

LOW VELOCITY IMPACT ANALYSIS OF FOAM – FILLED DOUBLE WALLED PRISMATIC COLUMNS

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ABSTRAKSI

Kolom prisma tipis digunakan untuk menyerap energi tumbukan pada berbagai sistem engineering, seperti struktur depan sasis pada mobil. Untuk perancangan struktur ringan, logam dengan berat jenis rendah dan kolom dengan dua dinding (double-walled) dapat dijadikan sebagai konsep alternatif untuk meningkatkan efisiensi berat dari struktur. Penelitian ini memberikan prediksi dan perbandingan kelakuan dari kolom dua dinding yang diisi dengan logam berat jenis rendah (double-walled sandwich columns) yang memiliki dua tipe penampang yaitu segi empat dan lingkaran; ketebalan inti, bentuk lipatan dan penyerapan energi menggunakan analisis numerik. LS-DYNA, sebuah perangkat lunak elemen hingga digunakan untuk memprediksi reaksi dari double-walled sandwich column yang diberi beban tumbuk dengan kecepatan rendah.

Ditemukan bahwa kolom sandwich yang berbentuk lingkaran memiliki gaya tumbukan rata-rata (mean crushing force) yang lebih tinggi dan panjang lipatan yang lebih pendek dibandingkan kolom sandwich yang berbentuk segi empat. Perbandingan specific energy absorption (SEA) double-walled sandwich columns yang memiliki penampang lingkaran dan segiempat juga dilakukan, dan dibandingkan dengan kolom dengan satu dinding (single wall column). Sandwich column berbentuk lingkaran dengan ketebalan inti $C = 8$ mm memiliki peningkatan SEA paling tinggi dibandingkan kolom dengan single column, walaupun beratnya meningkat sebesar 42%, nilai SEA bisa meningkat sampai dengan 85%.

Keywords : Crashworthiness; Double-walled sandwich structure; Impact; Crushing

INTRODUCTION

Modern automotive design practice calls for the use of front longitudinal members to behave as the primary load path for the impact forces and provide energy absorption in the form of axial collapse ensuring that the inertial forces result transferred to the occupants' compartment are within an acceptable safety level.

Furthermore, for weight saving considerations in the structural design, aluminum and aluminum alloys are an attractive alternative to traditional steel structures due to lower weight, good corrosion resistance, and good producibility. All these factors indicate that aluminum is an ideal material for the automotive industry.

The conventional way of increasing the crushing resistance of a thin-walled column is by increasing the wall thickness. However, this conventional method is not weight efficient since a small increase in the crushing resistance is off set by a large increase in column weight.

For light weight designs, low density metal fillers, such as aluminum honeycomb or foam, are preferred to the column with thicker tube walls in terms of achieving the same energy absorption. Metal fillers are able to increase the energy absorption of a thin walled column. This increase is the result of a large compressive deformation of the filler. Some

reported researches indicated that the interaction between filler and column walls produces some worthwhile crash characteristics and energy absorption properties [1, 2, and 6]. The mean crushing loads of filled tubes are found to be higher than the sum of the crushing loads of foam and tube alone.

Apart from the promising results of the aluminum foam as lightweight fillers, an alternative concept of double-walled sandwich column has been put forward to increase weight efficiency of crashworthy structures, but review of literature showed that not much information was available on the behavior of double-walled sections under crushing load in general and especially dynamic crushing load. Some researcher has focused their attention on performance of axial crushing of foam filled section of square tube and circular tube, both experimentally and numerically. Study of double-walled sandwich column itself has only conducted by Santosa et al. [3] using non-linear dynamic finite element analysis. The authors found significant increase of mean crushing force of square tube double-wall column with metal fillers compared with single wall columns with the same thickness.

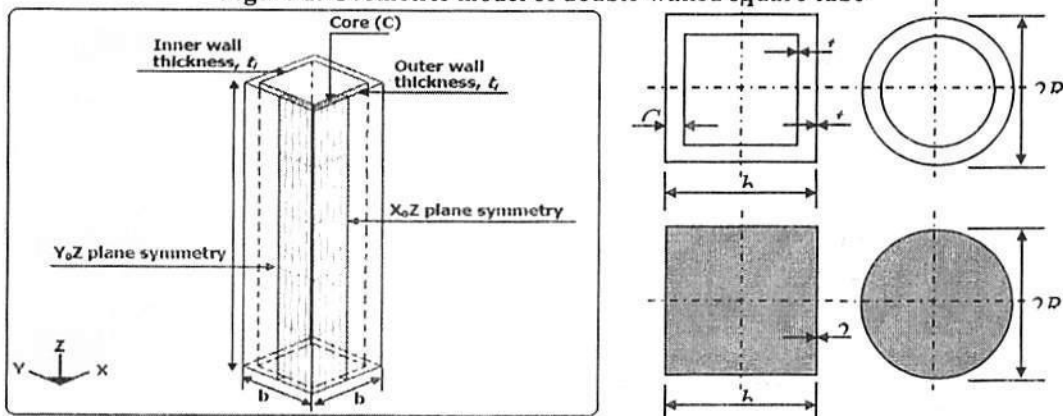
In this work, the study of a double-walled sandwich column subjected to low velocity axial impact loading using numerical analysis is conducted. The effect of double-wall sandwich structure with foam core and foam-filled section compare to single wall structure on the energy absorbing to be used as weight efficiency crashworthy structure is explored and investigated. The effect of cross-section geometry (circular and square column), core thickness (C) to fold formation and energy absorption is studied.

GEOMETRY OF STRUCTURE

In this work, double walled and full core square and circular columns were investigated. In all numerical simulation cases, Aluminum extrusion AA 6060 T4 wall materials were used. Aluminum foam ALPORAS was used for core material. The core thickness for double walled column is chosen to be 4, 6, and 8 mm respectively.

In order to be able to compare both square and circular sections, a square column having width $b = 37$ mm and length $L = 150$ mm is used as reference. Geometry of the circular columns having the same circumference is then defined, having radius of 23.6 mm. For single walled and full core column, wall thickness is chosen to be 1 mm, while for double walled column the thickness of each wall is 0.5 mm. The mass of the impactor is 65 kg, with the impact velocity 7.3 m/s.

Figure 1. Geometric model of double-walled square tube



FINITE ELEMENT MODELING

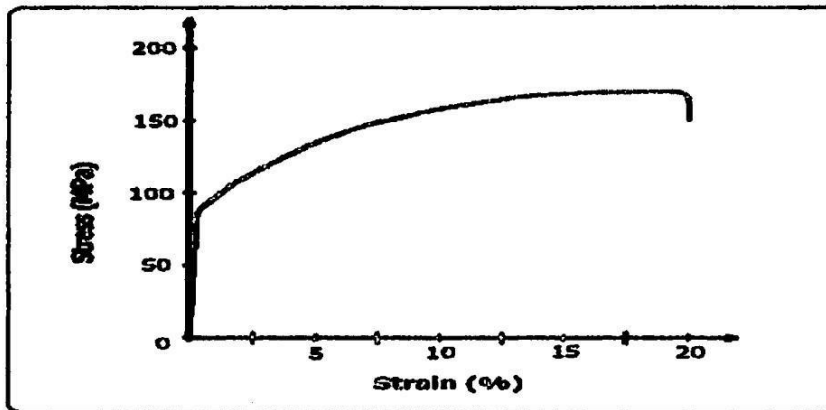
Fig. 2 illustrates a schematic representation of the geometry of the double-walled sandwich model. The model itself consists of an inner wall, an outer wall and a core (foam filler). The column wall was modeled with a Belytschko-Lin-Tsay four node thin shell element, while the foam core and the impactor were modeled with an 8 node solid element.

Material Modeling

Column Wall

The material that is used for the column wall is aluminum extrusion AA 6060 T4. The constitutive behavior of the thin shell element for the column material was based on the elastic-plastic material model (Mat Piecewise Linear Plasticity, No. 24) with Von Mises's isotropic plasticity algorithm. The transverse shear effect was considered by this material model. Plastic hardening was based on the polygonal curve definition, in which pairs of the plastic tangent modulus and the plastic stress were specified. This material model also allows for the input of an arbitrary true stress- effective plastic strain curve.

The mechanical properties for this material [6] are: Young's modulus $E = 68$ GPa, initial yield stress $\sigma_y = 80$ N/mm² and Poisson's ratio $\nu = 0.3$. The engineering stress-strain was given in table 3. Fig. 2 shows the stress-strain diagram for aluminum 6060 T4.



Plastic Strain (%)	Plastic Stress (MPa)
0.0	80
2.4	115
4.9	139
7.4	150
9.9	158
12.4	167
14.9	171
17.4	173

Figure 2

(a) Stress-Strain diagram, (b) Strain hardening data for Alaminum 6060 T4 [13]

Aluminum foam core [18]

Mechanical properties of ALPORAS [8] are density $\rho = 230 \text{ kg/m}^3$ and Young's modulus $E = 0.5516 \text{ GPa}$. ALPORAS was modeled with material number 57 (low density foam). Stress-strain curve of ALPORAS presents in Fig. 3 below.

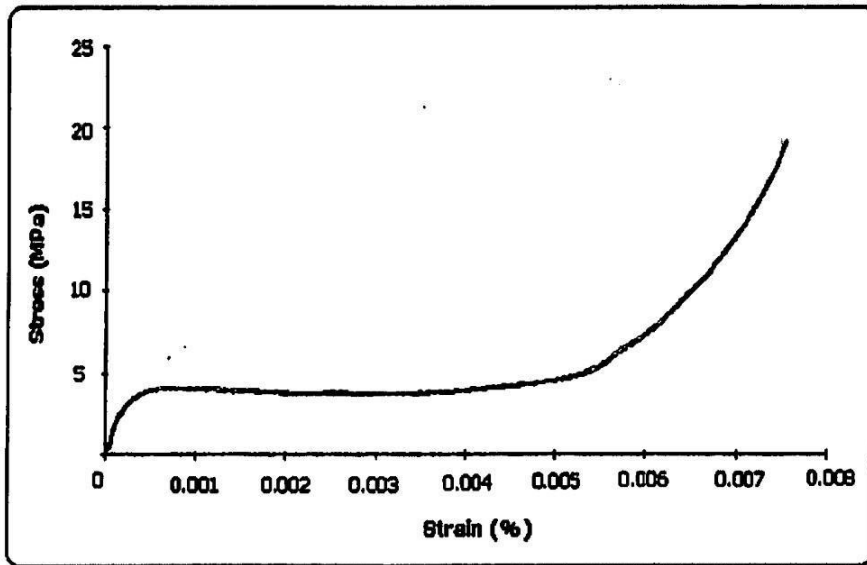


Figure 3
Stress-Strain diagram of ALPORAS [8]

Contact Condition

Four different contact algorithms available in LS-DYNA were used. The contact between rigid striker and tube and tube and supporter were modeled with an automatic node to surface contact. During progressive formation of plastic folds, interpenetration between two folds in the column wall was prevented by using automatic single surface contact. These contact types utilize a penalty formulation, when a penetration is found then a force proportional to the penetration depth is applied to resist and ultimately eliminate the penetration. Furthermore, internal solid anti-collapse (interior contact) has to be applied on the solid element. This internal contact can prevent numerical problem that can arise when solid elements are heavily compressed and distorted.

The bonding between the core and column faces was modeled with tied contact. Failure due to excessive tension and shear forces is not allowed from node to node (perfect bonding).

Boundary Condition

In the axial loading condition, the deformation of the column has two symmetry planes with respect to its cross section, i.e. y_{0z} and x_{0z} planes (see Fig. 1). Due to the expected symmetry of the deformation, only one quarter of the column was modeled to represent the axial crushing problem. On the y_{0z} plane of symmetry, the displacement in the x direction, rotation in the y and z axis were fixed, while on the plane y_{0z} the displacement in the y direction, rotation in the x and z axis were fixed.

No triggering imperfection was introduced to the model. Clamped boundary conditions were applied at the bottom of the column; another free end tube was struck by impactor which was applied initial velocity for all nodes, and the symmetry boundary conditions were applied on all free vertical edges.

NUMERICAL SIMULATION RESULTS

Analysis of the simulation results present in this section. First, sandwich column with several core thickness variations is investigated. Then, effect of cross section geometry is simulated at fixed core thickness. Finally, the weight efficiency is assessed for various sandwich configurations.

Sandwich Column with Core Thickness Variations

The crushing behavior of the sandwich column with varying core thickness is analyzed. The core thickness is varied for $C = 4, 6, 8$ mm and full core. Two types of geometry, i.e. circular and square are analyzed.

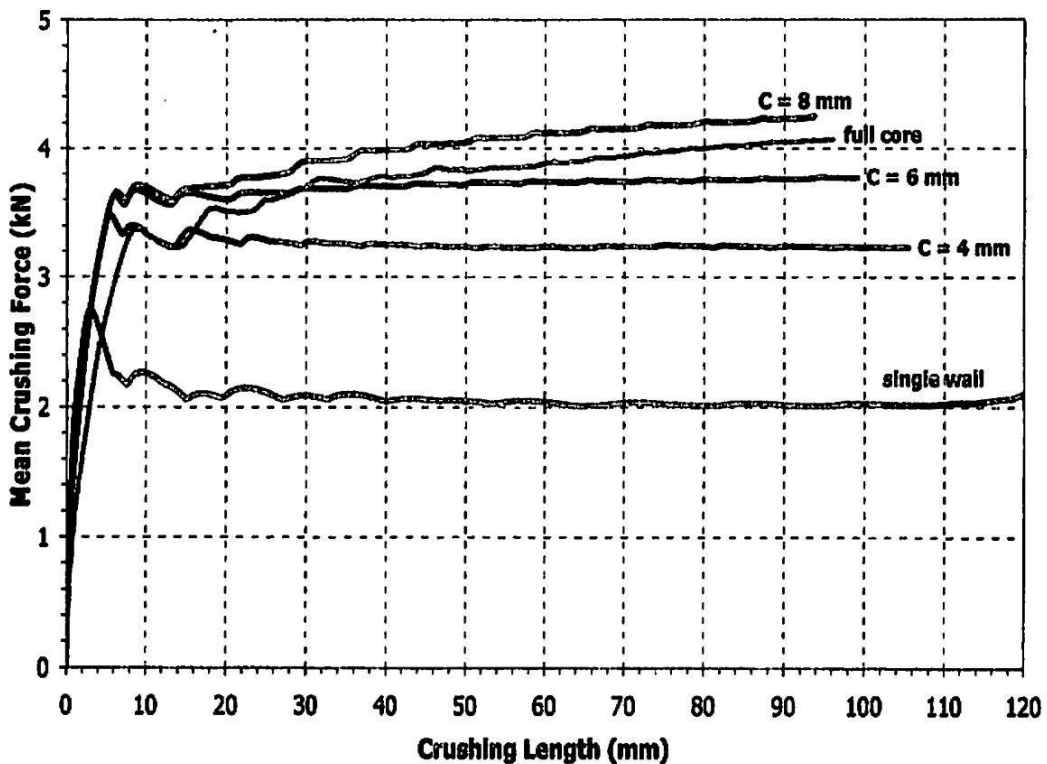


Figure 4
Crushing characteristic of circular sandwich with various core thicknesses

Table 1
Crushing characteristics of circular sandwich column

Core Thickness (mm)	Total Mass (kG)	Circular column				
		P_m^* (kN)	ΔP_m^{**} (kN)	EA (kJ)	SEA (kJ/kG)	ΔSEA^{**} (%)
Single wall, $t=1$ mm	0.0150	2.03	N/A	143	9.53	N/A
$C = 4$	0.0186	3.23	59	229	12.30	29
$C = 6$	0.0201	3.74	84	264	13.15	38
$C = 8$	0.0213	4.15	104	294	13.79	45
Full core	0.0232	3.94	94	279	12.01	26

* P_m are calculated at displacement = 70 mm

** ΔP_m and ΔSEA are calculated compare to single wall column

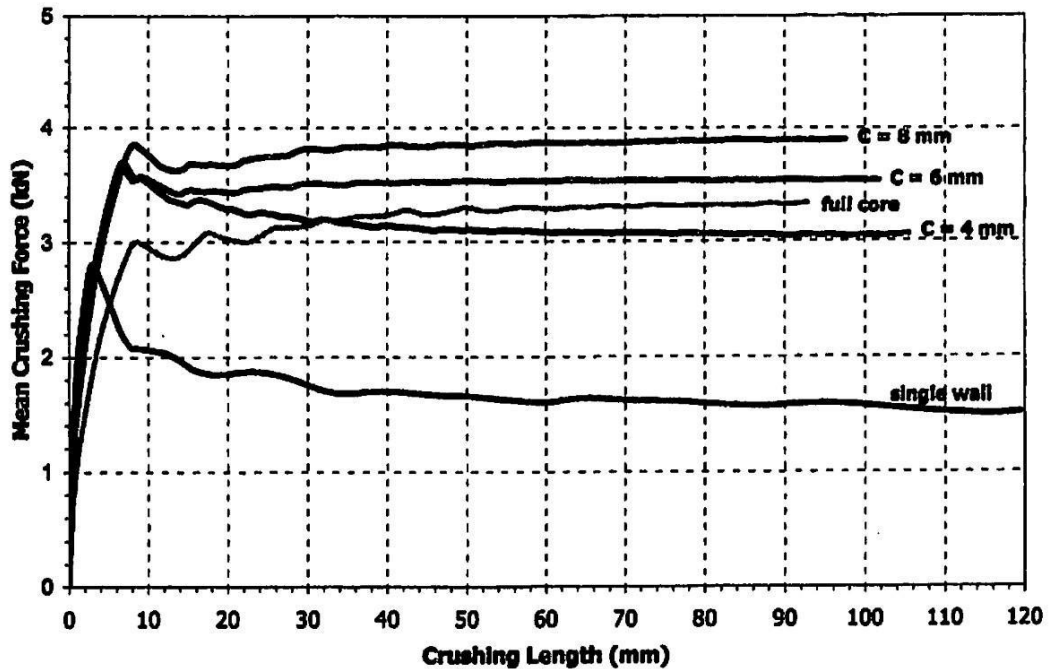


Figure 5
Crushing characteristic of square sandwich with various core thicknesses

Table 2
Crushing characteristics of square sandwich column

Core Thickness (mm)	Total Mass (kG)	Square column				
		P_m^* (kN)	ΔP_m^{**} (kN)	EA (kJ)	SEA (kJ/kG)	ΔSEA^{**} (%)
Single wall, $t=1$ mm	0.0150	1.62	N/A	114	7.60	N/A
$C = 4$	0.0186	3.08	90	218	11.71	54
$C = 6$	0.0201	3.54	119	250	12.45	64
$C = 8$	0.0213	3.87	139	273	12.80	69
Full core	0.0232	3.30	104	233	10.03	32

* P_m are calculated at displacement = 70 mm

** ΔP_m and ΔSEA are calculated compare to single wall column

From figure 5 and table 5, by analyzing sandwich columns with various core thicknesses at the same geometry, it is found that increasing the core thickness will significantly increase the crushing force. The maximum increase of mean crushing force is around 140% compare to single wall column. The highest mean crushing force found at core thickness, $C = 8$ mm. This is because sandwich plates have a much higher bending resistance than single sheets of the same weight. These results also validate the numerical results reported in [3].

Sandwich Column with Cross Section Variations

Sandwich columns with cross section variation are analyzed, which are circular and square column. The foam core thickness is fixed at constant core $C = 6$ mm.

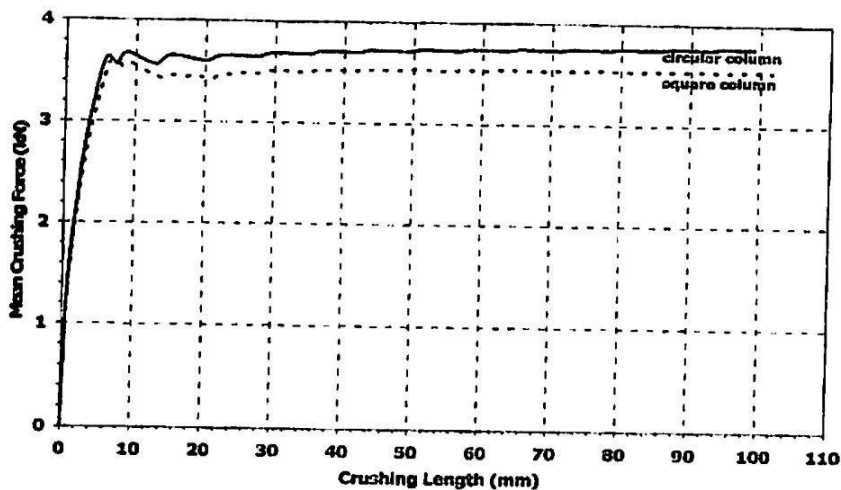


Figure 6
Crushing characteristic of sandwich column with both cross section at fixed core $C = 6$ mm

Table 3
Mean crushing force comparison for circular and square cross section

Core Height (mm)	Circular Column P_m (kN)	Square Column P_m (kN)
C = 6	3.74	3.54

Figure 6 and table 6 shows the comparison of mean crushing force and energy absorption of circular and square columns for the same 6 mm core thickness. It can be seen that the mean crushing force of circular column is 5.3 % higher than the one at square column.

Weight efficiency

Weight efficiency for various sandwich configurations is analyzed. The specific energy absorption is usually used as an indicator for weight efficiency of a given structure. The specific energy absorption (SEA) is defined by:

$$SEA = \frac{\text{Energy Absorbed}}{m_c + m_f} \quad (1)$$

where m_c and m_f are column and metal filler weight.

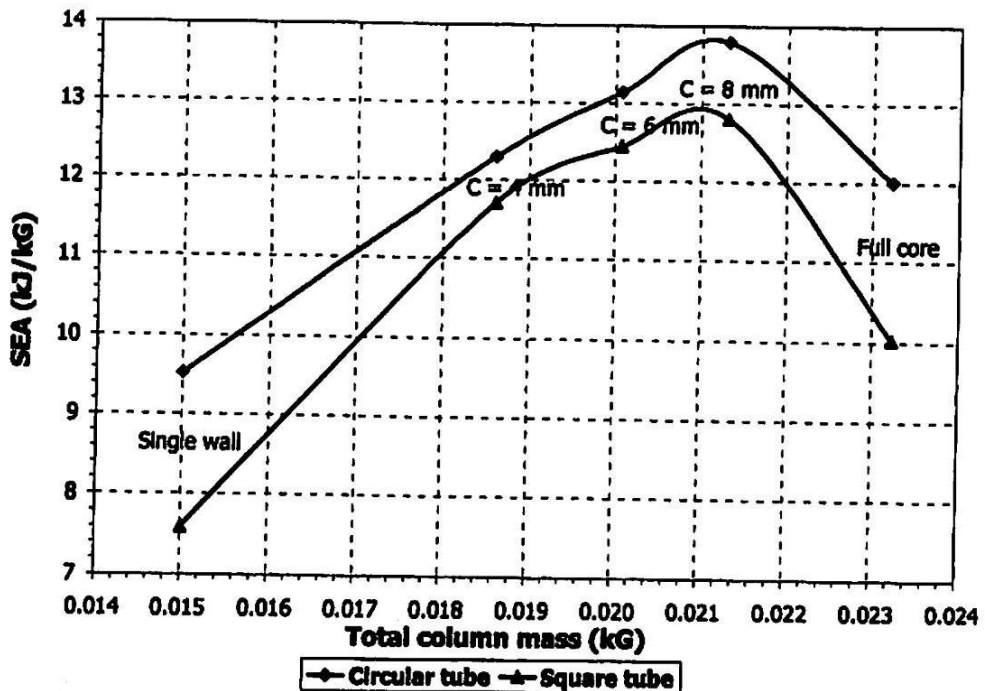


Figure 7
Comparison of weight efficiency for circular and square cross sections

Figure 7 shows the comparison value of SEA for square and circular columns with respect to SEA of single wall column. Circular sandwich column at core thickness $C = 8$ mm has the highest increase of SEA compare to single wall column. By increasing 42% of its weight, the SEA can be increased up to 85%.

Also found in this study, the weight efficiency for full core on both cross section is lower than weight efficiency of sandwich columns with $C = 4, 6,$ and 8 mm, although it is still higher than single wall column.

CONCLUSION

In this work, the energy absorption behavior and weight efficiency of prismatic double walled sandwich columns has been presented. By using explicit dynamics non-linear finite element code LSDYNA 970, the mean crushing force, crushing length, and energy absorption of prismatic sandwich columns with various core thickness and subjected to low velocity impact loading were simulated and analyzed.

It is found that by analyzing sandwich columns with various core thicknesses at the same geometry, it is found that increasing the core thickness will significantly increase the crushing force. The maximum increase of mean crushing force is around 140% compare to single wall column.

It also found for the same 6 mm core thickness, mean crushing force of circular column is 5.3 % higher than the one of square column. Circular sandwich column at core thickness $C = 8$ mm has the highest increase of SEA compare to single wall column, although its weight is increased by 42%, the SEA can be increased up to 85%.

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