Trends in

Applied Sciences Research

ISSN 1819-3579

Academic Journals Inc.

www.academicjournals.com

Trends in Applied Sciences Research 5 (1): 56-63, 2010
ISSN 1819-3579

Investigation of the Folding Angle Variations During The Folding Progress in the Columns

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Abstract: This study presents a theoretical relation to predict the folding angle versus the time during the folding process in the thin walled square columns. Using the theoretical relation, diagram of the instantaneous folding force versus the time is obtained. Then, some experimental tests were performed on the aluminum square columns with the different strain rates. Comparison of the folding results shows that the increasing in the loading rate causes the increasing in the absorbed energy. Finally, the theoretical and experimental diagrams of the instantaneous folding force versus the time in the square column were compared that shows a good correlation.

Key words: Absorbed energy, column, folding, instantaneous force, thin walled

INTRODUCTION

The interest of lattice structures with various core topologies has grown rapidly over the last decade for their superior properties (Zhang *et al*., 2009). Honeycombs, foams and other cellular materials have been proposed for use in impact energy absorption and shock mitigation applications (Zou *et al*., 2009). Honeycomb structures are widely used in various engineering fields as packaging and protective materials, core materials of sandwich panels, building materials, heat-insulating materials and sound-insulating materials (Nakamoto *et al*., 2009). Among honeycomb properties, its folding behavior under axial loading is the most important, since the highest portion of the absorbed energy occurs during this mechanism (Niknejad *et al*., 2008). In recent decades, many researchers have investigated the honeycomb behavior under the various loading (Niknejad *et al*., 2009).

Many efforts have been made in the past decades to understand and improve the energy absorption characteristics of columns and honeycombs under various load conditions: axial crushing, bending or oblique impact. Due to their widespread application, tubes with circular and rectangular cross-sections have received the most attention (Zhang *et al*., 2007). The experimental and theoretical analyses of the response of cellular materials to various types of loading are important for understanding the properties of these materials (Karagiozova and Yu, 2008). Liaghat and Alavinia compared the theoretical results with those of experimental and evaluated the analytical relations (Liaghat and Alavinia, 2003) and then, Liaghat *et al*. (2003) theoretically investigated the folding behavior of the honeycomb. Chen and Wierzbicki (2001) analytically calculated the mean folding force in a multi-cell square column. Zhang *et al*. (2006) calculated the mean crushing force in multi-cell columns, based on Superfolding Element. Nilsson and Nilsson (2002) discussed some dynamical properties of sandwich beams with lightweight honeycomb or foam cores. Mirfendereski *et al*. (2008),

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conducted a parametric study and numerical analysis on empty and foam-filled thin-walled tubes under static and dynamic loadings. Song *et al.* (2005) investigated the interaction effect between aluminum foam and metallic hat sections under axial loading.

Review of the published works on the folding behavior of the columns and honeycombs reveals that mean folding force in single-cell and multi-cell columns is calculated theoretically. In this study, the instantaneous folding force of the first fold creation in the square and rectangular columns is calculated versus the time.

THEORY

Wierzbicki and Abramowicz (1983) introduced a theoretical model for the folding deformation in the square and rectangular columns. This model was called Basic Folding Mechanism (BFM). Figure 1 shows a BFM during the folding deformation. In this figure, FBM is the height of the BFM or the length of that part of column that a fold creates along it. Using the BFM and calculation of the dissipated energy rate, the average folding force of a square column, P_{ave}, was obtained as (Wierzbicki and Abramowicz, 1983):

$$P_{ave} = 9.56\sigma_o \cdot \sqrt[3]{C \cdot h^5} \tag{1}$$

Moreover, the folding wavelength 2H was calculated as (Wierzbicki and Abramowicz, 1983):

$$H = 0.985\sqrt[3]{C^2 \cdot h} \tag{2}$$

where, C and h are the edge length and the wall thickness of the BFM, respectively. σ_0 is flow stress of the BFM material. Then, Niknejad *et al.* (2008) calculated a theoretical relation to predict the instantaneous folding force of the square columns versus the folding angle, α, as the following:

$$P = 0.75\sigma_o \sqrt[3]{K \cdot Ch^5} \tag{3}$$

where, coefficient K is a function of the folding angle, α, according to the following relation:

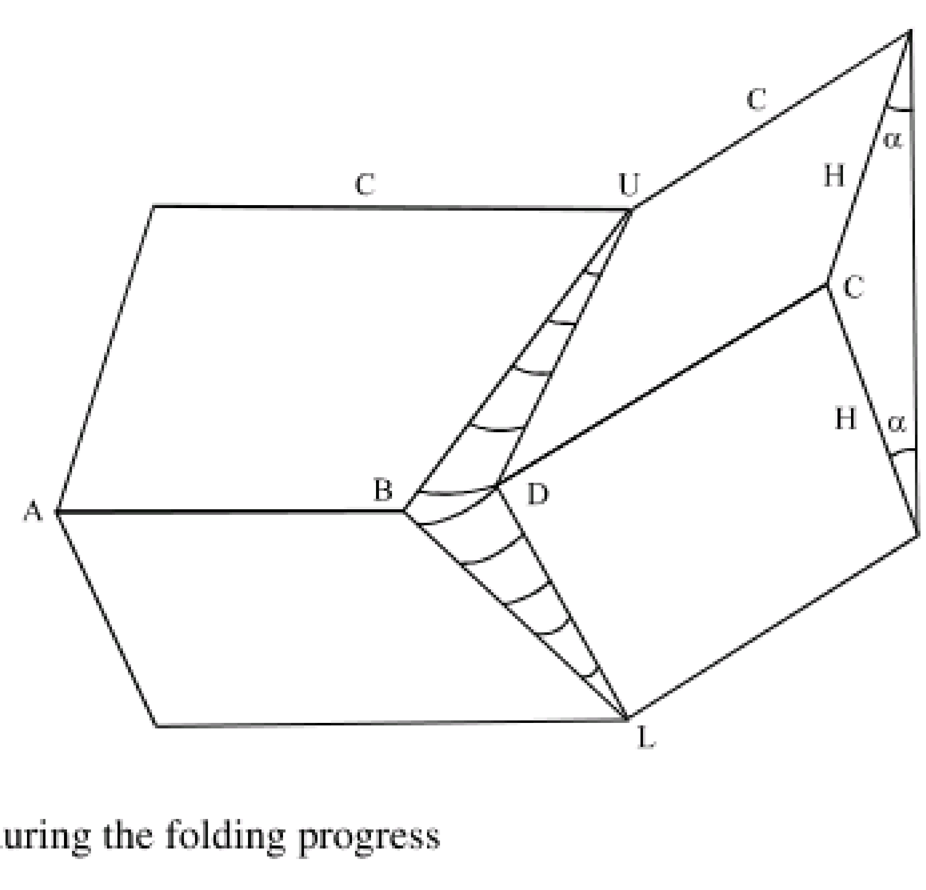

Fig. 1: A BFM during the folding progress

$$K = \frac{2048\sqrt{2}\cdot \mathrm{Cotg}^2\alpha \cdot \sqrt{1+\mathrm{Sin}^2\alpha}}{\mathrm{Sin}\alpha}\cdot\left[\sqrt{\frac{\sqrt{2+\mathrm{Sin}^2\alpha}-\mathrm{Sin}\alpha}{2\sqrt{2+\mathrm{Sin}^2\alpha}}}-\sqrt{\frac{\sqrt{2+\mathrm{Sin}^2\alpha}+\mathrm{Sin}\alpha}{2\sqrt{2+\mathrm{Sin}^2\alpha}}}+1\right] \tag{4}$$

At commence of the folding progress, α increases from zero to $\pi/2$ continuously (Fig. 1). Equation 2 results a curve of the instantaneous folding force versus the angle α in a square column. Following, a theoretical relationship is calculated to correlate between the value of α and the time.

For this purpose, Fig. 2 shows a geometrical image of the folding wavelength, 2H, axial displacement of the column, δ and the folding angle of α. According to the figure, the axial displacement of δ is calculated as:

$$\delta = 2H\cdot(1-\mathrm{Cos}\alpha) \tag{5}$$

Figure 3 shows a square column during the folding progress under the axial loading, P. It is assumed that the upper edge of the column is moved down with the constant velocity, V and the lower edge is fixed. So, the relation between the axial displacement, δ and the loading rate, V is resulted as:

$$V = \frac{\Delta x}{\Delta t} = \frac{\delta}{t} \tag{6}$$

The following relation is obtained from Eqs. 5 and 6:

$$\alpha = \mathrm{Cos}^{-1}(1-\frac{V\cdot t}{2H}) \tag{7}$$

Substituting Eq. 2 in Eq. 7 results in:

$$\alpha = \mathrm{Cos}^{-1}(1-(0.508)\cdot\sqrt[3]{\frac{V^3}{C^2\cdot h}}\cdot t) \tag{8}$$

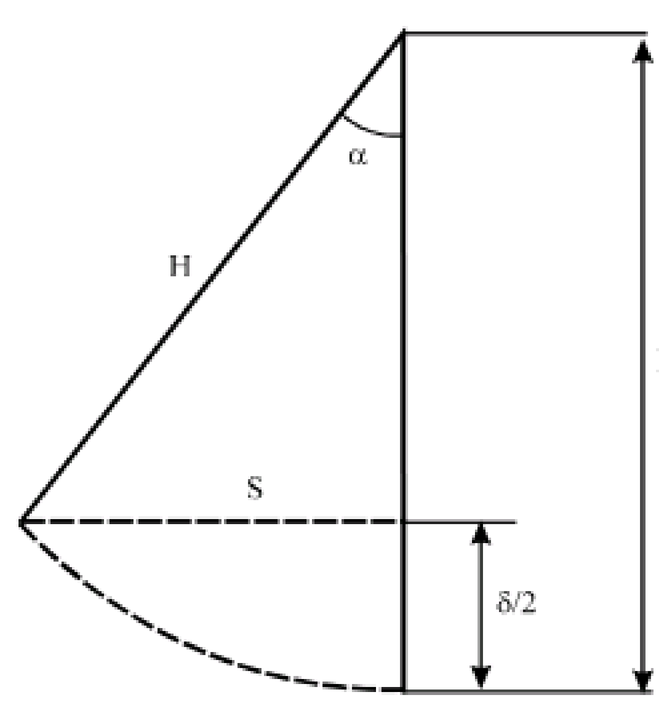

Fig. 2: Geometrical relation between H, δ and α

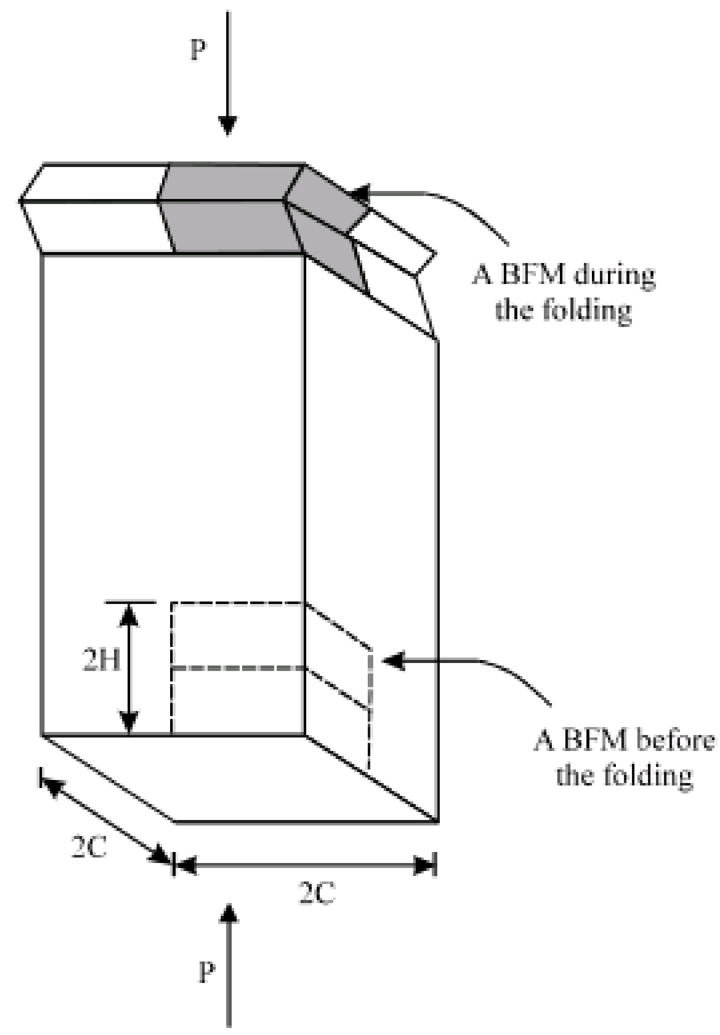

Fig. 3: A square column during the folding progress

Table 1: Material properties and dimensions of the aluminum specimens

Quantity	Value	Unit
Dimensions of the cross section	35×35	mm×mm
Wall thickness of column	1.5	mm
Length of column	100	mm
Young's modulus	71	GPa
Poisson's ratio	0.3	-
Yield stress	173	MPa
Ultimate stress	236.9	MPa
Power of strain hardening	0.121	-

According to the above equation, by substituting the values of the loading rate, the wall thickness and half of the square edge length in Eq. 8, a theoretical relation obtained between the folding angle of α and the time, t.

Then, using Eq. 3, 4 and 8, a theoretical graph of the instantaneous folding force versus the time is obtained during the crushing progress in the square column.

EXPERIMENTAL TEST

Some quasi-static tests with different loading rates were performed on the aluminum square column and the folding progress happened. All columns were prepared by an aluminum alloy with the material properties that given in Table 1. Flow stress of the aluminum alloy is obtained as δ_0 = 191.2. Table 1 shows the geometrical characteristics of the folding test specimens, too. The loading rate in the folding tests was selected as 5-500 mm min^{-1}.

RESULTS AND DISCUSSION

The predicted results of the instantaneous folding force by Eq. 3 and 8 are investigated. Figure 4 shows the instantaneous folding force versus the time in a square column with the loading rate of 5 mmmin^{-1}. Both the theoretical and experimental curves were sketched in this figure. To obtain the theoretical curve, the values of α are calculated versus the time, using Eq. 8. Then, by substituting the value of α in Eq. 3, the theoretical folding force is calculated versus the time.

Figure 5 and 6 show the theoretical and experimental curves of the folding force in a similar square column with the loading rates of 100 and 500 mm min^{-1}, respectively. As the diagrams show and considering the physical behavior of the column, at the onset of each fold, the folding force increases from a minimum value and then, follows by a decreasing trend. With the first completed folding, the folding force reaches a relative minimum value.

Comparison of two curves slopes in different points of these three figures shows that the general form of the calculated function for the folding force is correct.

Equation 8 shows that value of the folding angle, α depends on the one-third power of the wall thickness and two-thirds power of the half of the square edge length, inversely.

Comparing the difference between the coupled curves in three figures reveals that the when the loading rate increases, the further error percentage between the theoretical and experimental results occurs. Equation 8 is the first calculated relation that can predict the folding force versus the time during the folding progress. Thus, although the predicted value obtained from the theoretical Eq. 8 is smaller than the experimental value, but this difference is acceptable.

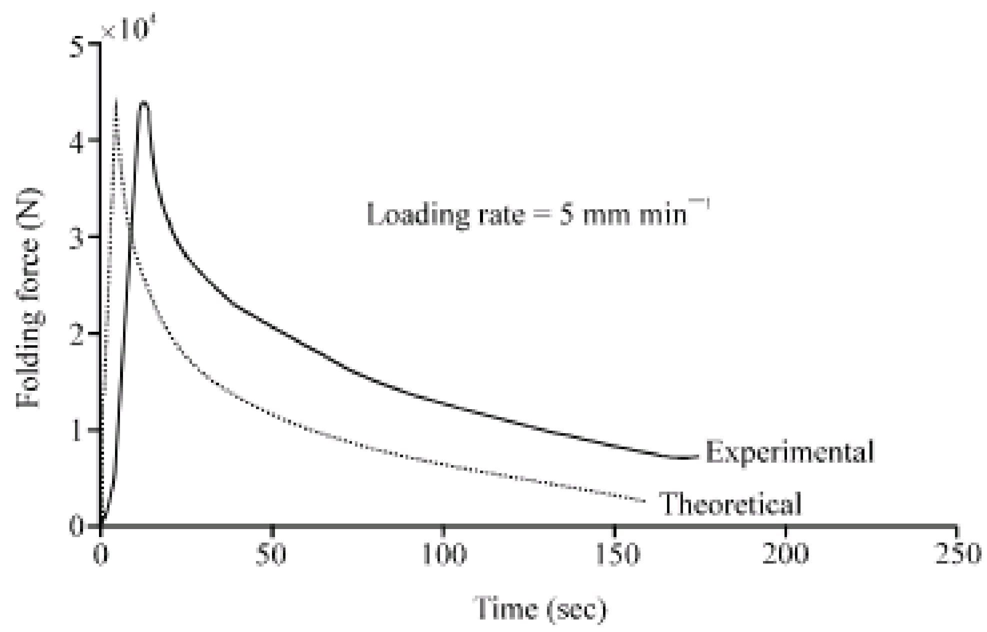

Fig. 4: Folding force versus the time in a thin-walled square column (V = 5 mm min^{-1})

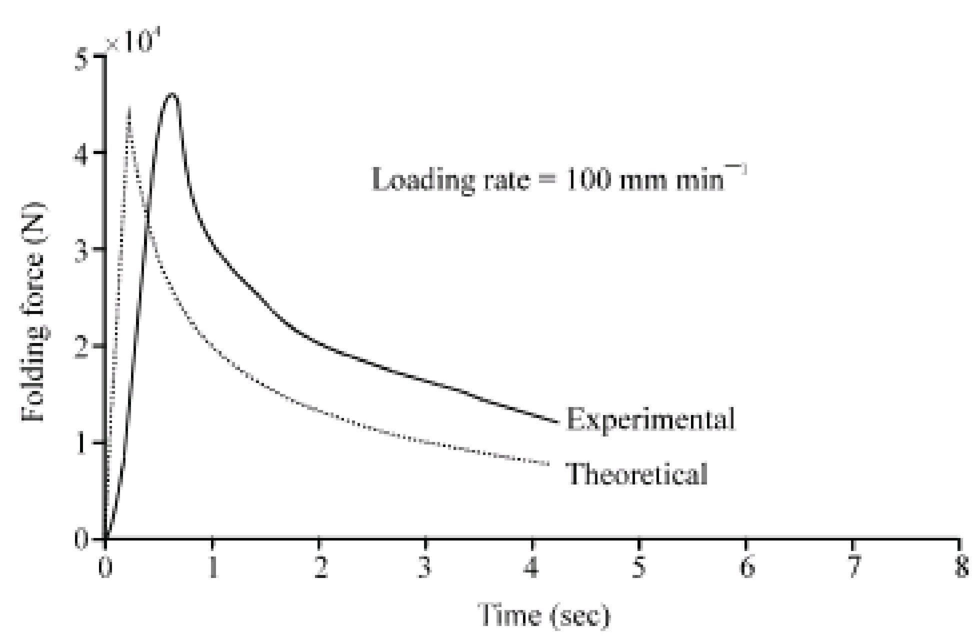

Fig. 5: Folding force versus the time in a thin-walled square column (V = 100 mm min^{-1})

Figure 7 shows the folding force of the square column in *lieu* of the different loading rates. According to this figure, when the loading rate increases, the first peak value of the folding force increases, too. This procedure is a result of the dependence of the material properties on the strain rate. In addition, when the loading rate increases, the folding wavelength increases, too. This is concluded by comparing the value of the axial displacement in the final point of the first fold of three curves.

Under curve area shows the among of the absorbed energy by the column during the folding progress. The absorbed energy by the column with the loading rates of 5 and 500 mm min^{-1} are equal to 1.039 and 1.232 KJ, respectively. This quantity was calculated up to the end of the forth fold creation in the column. Comparison of two values shows that the absorbed energy by the column was increased 18.6%, when the loading rate increases from 5 to 500 mm min^{-1}.

For further investigation, the obtained results in this paper are compared with the experimental results obtained by other researchers.

In order to increase the energy absorbing capabilities of thin-walled aluminium members under axial loading, Langseth *et al.* (1998) performed some folding test, that Fig. 8 shows an experimental result. In this study, some folding tests were performed on the square column with the dimension of the cross section 80×80 mm, the wall thickness of 2.5 mm and the

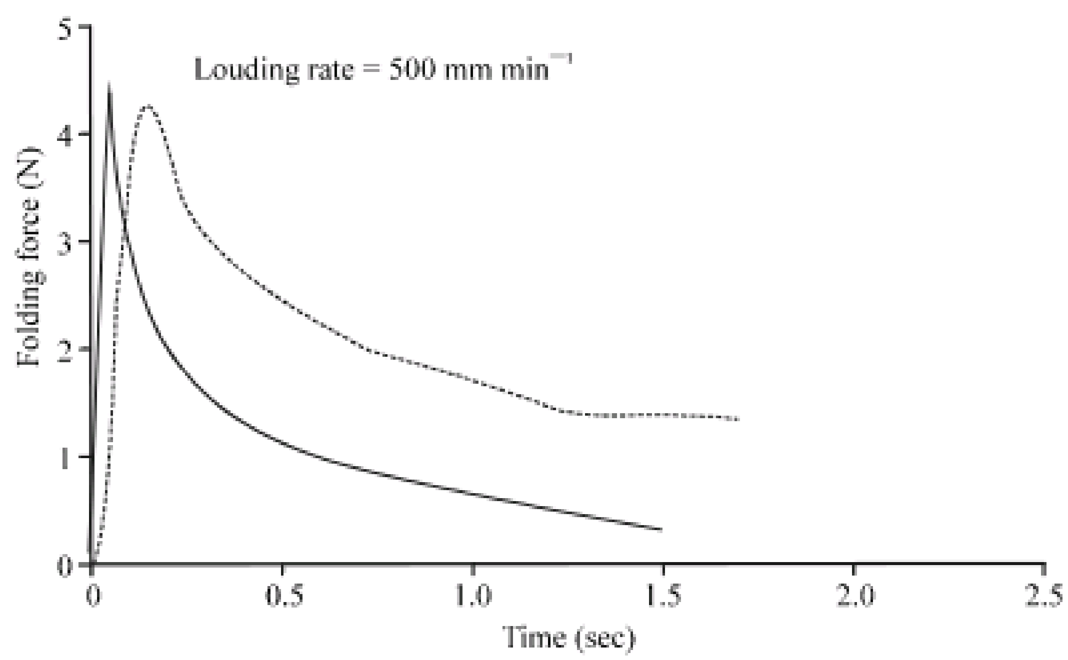

Fig. 6: Folding force versus the time in a thin-walled square column (V = 500 mm min^{-1})

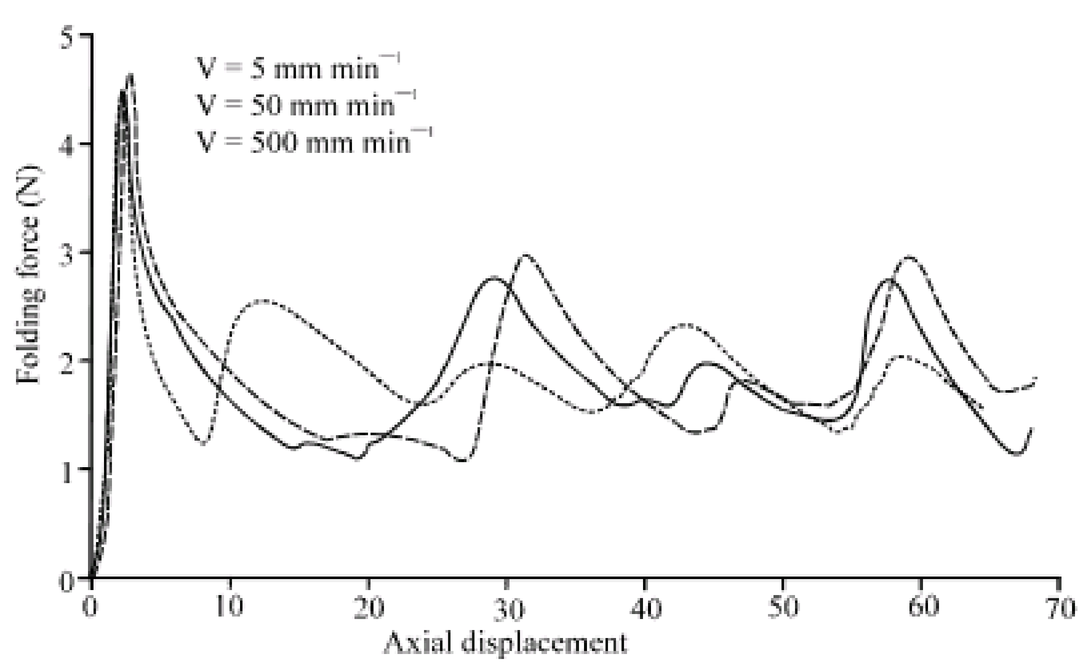

Fig. 7: Folding force versus the time in a thin-walled square column (different loading rates)

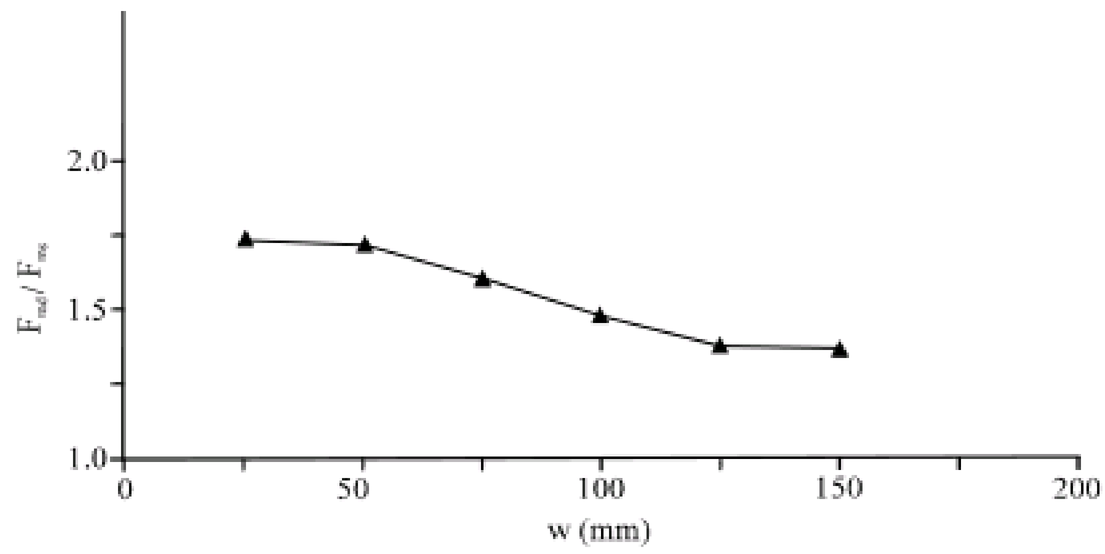

Fig. 8: Ratio between dynamic and static mean loads versus displacement (Langseth *et al.*, 1998)

column height of 310 mm. The test specimens were made of the aluminium alloy AA6060. Figure 8 shows the ratio between dynamic and static average forces versus the axial displacement of the column. Through the graph, the ratio is larger than 1, therefore the dynamic mean force is larger than the static mean force during the folding progress. Thus, according to the Langseth's results, when the loading rate increases from the static condition to the dynamic tests, the folding load and the absorbed energy rate increase comparing with the corresponding quantities (Langseth *et al.*, 1998). This result confirms the obtained results in this study.

Totally, review of the figures extracts the following results:

- Increasing in the loading rate causes the increasing in the energy absorption by the column. This result is very important, practically. That means in the crushes and impacts, the absorbed energy rate is more than the static condition
- Increasing in the loading rate causes the increasing in the first peak of the folding force. This causes the more energy absorption by the structure
- The maximum value of the folding force during the next folds is less than the first peak. This behavior is because the next folds create in the deformed column
- The value of the instantaneous folding force depends on the one-third power of the square edge length and the five-third power of the wall thickness, so, at the same time the dependence on the dimension C is much weaker and the increasing in the wall thickness (h) is more suitable, economically (Eq. 3)
- The variation of the axial loading rate does not change the deformation mode of the column during the folding progress and just the maximum, minimum and the amplitude of the folding force change, locally
- The analytical solutions show an acceptable agreement with the experimental results

CONCLUSION

In this study, a theoretical relation between the folding angle and the time was calculated to predict the instantaneous folding force of a square column. Then, some folding tests were performed on the aluminum square columns with the different loading rates and the dependence of the folding force and the folding wavelength were investigated on the loading rates. Comparison of the theoretical and the experimental results showed a good correlation.

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