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Failure mechanism of expanded metal tubes under axial crushing

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ABSTRACT

The failure mechanism of expanded metal tubes under axial crushing is addressed herein. Experimental results have shown that when collapsing the tubes, the expanded metal cells closes until the plastic moment in all nodes along the mid-section of the tubes is attained exhibiting a plastic collapse mechanism. From this deformed configuration, a simple analytical expression is developed for the ultimate strength of the tube based on a rigid-plastic analysis of a frame-like structure. In addition, the energy absorption capacity of the tubes is also calculated. Theoretical predictions for both strength and energy are in good agreement with experimental results taken from the literature. Thereafter, a numerical study was conducted in order to investigate the validity of the theoretical model depending on the expanded metal cell geometry. It is found that the load-displacement response and failure mechanism of the tubes depend upon the aspect ratio of the expanded metal cell.

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1. Introduction

In the last two decades, the expanded metal industry has diversified its production from the traditional construction, structural, filtration equipment and walkways sectors to innovative architectural facades, sports car grilles, biomechanical devices and energy absorbing components.

Expanded metal is manufactured through a process based upon the in-line expansion of partially slit metal sheets, producing a diamond-like cell pattern (Fig. 1). As seen, the pattern in the expanded metal cells is characterized by two axes, a minor one (l_2) in the slitting direction and a major one (l_1) orthogonal to the first.

Due to the nature of the manufacturing process and the subsequent profile of the mesh, any structural element made of expanded metal sheets can be used as an imperfection sensitive structure when subjected to axial crushing. This particular feature acts as a trigger or buckling initiator in engineering applications requiring a controlled plastic collapse mechanism in order to absorb impact energy. The cell patterns act as initial imperfections that may reduce peak loads and may lead to a stable load-displacement response [1].

Energy absorbers should dissipate kinetic energy into other forms within the device itself in an irreversible manner reducing mainly human injuries or loss in property. In this sense, structural elements made of expanded metal sheets could be used to dissipate energy by plastic deformation. In 2001, Alghamdi [2] presented an overview covering four decades of research on collapsible impact energy absorbers under compressive loading. According to the deformation patterns (axial crushing, lateral indentation, lateral flattening, inversion and splitting), Alghamdi [2] summarizes some formulae used to calculate the strength of the absorbers. More recently, Olabi et al. [3], presented a second overview of metallic tubes used as energy absorbers under axial crushing, bending and oblique impact. This review covers experimental, numerical and analytical methodologies used to describe the behavior of energy absorbers under high and low velocity impacts. The results for the research projects mentioned previously demonstrates that, at industrial level, there has been a great need for searching new materials, or to use known materials in alternative forms and shapes, able to withstand loads in impact or crash scenarios.

In both reviews, the use of expanded metal in energy absorbing systems is not mentioned in spite of existing information regarding its use in international patents [4]. Graciano et al. [1] investigated the axial collapse of squared and round tubes made of expanded metal sheeting under compressive loading. A set of experimental tests was conducted in order to study the influence of the angle formed between the major axis of the expanded metal and the compressive load. Square and round tubes were tested at angles $\alpha=0^\circ$, 30°, 45°, 60° and 90° (Fig. 2), so as to observe the various modes of collapse. From the results, Graciano et al. [1] observed three types of collapse responses depending on the orientation of the axes: for $\alpha=0^\circ$ a mode characterized by a plastic collapse mechanism; for $\alpha=30^\circ$, 45° and 60° a second one defined by local buckling of the individual cells; and a third one, for $\alpha=90^\circ$ where the tube failed by global buckling.

For $\alpha=0^\circ$, the strength was smaller than for the other configurations, but the structural response was more stable, which is advantageous for energy absorption applications. A similar failure mechanism was observed by Zhang et al. [5], using a kagome honeycomb sandwich bitubal circular column. The sandwich core

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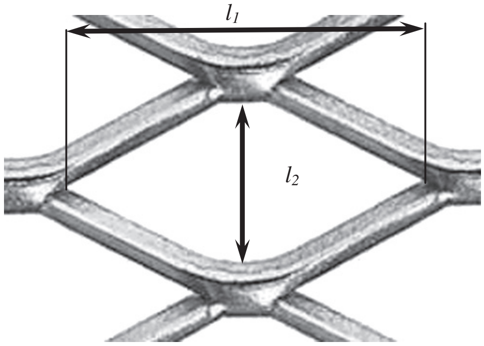

Fig. 1. Expanded metal sheet.

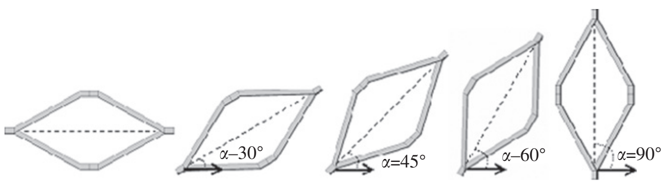

Fig. 2. Angles used in the experimental investigation [1].

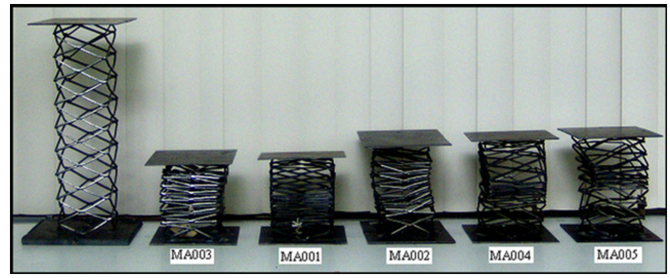

Fig. 3. Residual deformed shapes for square tubes $\alpha=0°$ [7].

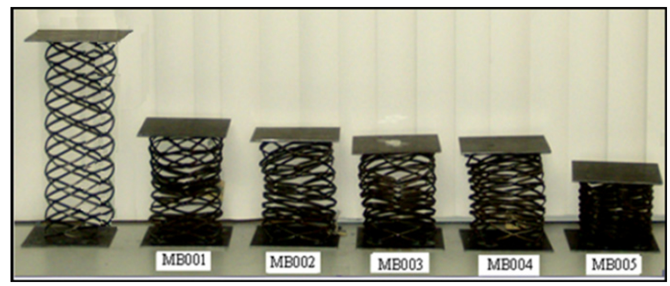

Fig. 4. Residual deformed shapes for round tubes con $\alpha=0°$ [7].

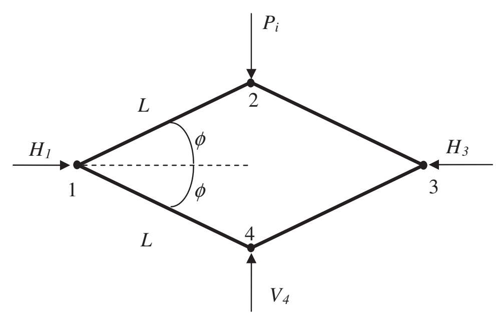

Fig. 5. Schematic view of pattern cell.

was a cylindrical kagome lattice that fails in a like manner as the expanded metal cell in [1]. In both works, it was found that the strength of the tube depends on the cell number in the circumferential direction.

The present investigation is aimed at developing a failure mechanism model to predict the strength of expanded metal tubes subjected to axial crushing based on the deformed configuration observed in the experiments. As a further study, this paper investigates the influence of the cell geometry on both the load-displacement response and the failure mechanism of the crushed tubes. The explicit non-linear finite element code ANSYS LS-DYNA [6] is used to predict the response of the expanded metal tubes subjected to axial crushing for various cell geometries.

2. Axial crushing of expanded metal tubes

2.1. Proposed theoretical model

As mentioned previously herein, in the experimental study conducted by Graciano et al. [1] three different collapse mechanisms were observed. It was observed that for $\alpha=0°$ the tubes failed due to progressive plastic collapse of the expanded metal cells until they were fully closed (Figs. 3 and 4). At first, the cells started to close with increasing load, and once the plastic moment of the cross section was attained in the nodes, the plastification progressively extends over the tube. This failure mechanism is characterized by the formation of plastic hinges at each cell junction at the mid-section of the tube, and the load-displacement response [1] shows a gradual increase of the load until a *plateau* is reached. This behavior is desirable for energy absorbing systems, where energy should be dissipated in a controlled way.

For this case with $\alpha=0°$, a mechanical model can be derived from the observation of the deformed configuration of the expanded metal tube at failure, then a mechanism resembling the deformation of the strands can be identified. Firstly, in the proposed model the material is assumed to behave according to a perfectly plastic model. Secondly, the strands can be represented as beams within a frame as shown in Fig. 5.

In this model, a vertical compression load P_i is applied at node 2 causing the inclined strands to bend and resulting in horizontal reaction forces at nodes 1 and 3. According to a rigid-plastic analysis, four plastic hinges are necessarily formed at the nodes to produce the total collapse of the cell [8]. Eqs. (1) and (2) consider the balance of forces in both the horizontal and vertical directions, respectively. It can be established that

$$H_1 = H_3 = H \tag{1}$$

$$V_4 = P_i \tag{2}$$

where H_1 and H_3 are horizontal reactions in nodes (1) and (3), respectively; V_4 is the vertical reaction in node 4. From the cell geometry the length of the strands is $L = 1/2\sqrt{l_1{}^2 + l_2{}^2}$.

Due to cell symmetry in geometry and load configuration, only one strand is analyzed (Fig. 6). Considering moments at node 1 for the element 1–4 and using Eq. (2) for V_4, results in the following equilibrium equation:

$$M_{14} + M_{41} - \frac{P_i}{2}\left(\frac{l_1}{2}\right) = 0 \tag{3}$$

At the ultimate limit state, plastic hinges form at each node; hence moments at those points reach the plastic moment capacity:

$$M_P = M_{41} = M_{14} \tag{4}$$

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