Поглинання питомої енергії круглими трубами з поліуретановим пінонаповнювачем у процесі вирівнювання

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Система поглинання енергії перетворює, повністю або частково, кінетичну енергію на іншу форму енергії. Перетворена енергія є або оборотною, як наприклад, енергія тиску в рідинах, що стискаються, та енергія пружної деформації в твердих тілах, або необоротною, як наприклад, енергія пластичної деформації. Енергія розсіяна при пластичній деформації металевих поглиначів енергії становить систему поглинання енергії, що розглядається у цій роботі. При розробці складаного поглинача енергії основною метою є необоротне поглинання більшості кінетичної енергії удару самим приладом, що дасть можливість мінімізувати людські травми та пошкодження обладнання. Перетворення кінетичної енергії на енергію пластичної деформації залежить серед інших факторів і від величини та методу застосування навантажень, швидкості передачі, моделей деформації та зміщення, а також характеристик матеріалу. У процесі вирівнювання труба чи стиснутий стержень затискаються між двома твердими пластинами, і енергія розсіюється під час пластичної деформації. У цій статті експериментально досліджується процес вирівнювання круглих мідних труб, пустих або наповнених поліуретановою піною. П’ять геометричних типів зразків з різним діаметром, товщиною та довжиною, в пустому та наповненому піною стані, були використані в дослідах на бокове стискання. Досліджувалась здатність зразків поглинати енергію. Напівемпіричні співвідношення були використані для того, щоб розрахувати енергію поглинуту пустими металевими трубами та трубами наповненими піною. Результати дослідів показують, що зміни питомої поглинутої енергії в залежності від співвідношення діаметр/товщина є різними для пустих труб і труб наповнених піною, а найкращим вибором для поглинання енергії круглими трубами є труба наповнена піною, де *D/т* є далеким від області 25–35.

Specific Energy Absorption by the Circular Tubes with the Polyurethane Foam-Filler in Flattening Process

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In this article, flattening process of empty and polyurethane foam-filled circular brazen tubes is studied, experimentally. Five geometrical types of specimens with different diameters, thicknesses and lengths were used in the lateral compression tests in the empty and foam-filled conditions and the energy absorption capability by the specimens were investigated. The semi empirical relations were introduced to predict the absorbed energy by the empty and the foam-filled metal tubes. Experimental results show that the variations of specific absorbed energy versus the ratio of diameter/thickness is different in empty and foam-filled tubes and the best selection for energy absorption by the circular tubes is a foam-filled tube that it's **D/t** ***is far from region 25 to 35.***

Keywords – Flattening, Lateral compression, Circular tube, Polyurethane foam, Energy absorption.

I. Introduction

Metal tubes or metal rings, as efficient energy absorbers, are widely used in engineering applications. In numerous large structures, metal tubes and metal rings are installed as impact-protective and energy-absorbing devices [1].

The behavior of metal tubes or metal rings subjected to axial or lateral compression loading has been studied by many researchers. Ghosh et al. [2] experimentally investigated deformation behavior of thin rings and short tubes under centrally opposed concentrated loads. Zhao et al. [3] estimated load capacity of circular rings with arc-shaped supports and the position of created plastic hinges. Leu [4] simulated the lateral compression of aluminum and clad tubes due to large deformation by finite element method. Gupta et al. [5] investigated square and rectangular metallic tubes under quasi-static lateral load. Karamanos and Eleftheriadis [6] presented some numerical relations to predict pressure effects on the ultimate lateral load of tubes and on their energy absorption. Morris et al. [7] studied the lateral compression of nested tubes with side constrains as a type of energy absorbers, experimentally and numerically. Olabi et al. [8] investigated optimized design of nested circular tubes subjected to lateral impact. Niknejad et al. [9] developed a theoretical relation to calculate the instantaneous folding force in the hexagonal columns under the axial loading. They also discussed folding force versus the displacement in square and rectangular columns pressurized by axial load [10].

This paper reports some investigations on energy absorption by empty and polyurethane foam-filled circular tubes under lateral compression.

II. Experiment

For lateral compression testing of the samples, an Instron machine version 5500R was employed. For each empty and foam-filled group, a total of five brazen circular tubes, with different diameters, thicknesses and lengths, were tested. Tables I and II give the geometrical dimensions and mass of the empty and polyurethane foam-filled specimens, respectively.

Table 1

Geometrical properties of empty specimens

Part No.	D (mm)	t (mm)	L (mm)	m (gr)	D/t
E-01	18	1	20	9.2	18
E-02	20	1	40	19.8	20
E-03	30	1	15	11.6	30
E-04	50	1	25	32.4	50
E-05	28	0.5	20	6.9	56

Table 2

Geometrical properties of foam-filled specimens

Part No.	D (mm)	t (mm)	L (mm)	m (gr)	D/t
E-06	18	1	18	10.0	18
E-07	20	1	15	8.7	20
E-08	30	1	30	31.8	30
E-09	50	1	100	183.0	50
E-10	28	0.5	20	10.7	56

In Tables I and II, outer diameter, wall thickness, length and mass of tubes are defined as D, t, L and m, respectively.

All the tests were carried out with the constant loading rate of 10 mm/min. The polyurethane foam with density of 256 kg/m^3 and plateau stress of 1.76 MPa was used as filler.

III. Results and Discussion

Variations of specific absorbed energy (*E/m*) versus *D/t* ratio for empty brazen specimens were depicted in Fig. 1. This figure sketched based on curve-fitting method. According to this figure, it is obvious that *E/m* of empty specimens decreases by increasing of *D/t*. By observing the Fig. 1, it is clear that the specific energy varies like a power function of *D/t* ratio during the lateral compression process. Thus, the relationship may be written as:

$$\frac{E}{m} = 51754 \times \left(\frac{D}{t}\right)^{-1.2279} \qquad (1)$$

where, *E/m* is in Joule/Kilograms (J/kg). In the above equation, the negative sign of *D/t* exponent shows that increasing of *D/t* causes decrease in specific energy by the empty tubes.

Fig. 2 gives error percentages of predicted value by Eq. (1), comparing the experiments. The figure shows that error of specimens with lower ratio of *D/t* is less. Based on the Eq. (1), it is resulted that the empty specimens with lower ratio of *D/t* absorb more energy, during the flattening process.

Fig. 3 illustrates variations of *E/m* versus the ratio of *D/t* for polyurethane foam-filled specimens. Comparison of Figs. 2 and 3 shows that variations of the specific absorbed energy versus the ratio of *D/t* in the empty and foam-filled tubes under lateral compression loading are not the same. For example, the curve of *E/m* versus *D/t* of the filled specimens has a minimum point. That means there is a critical value for the ratio of *D/t* and in this point, the specific absorbed energy by the foam-filled tube is minimum, comparing of the other values of *D/t* ratio.

According to Fig. 3, the following semi empirical relationship is derived:

$$\frac{E}{m} = 5\times10^{6}\cdot\left(\frac{D}{t}\right)^{-2.9384} + 2.4\times10^{-3}\cdot\left(\frac{D}{t}\right)^{3.3642} + 1605.477 \qquad (2)$$

where, *E/m* is in J/kg. The above relation predicts the specific absorbed energy by the polyurethane foam-filled brazen tubes with the circular cross section. Fig. 4 shows error percentages of the predicted value by Eq. (2), comparing of the experiments.

Fig. 3 shows a peak point corresponding of the minimum specific absorbed energy. The critical value of *D/t* ratio is theoretically obtained equals to 29.46, based on the equation of derivation is equal to zero. Substituting the critical ratio in Eq. (2) results the minimum value of *E/m* equal to 2056.72 J/kg. These show good agreement with the experimental results in Fig. 3. According to the experimental results, for the foam-filled circular tubes with the *D/t* ratio less than 26.46, when the *D/t* ratio decreases the specific absorbed energy increases. Also, for the foam-filled circular tubes with the *D/t* ratio larger than 26.46, when the *D/t* ratio increases the specific energy absorption increases, too.

For example, specific absorbed energy and mass of specimen E-07 are equal to 2717.24J/kg and 8.7gr, respectively. Also, specific absorbed energy and mass of specimen E-08 are equal to 2015.72J/kg and 31.8gr, respectively. Fig. 5 illustrates the experimental curves of lateral compression load versus lateral displacement during the flattening process in two types of foam-filled circular tubes with the dimensions of *D*=20mm, *t*=1mm, *L*=55mm and *D*=30, *t*=1, *L*=30mm and with the same mass.

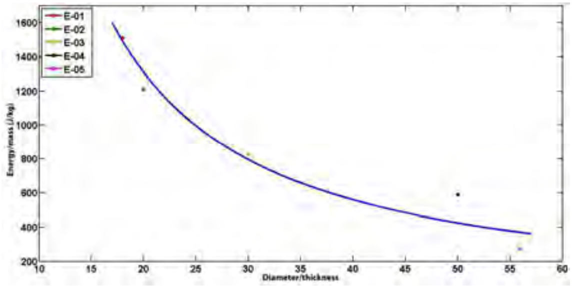

Fig. 1. Specific absorbed energy (E/m) versus D/t ratio diagram of empty tubes

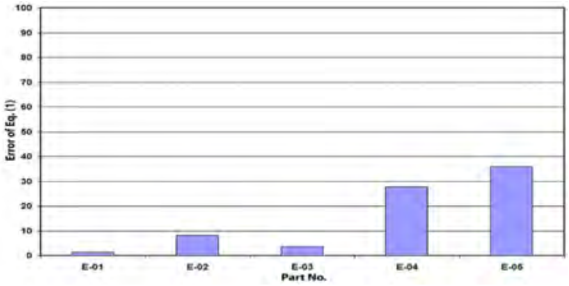

Fig. 2. Error percentages of Eq. (1) for different empty specimens

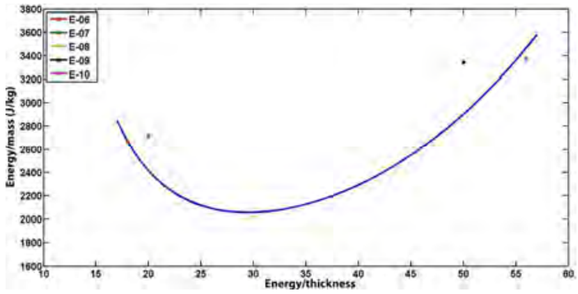

Fig. 3. E/m versus D/t ratio diagram of foam-filled tubes

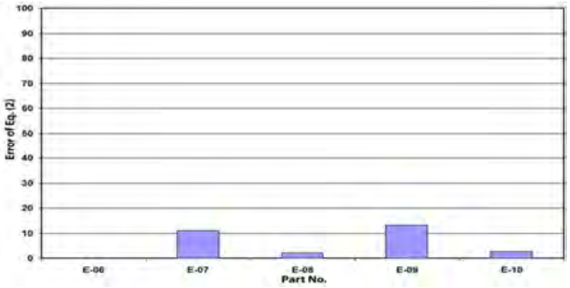

Fig.4. Error percentages of Eq. (1) for different foam-filled specimens

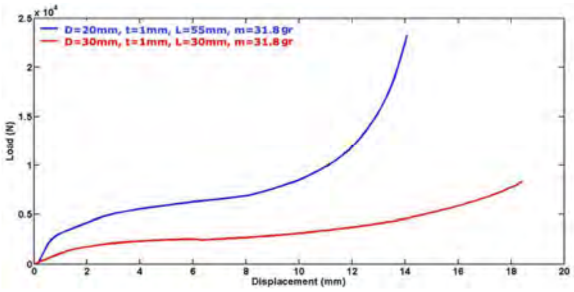

Fig. 5. Comparision of experimental load-displacement diagrams of two foam-filled tubes with the same mass and different geometries

The area under the load-displacement shows the absorbed energy by the specimens. According to Fig. 5, the filled-tube with diameter of 20mm absorbs more energy than the filled-specimen with diameter of 30mm, while their mass and thickness are the same.

According to mixtures law and the previous equation, the following relation is derived to predict the absorbed energy by the polyurethane foam-filled tubes during the flattening process:

$$E = (r_m \cdot V_m + r_f \cdot V_f) \cdot [5 \times 10^6 \cdot (\frac{D}{t})^{-2.9384} + \\ +2.4 \times 10^{-3} \cdot (\frac{D}{t})^{3.3642} + 1605.477] \quad (3)$$

where, ρ_f and V_f are density and volume of the foam, respectively and ρ_m and V_m are density and material volume of the circular tube, respectively.

Conclusion

An experimental program has been reported describing the specific energy absorption variation versus *D/t* ratio in the circular brazen tubes subjected to lateral compression load, in two conditions of empty and polyurethane foam-filled. The experimental investigations show that in empty tubes, *E/m* decreases when *D/t* increases and this decrement was described by a power function. Also, it is obvious that the variations of specific absorbed energy versus the *D/t* ratio are different in foam-filled tubes, comparing to the empty tube. The experiments show that the *E/m-D/t* diagram of the foam-filled specimens has a minimum and therefore, in lieu of the critical ratio of *D/t*, the specific absorbed energy by the polyurethane foam-filled tube is global minimum.

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