global buckling and progressive local buckling or crushing, with the last one being more preferable due to much larger energy absorbing capacity. By studying the axial collapse of steel tubes with different cross sectional dimensions and lengths Abramowicz and Jones [1] have found the critical value of length/width ratio marking the transition from progressive to global buckling. It was shown that the critical value of the ratio is increased with the increasing of width/thickness ratio.

For progressive buckling the energy absorption capability increases with the increase of a number of buckling lobes formed during the impact, as clearly demonstrated by the analytical solution for the axial crushing of square tube obtained by Abramowicz and Wierzbicki [2]. The number of lobes is not sensitive to the small thickness variations, but heavily depends on the material yield strength [3]. By filling the crashbox with the low-density material such as aluminum form, the number of lobes can be increased, leading to the increase in the energy absorbing capability [4] The similar effect can be achieved by using the concentric and multi-cell tubes [5, 6 ,7].

Together with energy absorbing capability, the peak crushing force generated during the impact is another important design criteria. High peak force will result in the increased acceleration transmitted from the frame to the passenger compartment. Since the peak force typically appears during the formation of the first lobe, it can be decreased by decreasing the initial stiffness of the

tube by means of the local geometry modifications in the form of holes, dents, etc. [8]. Such crush initiators are able to decrease the initial peak load and trigger the regular collapse behavior. Qureshi et al. [9] studied the effect of sinusoidal shape alternation on the collapse behaviour of the thin tubes. It was found, that both the energy absorbing capability and the peak force can be controlled by changing certain parameters of the sinusoidal pattern.
A number of additional crashworthiness criteria is developed for specific applications. To compare different crush initiator designs for a constant energy absorption, a load uniformity parameter can be used [10]. The energy absorbing capability of different materials can be evaluated using energy-absorbing effectiveness factor [5]. Most of the general crashworthiness optimization problems are formulated as either multiobjective optimization of both energy absorption and peak force [6, 11], or a single objective optimization with the constraints on other criterial parameters [7, 12, 13]. Since the choice of the weighting coefficients and fixed constraint values are subjective, there is still a call to search for alternative formulation of crashworthiness optimization problems.

In the present paper the attempt is made to perform the numerical study of the properties of the optimally designed crashboxes and compare different crashworthiness criteria used for the crashbox evaluation. First, a parametric study on crashbox shape modification is carried out to identify the effective designs, and then the designs are compared in terms of number of common crashworthiness criteria.

2 Numerical Test Setup

The parametric study is targeted to identify the efficient crashbox designs of the given length, cross-sectional dimensions and loading condition, by varying tube thickness and shape. The study is performed using LS-DYNA® explicit finite element model for simulation of the crashbox axial impact.
The impact test setup for numerical analysis was chosen to be identical to the one used in the reference [3]. The aluminum crashbox with square cross section of 80 x 80 mm and free length of 310 mm is fixed in the clamping device on one end and is impacted by the 56 kg rigid mass at initial velocity of 15.6 m/s from the other end (Figure 1).
For each crashbox design, force-deflection curve is extracted from the simulation results. Based on the curve, the following common crashworthiness criteria are used to evaluate crashbox performance:

- Energy Absorption (EA) is a total amount of energy absorbed by a crashbox, calculated as area under force-deflection curve: $EA = \int_0^{\delta_{max}} F(\delta) d\delta$, where F is the instantaneous crushing force; δ is the vertical displacement of the mass;
- Specific Energy Absorption ($SEA = EA/M$) is energy absorption per unit mass;
- Peak Crushing Force (PCF) is the maximum reaction force generated during the impact;
- Mean Crushing Force is $MCF = EA/\delta_{max}$;
- Load Uniformity is $LU = PCF/MCF$.

Additionally, maximum deflection (MD) and peak acceleration (PA) are recorded.
The energy-absorbing effectiveness factor is not considered in the study, since the geometry variations are made for the same material, and the factor is equivalent to energy absorption.

The finite element model of the crashbox is built for one quarter of the crashbox, utilizing two vertical planes of symmetry. The geometry is meshed using standard Belytschko-Tsay finite elements with five integration points across the thickness and stiffness-type hourglass control. The impacting mass is modeled using rigid brick elements. The initial velocity is assigned to the mass, and gravity acceleration is applied to all bodies in the model. The lower edge of the crashbox is constrained in all degrees of freedom. The nodes at the part of the tube constrained in the camp during the physical test are allowed to move only in the vertical direction. The contact between crashbox and impacting mass is defined using nodes-to-surface algorithm with a friction coefficient of 0.2, while crashbox self-contact is modeled using the frictionless single surface contact. Since the crashbox geometry will be varied in the broad range, additional contact is defined between the impacting mass and rigid buffer to prevent the complete bottoming-out of the tube (Figure 1). The buffer is rigidly constrained in the space. The distance from the upper crashbox end to the buffer is 300 mm.

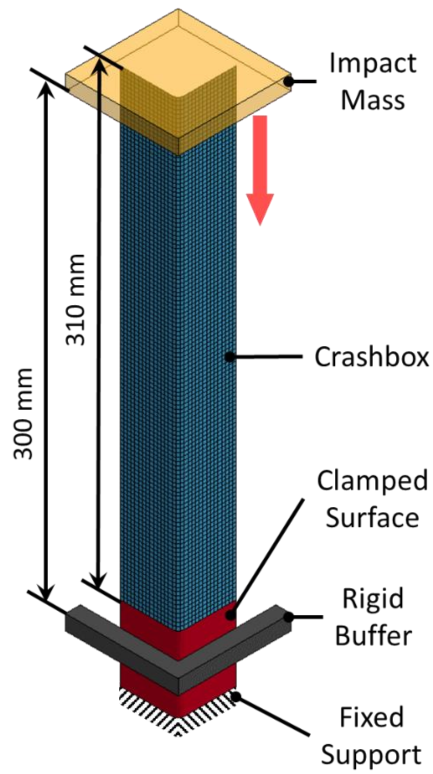

Figure 1 – Model Setup

The model is validated against experimental data [3]. The comparison of the force-deflection curves is presented in Figure 2, while Table 1 gives the qualitative comparison in terms of energy absorption, peak, and mean crushing forces.

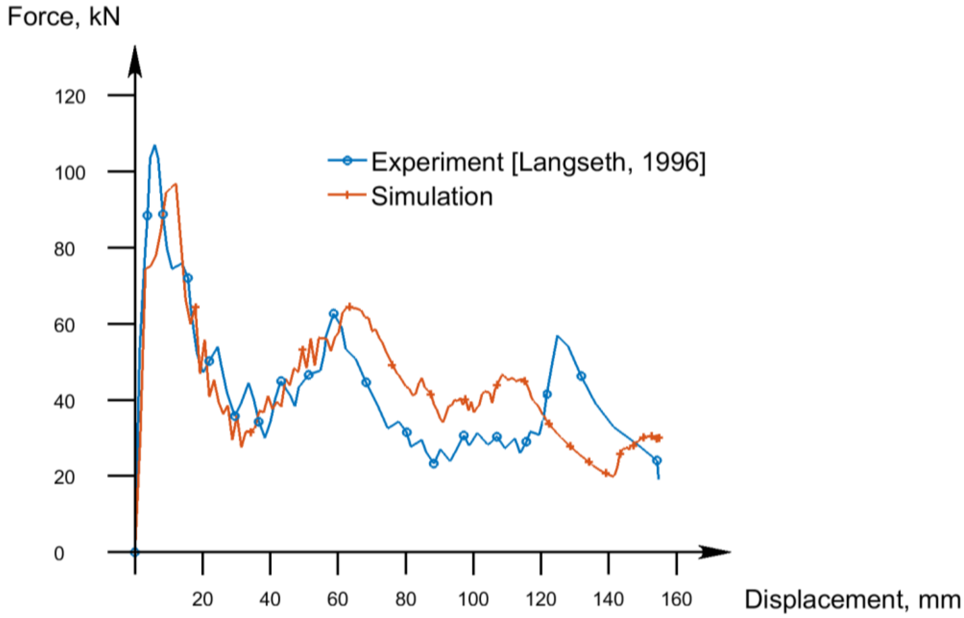

Figure 2 – Comparison of Force-Deflection Curves

Table 1 – Comparison of Criteria Values

	EA, J	PCF, kN	MCF, kN
Experiment [Langseth, 1996]	6578.5	107.0	42.5
Simulation	6872.8	96.9	44.4
Difference	4.5%	9.4%	4.3%

2 Thickness variation

At the first stage, the thickness of a crashbox is varied in the range from 0.5 mm to 5 mm. The lower values of the thickness is selected to produce bottomed-out designs, while the highest thickness value results in the formation of only one buckling lobe.

The comparison of different crashworthiness criteria is presented in Table 2. Here t is a crashbox thickness, M is a mass. All other abbreviations have been explained in the previous section. The input energy is the sum of the kinetic energy of the impacting mass and the work done by gravity on the maximum deflection of the mass. Crushing force is measured at the impact mass, but does not include forces produced by the impact to the buffer. Deflection and acceleration are measured at the mass and do include the effect of impact to the buffer. Due to symmetry, two crushing modes are found in the simulation: extensional and symmetrical. In the Table 2 these modes are marked as S for symmetrical and E for extensional. The modes are illustrated in Figure 3.

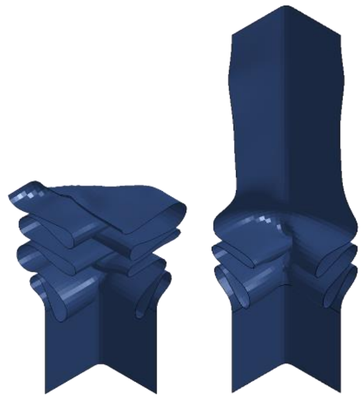

Figure 3 – Crushing Modes of the Specimens
a) Symmetric Mode (S) of 2 mm tube; b) Extensional Mode (E) of 2 mm tube

Table 2 – Comparison of Crashworthiness Criteria for Thickness Variation

t, mm	M, kg	Input Energy,kJ	EA, kJ	SEA, kJ/kg	PCF, kN	MCF, kN	LU	PA, m/s²	MD, mm	Mode	Number of Lobes
0.5	0.15	6.98	1.51	10.3	36.4	5.0	7.2	79573	300.0**	S	4
1.0	0.29	6.98	3.78	12.9	81.8	12.6	6.5	61284	300.0**	S	4
1.5	0.44	6.97	6.96	15.8	111.7	24.2	4.6	1986	288.2	S	4
2.0	0.59	6.95	6.96	11.8	74.1	27.5	2.7	1318	253.3	S	4
2.5	0.73	6.89	6.89	9.4	95.9	48.6	2.0	1706	141.7	E	2+
3.0	0.88	6.87	6.87	7.8	117.9	65.7	1.8	2098	104.6	E	1+
3.5	1.03	6.85	6.84	6.7	145.6	91.9	1.6	2591	74.4	E	1
4.0	1.18	6.85	6.84	5.8	179.6	108.8	1.7	3195	62.9	E	1
4.5	1.32	6.84	6.83	5.2	214.2	135.1	1.6	3816	50.5	E	1
5.0	1.47	6.84	6.81	4.6	244.0	172.0	1.4	4349	39.6	E	1

For each criteria the color is varied according to the value in the cell from "best" to "worst"

* – Peak value is reached at the end of the impact
** – Specimen is bottomed-out
S – Symmetrical Crushing Mode
E – Extensional Crushing Mode

As can be seen from Table 2, the specimens with two smallest thicknesses of 0.5 mm and 1 mm are not able to absorb all the impact energy, which results in the bottoming-out. For all other designs the amount of energy absorbed is equal to the amount of input energy, with negligible variations due to numerical noise. Maximum deflection of two thinnest specimens is equal to the distance from the impact end of the crashbox to the buffer. The impact of the rigid mass to the rigid buffer results in extremely high acceleration levels (PA column in Table 2).

The thinnest tube with no bottoming-out (1.5 mm thickness) shows the highest specific energy absorption and lowest acceleration level. Although the peak crushing force is relatively high compared to the tubes with similar thickness, which can be explained by the analysis of the force-deflection curve (Figure 4).

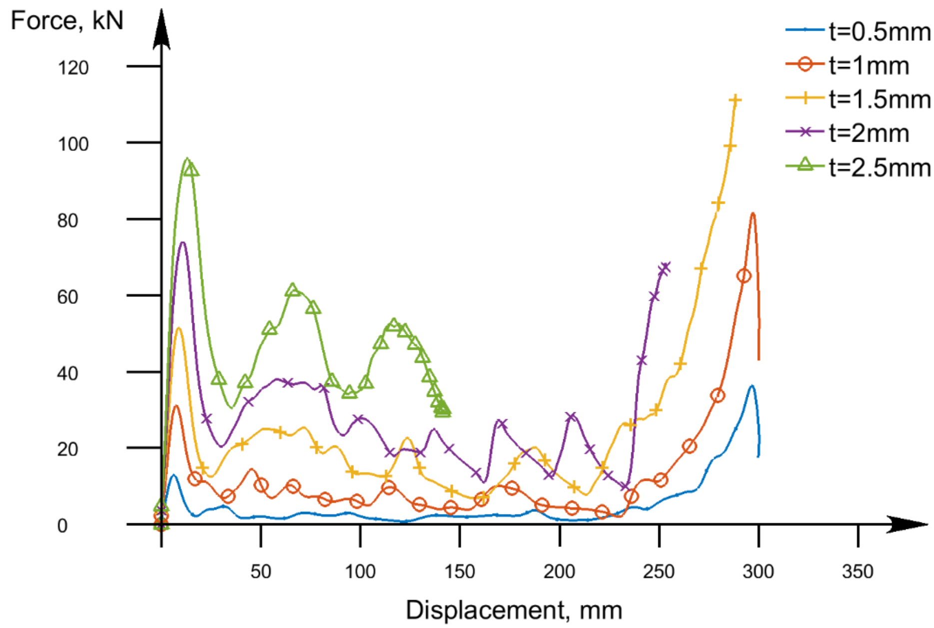

Figure 4 – Force-Deflection Curves for Thickness Variations

For the tubes with thickness from 0.5 mm to 2.0 mm the peak crushing force is achieved in the end of the impact, when fully formed lobes come into self-contact and stiffness of the deformed tube rapidly increases with the increase of the deformation. For 0.5 mm and 1.0 mm thickness the high force is prevented by the buffer. For larger thickness, the force at the end of the impact decreases with the increase in stiffness and decrease in deformation. With further increase in thickness, the initial impact peak becomes dominant. That explains the sudden increase in the peak force between 2.0 mm and 2.5 mm tubes.

For the thicknesses from 2 mm to 3 mm a transition from the symmetrical collapse mode to extensional mode is observed with rapid decrease in number of formed buckling lobes with increase in thickness (last two columns in Table 2). For the thicknesses greater than 3 mm all criteria have similar values, since the number of lobes stays constant.

As the summary for thickness variation study, a crashbox with 1.5 mm thickness is selected as the most efficient design, having highest specific energy absorption and lowest peak acceleration magnitude.

3 Wall Shape Modifications

Many researches have pointed out the positive effect of local wall shape modification on the value of peak crushing force (e.g. see [8] for the review). Thus, shape modification is used in the present study to improve the performance of the tube with given thickness. The shape modification is done based on the first buckling mode, obtained from the linear (eigenvalue) buckling analysis. The first buckling mode represents the preferable deformation mode for the tube under compressive axial loading, thus it is interesting to investigate the effect of triggering that mode during dynamic crushing by shape modification.

The buckling analysis is performed using implicit solver. The unclamped portion of the crashbox is simply supported at both ends, and compressed by the means of compressive displacement applied at the upper end (Figure 5). The first five mode shapes are shown in Figure 6.

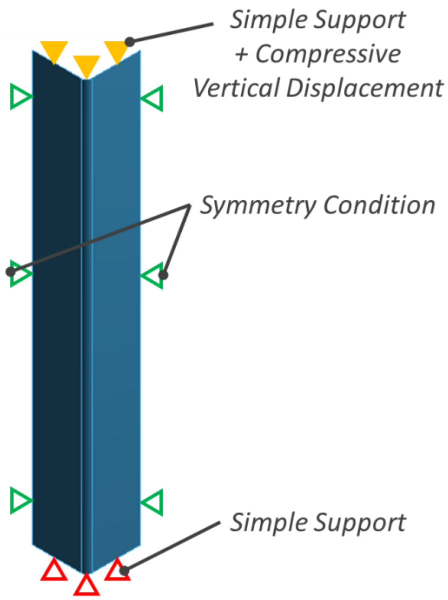

Figure 5 – Boundary Conditions for Linear Buckling Analysis

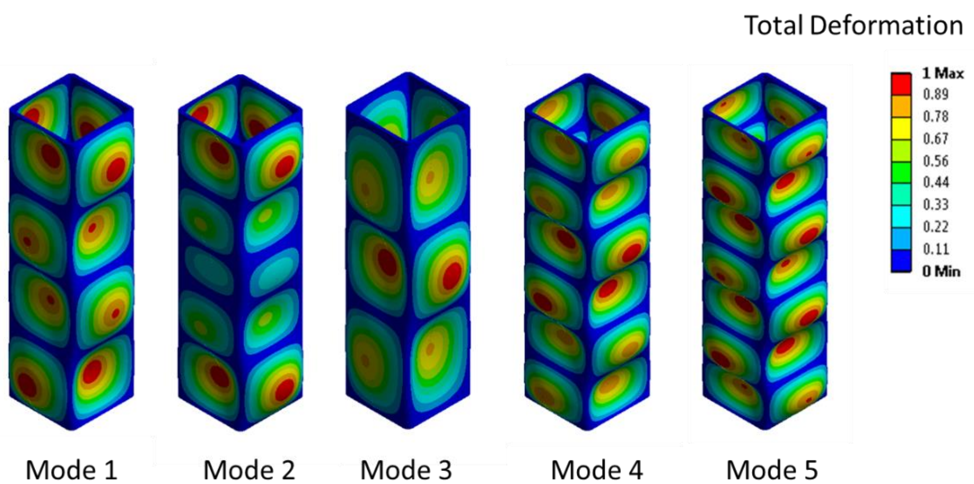

Figure 6 – Linear Buckling Mode Shapes for the tube with 3.5 mm thickness

The normalized first buckling mode shape (Figure 6) with unit amplitude, is extracted from the results, scaled, and applied to the nodes of the explicit model for impact simulation. Four amplitudes of the shape modifications is considered, relative to the crashbox thickness: 0.1%, 1%, 10%, 100%. The lowest amplitude has almost no effect on the impact behavior of the crashbox and included for verification purposes. Alternations with amplitude of 1% of the wall thickness is the typical imperfection amplitude in the real tubes, resulting from manufacturing

process [14], while the amplitude equal to tube thickness is considered as practical limit in terms of manufacturability and static strength.
For shape modification, the tube with 3.5 mm thickness is selected based on the results of thickness variation study. Little positive effect can be expected form the modification of the 1.5 mm tube, since it is already close to the bottoming out, and further decrease in stiffness will result in mass impacting the buffer. The 3.5 mm tube, form other hand, is considered as representative of the thick tubes, producing only one buckling lobe, and consequently having high peak force and peak acceleration values. The shape alternations is applied in the attempt to lower these values and improve overall crush performance.
The results of the impact simulation of the crashbox with wall shape altered to a different magnitudes are shown in Table 3 and Figure 7.

Table 3 – Comparison of Crashworthiness Criteria for Different Shape Alternation Magnitudes (w)

w, mm	Input Energy, mJ	EA, kJ	PCF, kN	MCF, kN	LU	PA, m/s²	MD, mm
Unmodified	6.85	6.84	145.6	91.9	1.6	2591	74.4
0.0035	6.86	6.85	145.4	90.6	1.6	2589	75.5
0.035	6.87	6.87	139.6	68.8	2.0	2486	99.8
0.35	6.88	6.89	119.2	55.1	2.2	2119	125.0
3.5	6.90	6.90	73.9	44.6	1.7	1303	154.7

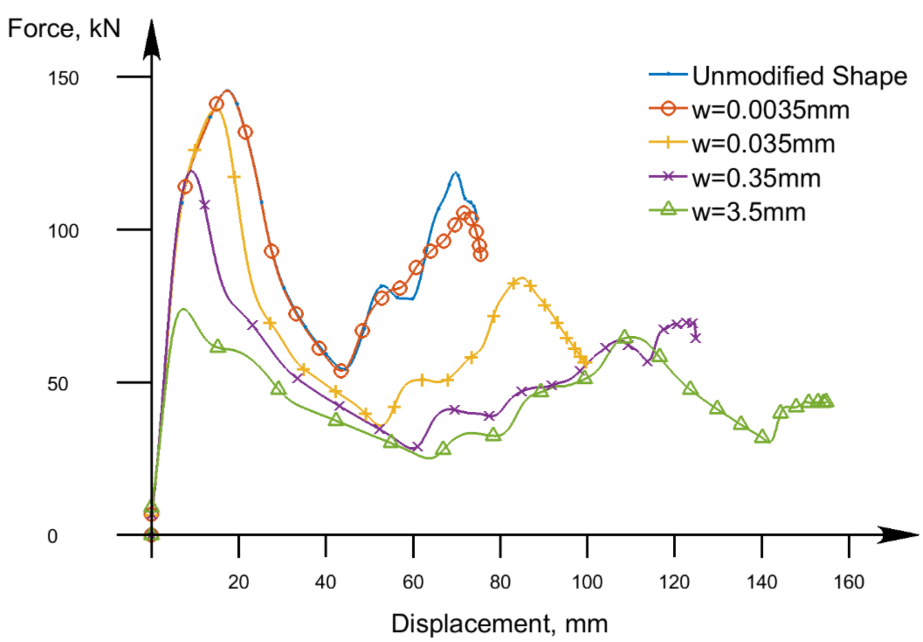

Figure 7 – Effect of Alternation Magnitude (w) on Force-Deflection Curves

As expected, the smallest magnitude of 0.1% of the thickness has almost no effect on the tube crush behavior. With the exception of this tube, all other modified tubes produce the same deformation mode, dictated by the applied shape pattern. Thus, with the modification of the wall shape the deformation mode changes from extensional to symmetrical (Figure 8). Both the peak force and peak accelerations are reduced significantly with the increase in the alternation magnitudes. For the highest amplitude considered (equal to the crashbox thickness) the peak crushing force is reduced by 50%, while the peak acceleration is reduced by almost 60%.

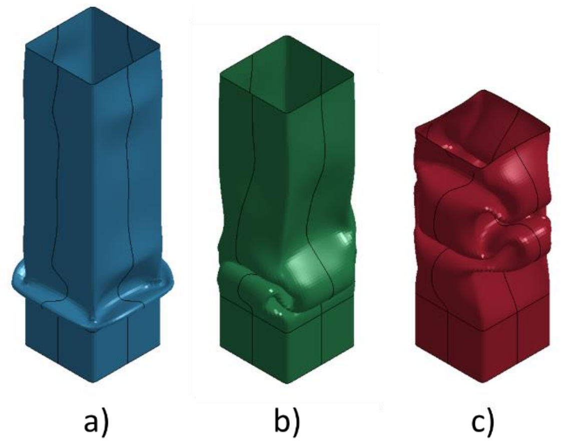

Figure 8 – Effect of Shape Alternations on Deformation Mode:
Extensional Mode for Unmodified Tube (a)
Symmetrical Mode for Modified Tubes: b) w=0.035 mm, c) w=3.5 mm

To investigate the effect of number of half-waves in the shape alternation pattern on the crashbox performance, the tube shape is modified according to the first five linear buckling modes with the constant amplitude of 3.5 mm. The results are summarized in the Table 4.

Table 4 – Comparison of Crashworthiness Criteria for Alternations According to Different Buckling Modes

Buckling Mode	Number of half-waves	Input Energy, mJ	EA, kJ	PCF, kN	MCF, kN	LU	PA, m/s²	MD, mm
Unmodified		6.85	6.84	145.6	91.9	1.6	2591	74.4
1	4	6.90	6.90	73.9	44.6	1.7	1303	154.7
2	5	6.89	6.89	73.6	47.3	1.6	1294	145.8
3	3	6.89	6.89	85.0	50.7	1.7	1489	135.8
4	6	6.90	6.90	63.6	44.0	1.4	1122	156.9
5	7	6.90	6.89	61.1	45.2	1.4	1079	152.5

As can be seen from Table 4, the increase in the number of lobes have positive effect of the peak crushing force and peak acceleration. However the effect is not such pronounced as increase in the alternation magnitude. The switch from 3 to 7 half-waves decreases the peak force level by about 17%.

4 Summary & Discussion

Table 5 summarizes the results obtained for the selected variation in crashbox geometry. The unmodified 1.5 mm tube and two 3.5 mm tubes with altered shape are considered as efficient designs, while unmodified tubes with 1 mm and 3.5 mm are included for comparison.

Table 5 – Summary of the Results

Shape		t,mm	M, kg	Input Energy, kJ	EA, kJ	SEA, kJ/kg	PCF, kN	MCF, kN	LU	PA, m/s²	MD, mm
Unmodified		1.0	0.29	6.81	3.78	12.9	81.8	12.6	6.5	61284.2	300.0
		1.5	0.44	6.97	6.96	15.8	111.7	24.2	4.6	1986	288.2
		3.5	1.03	6.85	6.84	6.7	145.6	91.9	1.6	2591.4	74.4
Altered to	Mode1	3.5	1.03	6.90	6.90	6.7	73.9	44.6	1.7	1303	154.7
	Mode5	3.5	1.03	6.90	6.89	6.7	61.1	45.2	1.4	1079	152.5

The following crashworthiness criteria are used to compare the crashbox design in the present study: energy, absorption, specific energy absorption, peak and mean crushing forces, load uniformity and peak acceleration. All of these crashworthiness criteria are indirectly related to the safety of the passengers, with the peak acceleration having the clearest influence.

If bottoming out is avoided, the amount of absorbed energy is equal to the amount of input energy. In the absence of gravity, affecting the movement of the impact mass, the energy absorption for all considered crashboxes will be the same. Thus, the energy absorption cannot be used as standalone criterion in this case.

In case of variation in the amount of material, specific energy absorption can be a valuable criteria, with the highest number achieved for the lightest crashbox, capable of absorbing all the input energy (Table 2). However, the criterion cannot be used for the shape modifications, since the mass of the crashbox stays constant in that case.

Peak crushing force, as measured in the present work, does not include the effect of the rigid rebound from the buffer in case of the bottoming out. Consequently, the low value can be achieved for the weakest crashbox, which produces the smallest resistance to the deformation. If the peak force will be measured taking into account the effect of the impact with the buffer, it will be equivalent to the peak acceleration presented here.

For the constant energy absorption the mean force is inversely proportional to the peak crushing force. So the design efficient in terms of peak force should be efficient in terms of mean crushing force. This can be seen in the Table 5, where the 3.5 mm tube with shape modified to the 5th buckling mode is the most efficient one in terms of peak crushing force, mean crushing force and load uniformity. However, for the broad variations in thickness and shape, considered in the paper (Tables 2 – 4) the MCF and LU show contradictory results. The designs preferable in terms of mean force and load uniformity appear to have large peak crushing force and acceleration magnitudes.

Based on the above discussion the peak acceleration can be concluded to be most appropriate criterion for the general crashbox design optimization, since it takes into account bottoming-out effects and in some way is related to the safety of the occupants. However, its application is limited to a very simple problems, where it can be measured in the way that it is only affected by the process of energy absorption, and does not include secondary effects. Additionally, minimization of the peak acceleration does not guarantee increase in the passenger safety, due to complex kinematics of the occupants during the impact. Effect of acceleration time history should be taken into account. Some researchers have pointed out [15], that for the given impact momentum, higher acceleration at the beginning can result in smaller injury risk for the passengers.

As no single criteria can be used for the final selection of the optimal crashbox design, further research in the crashworthiness criteria is needed.

5 Conclusions

In the present study the thickness and shape of a thin-walled tube is varied, and its performance under axial impact is evaluated. For thickness variation, the most efficient design is found on the border of bottoming-out. The decrease in the thickness from the optimal value will result in the mass impacting the rigid buffer, and, consequently, in high acceleration levels. The increase in the thickness causes increase in both the mass and stiffness, decreasing the efficiency of the crashbox.

The positive effect of the tube wall shape modification on its crushing performance is illustrated by altering the shape according to the linear buckling modes. It is demonstrated, that peak crushing force is decreasing with increase in both alternation amplitude and number of half waves in the mode shape. No considerable increase in energy absorption is found as a result of shape modification.

The performed parametric study is used as a basis for comparison of different crashworthiness criteria. As it can be expected, no single criteria can identify the single optimal crashbox design. For the modifications considered, two effective designs are identified – one with highest specific energy absorption and lowest acceleration level and one with low peak force, large mean force and high load uniformity.

The acceleration imposed to the impacting mass seems to be most closely connected to the passenger safety, however it cannot be used as standalone criterion. Variation of acceleration with time should be taken into account, and further research in this area in needed.

References

[1] W. Abramowicz, N. Jones, "Transition from initial global bending to progressive buckling of tubes loaded statically and dynamically", International Journal of Impact Engineering, 19 (5-6) (1997), pp. 415-437.

[2] T. Wierzbicki, W. Abramowicz, "On the Crushing Mechanics of Thin-Walled Structures", Journal of Applied Mechanics, 50 (4a) (1983), pp. 727-734.

[3] M. Langseth, O. S. Hopperstad, "Static and Dynamic Axial Crushing of Square Thin-walled Aluminium Extrusions." International Journal of Impact Engineering, 18 (7-8) (1996), pp. 949-968.

[4] A. G. Hanssen, M. Langseth, O. S. Hopperstad, "Static crushing of square aluminium extrusions with aluminium foam filler", International Journal of Mechanical Sciences, 41 (8) (1999), pp. 967-993.

[5] N. Jones, "Energy-absorbing effectiveness factor", International Journal of Impact Engineering, 37 (2010), pp. 754-765.

[6] H. Yin, G. Wen, Z. Liu, Q. Qing, "Crashworthiness optimization design for foam-filled multi-cell thin-walled structures", Thin-Walled Structures, 75 (2014), pp. 8-17.

[7] S. Hou, Q. Li, S. Long, X. Yang, W. Li, "Design optimization of regular hexagonal thin-walled columns with crashworthiness criteria", Finite Elements in Analysis and Design, 43 (2007), pp. 555-565.

[8] S. C. K. Yuen, G. N. Nurick, "The energy-absorbing characteristics of tubular structures with geometric and material modifications: An overview", Applied Mechanics Reviews, 61 (2) (2008), pp. 1-15.

[9] O. M. Qureshi, E. Bertocchi, "Crash behavior of thin-Walled box beams with complex sinusoidal relief patterns", Thin-Walled Structures, 53 (2012), pp. 217-223.

[10] M. Avalle, G. Chiandussi, G. Belingardi, "Design optimization by response surface methodology: application to crashworthiness design of vehicle structures", Structural and Multidisciplinary Optimization, 24 (2002), pp. 325-332.

[11] Z. Zhang, S. Liu, Z. Tang, "Design optimization of cross-sectional configuration of rib-reinforced thin-walled beam", Thin-Walled Structures, 47 (2209), pp 868-878.

[12] D. J. Eby, R. C. Averill, E. D. Goodman, R. S. Sidhua, "Shape optimization of crashworthy structures", Proceedings of 7th international LS-DYNA Users Conference, 2002.

[13] H. Wang, H. Müllerschön. T. Mehrens, "Shape optimization of a crashbox using hyperMorph and LS-OPT®", Proceedings of 4th German LS-DYNA forum, 2005
[14] V. Tarigopula, M. Langseth, O. S. Hopperstad, A. H. Clausen, "Axial crushing of thin-walled high-strength steel sections", International Journal of Impact Engineering, 32 (2006), pp. 847-882.
[15] W. J. Witteman, R. F. C. Kriens, "Numerical Optimization of Crash Pulses", Proceedings of PAM'99, Ninth European Seminar on Advanced Finite Element Simulation Techniques. Darmstadt, Germany, 1999