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Full Length Research Paper

Crash of automotive side member subjected to oblique loading

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This paper presents the crash behavior analysis of automotive side member represented by aluminum square column subjected to oblique loading via finite element method. In crash research, energy absorption capacity is greatly affected by the deformation pattern, thus the collapse behavior and deformation pattern of this column is studied and observed. Effect of the geometrical parameters and loading angle, effect of these parameters on crashworthiness parameters that is specific energy absorption (SEA) and crush force efficiency (CFE) are explored. Observation on deformation pattern of the column shows that the bending is more apparent at the upper end for loading angle of 5 to 15° and at the bottom end for loading angle of 20 to 30°. Results also show that SEA and CFE have less effected on the variation of column width. Ultimately, an equation that is expressed as a function of length and thickness is proposed to estimate crashworthiness parameters.

Key words: Column, oblique loading, crashworthiness.

INTRODUCTION

During crash event, automotive side member will play an important role of absorbing the kinetic energy transferred. Automotive side member component is shown in Figure 1. The automotive side member is unlikely to be subjected to either pure axial or bending collapse, but rather a combination of the two modes. Due to that fact, the frontal barrier crash test of federal motor vehicle safety standards (FMVSS) No. 208 requires a rigid barrier test of up to 48 kmph, for an angle between 0 to 30°. If a thin-walled column experiences global bending instead of axial crushing, the energy absorption will be lower. Numerous studies of both pure bending and axial crushing of square columns have been carried out previously, resulting in an experimental and numerical observation and analytical expressions for mean axial forces and bending moment. In contrast, studies on the oblique loading are limited. Reyes et al., (2002, 2003), (Nagel and Thambiratnam (2006) and Ahmad et al. (2010) has conducted an experimental quasi-static test of oblique loading. Oblique loading for high velocity impact was hard to achieve, thus it is often carried out through numerical simulation. High velocity oblique loading simulation in this study is adopting geometry, loading and boundary conditions from experimental work done by Reyes et al. (2002, 2003) as a basis. An increasingly popular material for vehicle structure that is aluminum alloy is used (Amiruddin et al., 2011; Carle and Blount, 1999; Davies, 2003a, b. The objective of this study is to analyze the crash behavior of aluminum square column subjected to oblique loading and to provide general expression concerning the oblique loading angle and crashworthiness parameters. Good understanding on

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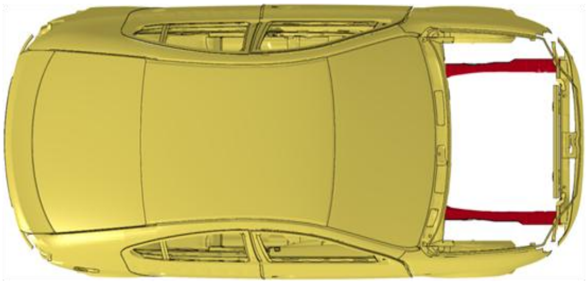

Figure 1. Location of automotive side member.

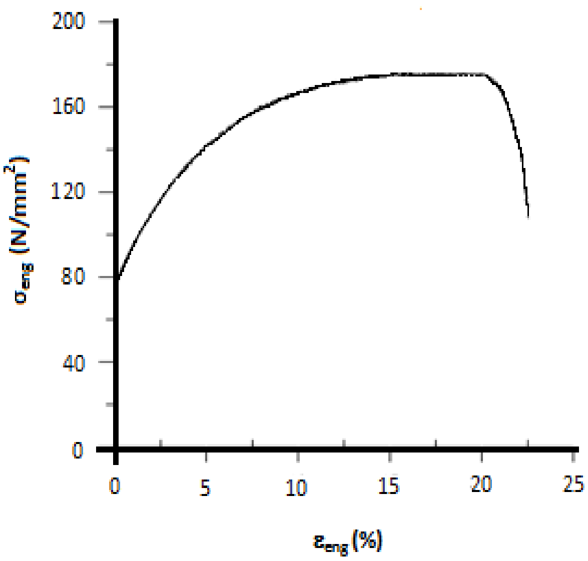

Figure 2. Engineering stress-strain curve for AA6060-T4 (Reyes et al., 2002).

collapse behavior of thin walled column can provide guidelines in improving structure crashworthiness while taking hold of lightweight opportunity offered by aluminum.

In this work, the 'finite element crash' commercial software named Ls-Dyna is used for the numerical simulation. Crash behavior was first examined and then followed by the parametric study.

THEORETICAL BACKGROUND

A few crashworthiness parameters are used to assess the performance of square aluminum column. A good crashworthiness structure can absorb high energy in a controlled manner and yet the forces experienced during collapse do not exceed the allowable range. Parameters involve in this study are the mean load, specific energy absorption (SEA) and crush force efficiency (CFE).

Mean load

The mean crush load is used as the response parameter for energy absorption capability. The mean crush load P_m is defined as (White and Jones, 1999):

$$P_m = \frac{E_a}{\delta} \qquad (1)$$

Where E_a is the energy absorbed during collapse and δ represents displacement.

In this study, value of energy absorbed is taken once in the displacement $\delta = 0.25l$. Resultant displacement in the numerical simulation is given by the node at the upper end of the column.

Specific energy absorption

In the light of structure efficiencies, automotive energy absorbing structure is expected to absorbed more energy with least possible weight. Thus, specific energy absorption is introduced:

$$SEA = \frac{E_a}{m} \qquad (2)$$

Where energy is defined per unit mass, m.

Crush force efficiency

The crush force efficiency (CFE) is defined as the ratio of the mean crush load to the peak crush load (Reyes et al., 2004), $P_{\max}$ as presented in Equation 3:

$$CFE = \frac{P_m}{P_{\max}} \qquad (3)$$

A value of unity represents the most desirable value of the CFE, corresponding to a constant load versus displacement curve.

FINITE ELEMENT MODELING

In this study, the dynamic numerical simulation of oblique loading was carried out on the nonlinear finite element (FE) code LS-DYNA 971. The adopted geometry, loading and boundary conditions and material properties of aluminum thin-walled square specimens reflect the experimental work done by Reyes et al. (2002). Piecewise-linear plasticity model was used to model the square column and inputs are extracted from stress-strain curve as shown in Figure 2. A model of square aluminum column is developed using the Belytschko-Tsay shell element. Material properties of the aluminum column are shown in Table 1. The load was applied at an angle θ through a rigid body as illustrated in Figure 3. The bottom

Table 1. Mechanical properties of AA6060.

Material	E (N/mm^2)	ν	ρ (kg/m^3)	σ_y (N/mm^2)
AA6060	66820	0.33	2700	175

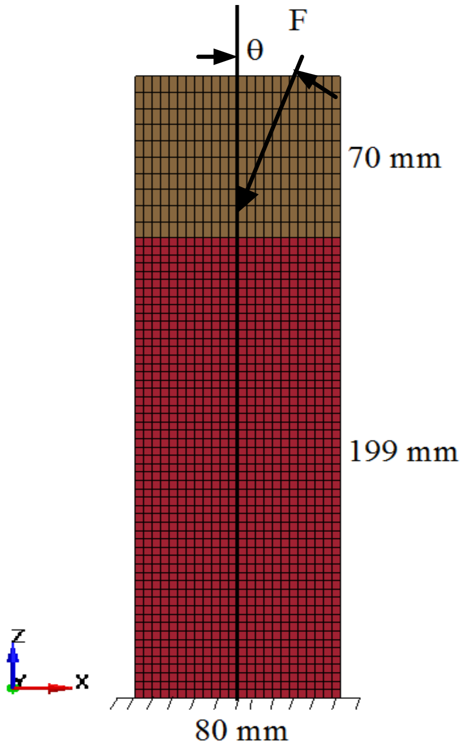

Figure 3. Simulation setup.

end of the column is fixed in all degrees of freedom and the upper end is constrained to the rigid body. A velocity of 48 km/h as indicated in the frontal barrier crash test in FMVSS No. 208 is prescribed to the rigid body.

RESULTS

Collapse behavior

The primary collapse mode of a column is axial and bending collapse. Obliquely loaded column will collapse in both modes (Han and Park, 1999). As shown in Figure 4, the critical angle for transition from axially dominated mode to bending mode is identified to be between 7.5 to 10°. Energy absorption is greatly influenced by the deformation pattern. Figure 4 depicts deformation pattern

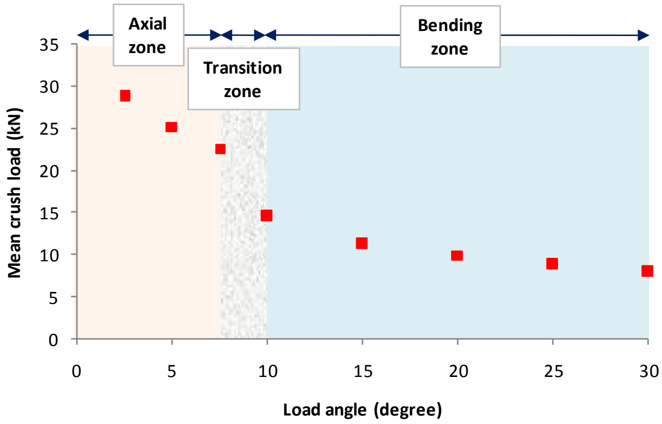

Figure 4. Mean crush load versus load angle.

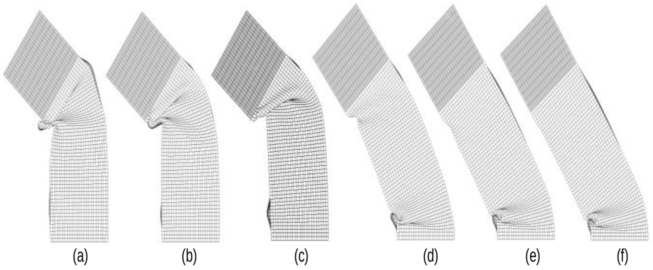

Figure 5. Deformation pattern under loading angle of (a) 5°, (b) 10°, (c) 15°, (d) 20°, (e) 25° and (f) 30°.

for the aluminum square column under different loading angles. It is apparent from Figure 5 that the bending occurred at the upper end for loading angle of 5 to 15°and at the bottom end for loading angle of 20 to 30°. In a pure axial loading, peak force was detected when the column start to buckle and the first lobe appears. The force values then fluctuate as the new lobes are formed. The obliquely loaded column in this study however, reach the peak force indicated by point A in Figure 6 as the column start to buckle and after that, the force decreases as the deformation mode switch from axial to global bending. In contrast to quasi-static obliquely loaded column, column in this study is initially deformed at the upper end. At peak force (point A in Figure 6), the column start to buckle as shown by A in Figure 7. The force rapidly decreases after the peak force as the collapse behavior is switching to bending mode. Upon reaching point B in Figure 6, the deformation has extended towards the bottom end (B in Figure 7). Finally, the local bending deformation arises near the fixed end (point C).

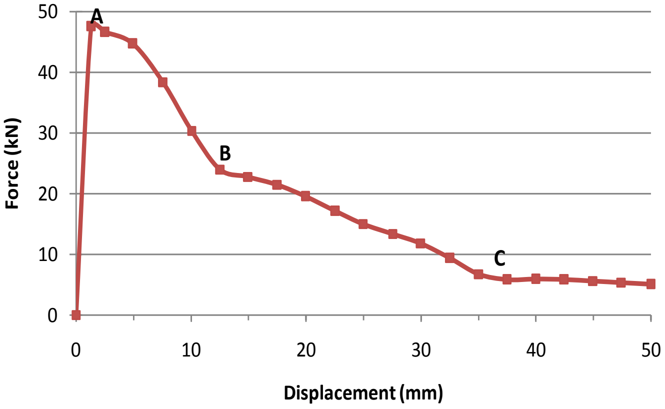

Figure 6. Force versus displacement for square column under 30° oblique loading.

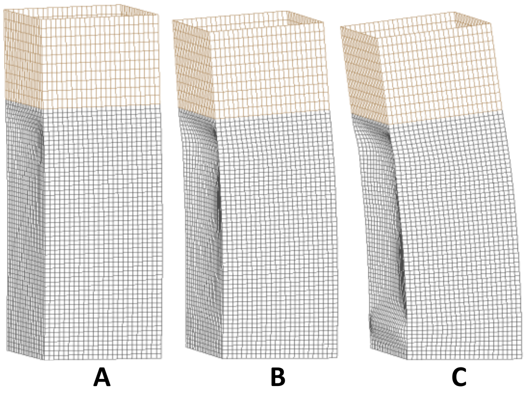

Figure 7. Collapse behavior under oblique loading corresponding to force-displacement curve in Figure 3.

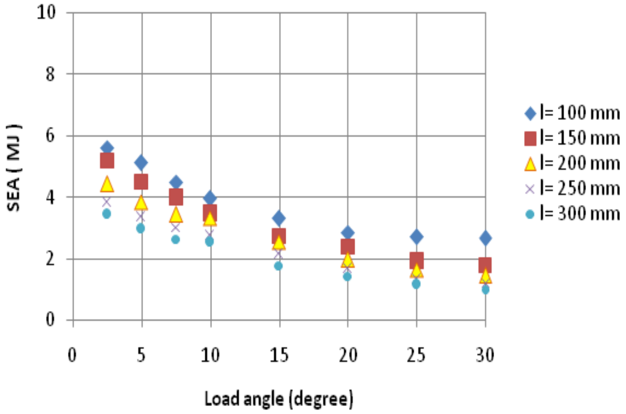

Figure 8. Specific energy absorption versus load angle for different length.

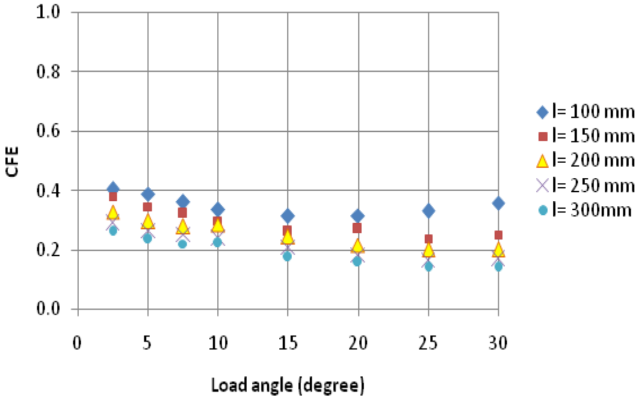

Figure 9. Crush force efficiency versus load angle for different length.

Effect of square column geometries

In this study, three geometrical parameters under considerations are length, width and thickness. The baseline model is shown in Figure 2 that is l = 200 mm, w = 80 mm and t = 1.9 mm. The length is varied between 200 to 300 mm, width is varied between 70 to 90 mm and thickness is varied between 1.4 to 2.7 mm. For the parametric study, the load is applied at an angle from 2.5 to 30°.

Effect of column length

Figure 8 shows the SEA-load angle response of aluminum square columns with varying length. The length is varied with an increment of 50 mm. The displacement considered to calculate for SEA is one-fourth of the column length. Results of the numerical simulation indicates that shorter column are more mass efficient in absorbing energy. The same conclusion was drawn by Jensen et al. (2004) in his experimental investigation of short to long column subjected to axial loading. Long column can absorb big amount of energy but at the cost of adding more mass, thus reducing the amount of energy absorb per unit mass. SEA of the column also decreases as the load angle increase. This phenomenon suggests that by increasing the load angle is actually promoting the local bending to dominate the collapse behavior. Figure 9 depicts the CFE-load angle response of aluminum square columns with varying length. CFE that is close to 1 indicates that the crush load is more

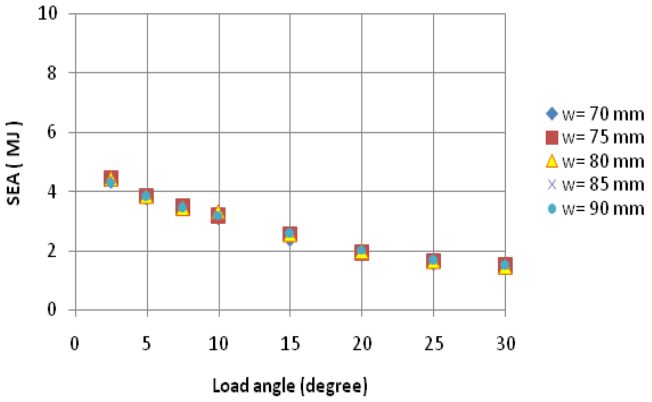

Figure 10. Specific energy absorption versus load angle for different width.

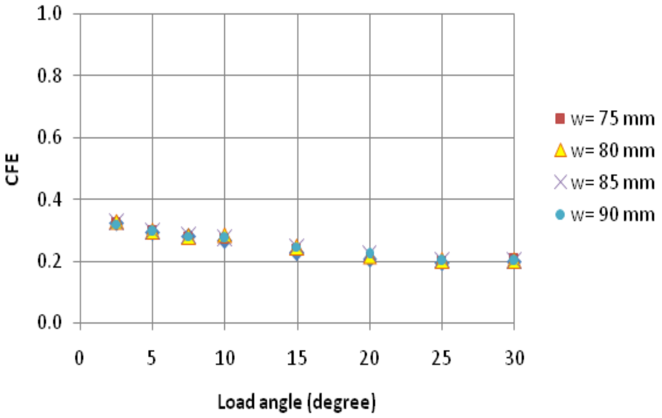

Figure 11. Crush force efficiency versus load angle for different width.

stable. In this obliquely loaded column, a big gap between the value of P_m and $P_{\max}$ contribute to a very low CFE. In this study, the P_m is found to be relatively low since the crush load drastically drop as the bending collapse mode takes place. Moreover, an increment in column length is also found to bring the CFE down because long column is more exposed to unstable deformation.

Effect of column width

Figure 10 shows the SEA-load angle response of aluminum square columns with varying width. The width is varied with an increment of 5 mm. The displacement considered to calculate for SEA is one-fourth of the baseline column length. Results of the numerical simulation indicate that SEA is less affected by the changes in width. Wider column absorbs more energy, but since the energy absorbed increase at almost the same rate as the increase in column weight, the ratio of energy absorb to mass remain the same. As expected, the SEA of the column also decreases as the load angle increase. Figure 11 depicts the CFE-load angle response of aluminum square columns with varying width. An increment in column width demonstrate negligible effect on CFE since the P_m and $P_{\max}$ increase at almost the same rate when the width is increased.

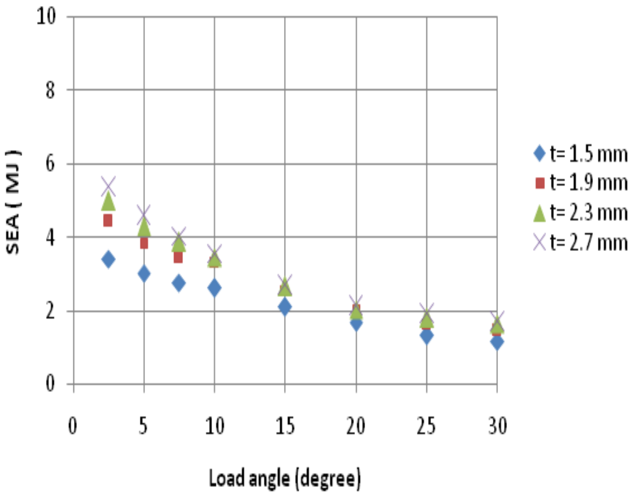

Figure 12. Specific energy absorption versus load angle for different thickness.

Effect of column thickness

Figure 12 shows the SEA-load angle response of aluminum square columns with varying thickness. The thickness is varied with an increment of 0.4 mm. The displacement considered to calculate for SEA is one-fourth of the baseline column length. Results of the numerical simulation indicate that SEA is more sensitive to thickness variation for the loading angles of 2.5 to 10°. As load angle increases, the SEA is negligibly affected by the thickness. Energy absorbed is an integration of P_m and displacement since P_m was found to be less affected by thickness by Han and Park (1999); the same response is shown in SEA of the column. Figure 13 depicts the CFE-load angle response of aluminum square

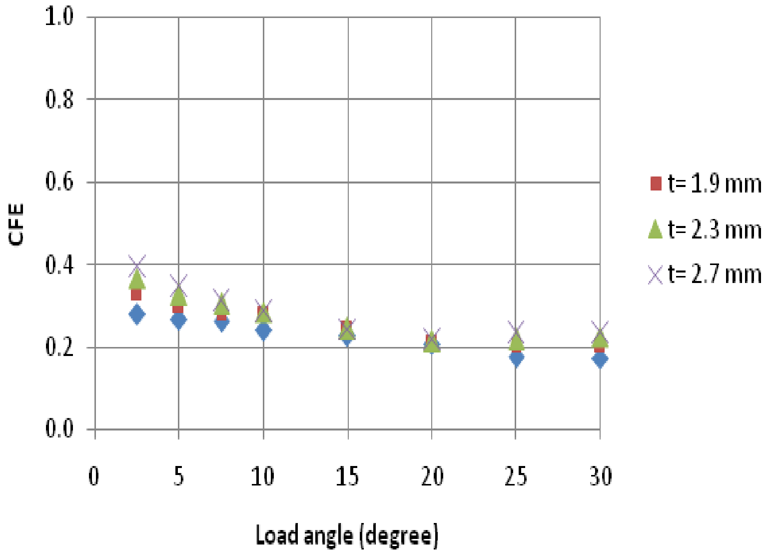

Figure 13. Crush force efficiency versus load angle for different thickness.

Table 2. SEA and CFE obtained for each column geometries combination.

Thickness (mm)	**SEA**					**CFE**				
	Length (mm)					**Length (mm)**				
	100	**150**	**200**	**250**	**300**	**100**	**150**	**200**	**250**	**300**
1.5	2.21	1.58	1.17	1.08	0.91	0.31	0.23	0.17	0.15	0.13
1.9	2.67	1.79	1.46	1.22	1.01	0.36	0.25	0.20	0.17	0.14
2.3	3.00	2.05	1.65	1.39	1.14	0.39	0.29	0.23	0.19	0.16
2.7	3.18	2.20	1.72	1.45	1.23	0.41	0.31	0.24	0.20	0.17

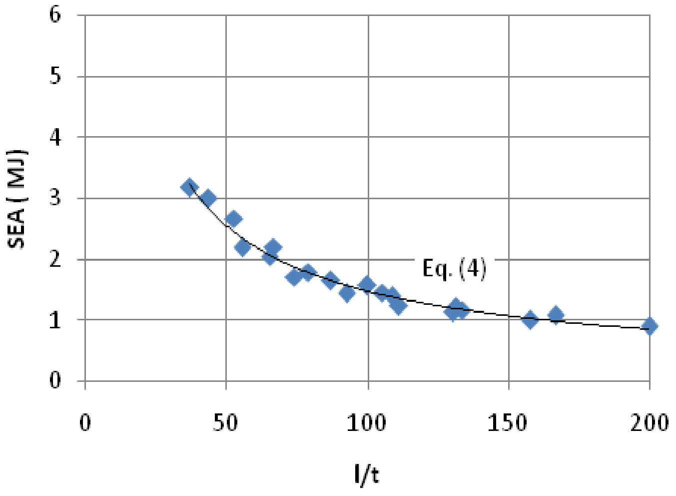

Figure 14. SEA versus ratio of length to thickness for 30° loading angle.

columns with varying thickness. An increment in column thickness demonstrates negligible effect on CFE.

GENERAL EXPRESSIONS

In this analysis, CFE is found to be less affected by the width. Thus, general expression is developed for CFE in terms of length and thickness.

Table 2 depicts the SEA and CFE obtained from numerical simulation of column under worst oblique loading scenario that is 30° loading angle. The curve-fitting method has been used widely to formulate the distributed data. As a result of the power-law curve-fitting method, the expression for SEA of obliquely loaded column is obtained in Figure 14. SEA of square aluminum column subjected to 30° oblique loading angle is written as Equation 4:

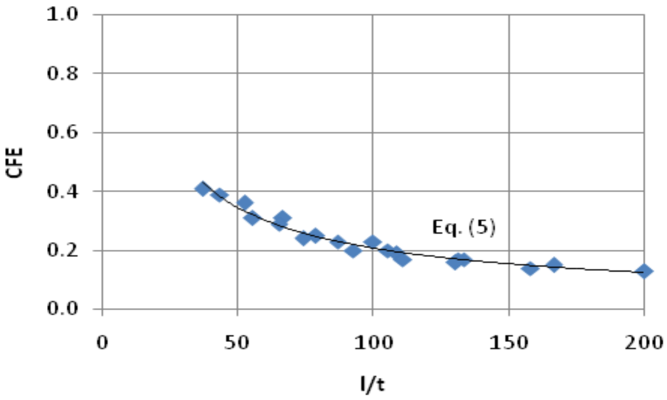

Figure 15. CFE versus ratio of length to thickness for 30° loading angle.

$$SEA = 54.30\left(\frac{l}{t}\right)^{-0.78} \qquad (4)$$

where l is column length and t is column thickness. CFE corresponding to the ratio l/t and the curve-fitted data is shown in Figure 15 and the expression for CFE is written as:

$$CFE = 6.314\left(\frac{l}{t}\right)^{-0.74} \qquad (5)$$

From Figures 14 and 15, it can be seen that the performance of the column degrades as the l/t ratio increases. Automotive structure should consider the oblique loading in its design to satisfy lightweight and crashworthiness goal.

Conclusion

It is evident from the analysis that the column under oblique loading is associated with both deformation modes, axial and bending where the bending is more obvious at the upper end for loading angle of 5 to 15° and at the bottom end for loading angle of 20 to 30°.

Parametric studies on the column at different loading angle shows that SEA and CFE is less affected by the variation of column width. Finally, general expression length and thickness.

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