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# Quasi-static axial compression of concentric expanded metal tubes

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ABSTRACT

Previous studies have demonstrated that the failure mechanism and energy absorption capacity of expanded metal tubes strongly depends on the orientation of the cells. This paper presents an experimental investigation on the collapse of concentric expanded metal tubes subjected to quasi-static axial compression. Square tubes with two different cell orientations are tested to failure, and the energy absorption characteristics are calculated. The results show that the combination of cell geometries lead to a complex buckling mode interaction, which enhances the energy absorption capacity of expanded metal tubes.



## 1. Introduction

At designing crashworthy structures, a primary concern is to find structural configurations with high strength and light weight, capable to undergo progressive collapse. In this way, impact energy can be either absorbed or dissipated in a stable manner.

Over the last decades, energy-absorbing components have been the focus of several investigations. Alghamdi [1] conducted a review on the behavior of the common structural shapes, and their corresponding deformation patterns, used as collapsible impact energy absorbers subjected to compressive loading. Olabi et al. [2] presented a state-of-the-art review on metallic tubes used as energy absorbers under various loading cases. Furthermore, Yuen and Nurick [3] also presented a review on the effect of initial imperfections (geometric or material) on the structural response of tubular members subjected to axial loading. Concerning material behaviour, Meidell [4] offered guidance for material selection in the design of axially crushed tubes. More recently, using an analytical approach, Jones [5] reviewed the performance of various energy-absorbing systems based on the energy-absorbing effectiveness factor. These reviews revealed that metallic energy absorbers under axial compressive loads fail in various modes depending essentially on: *material properties* (elasticity modulus, yield stress, and strain hardening), *geometrical parameters* (length and cross-sectional variables such as thickness, width and/or diameter), and *initial imperfections* (patterns, grooves, corners and indentations).

Moreover, the development of crashworthy structural elements is under continuous progress. Improvements in the collapse response and energy absorption capacity have been achieved using multicorners structural shapes [6,7]. The progressive collapse of the structural members is a major issue in this field, as mentioned in Ref. [3] structural imperfections have become a mean for this purpose. Tubes with large openings [8–10] and corrugations [11] have been used to trigger the collapse of the tubes and to reduce the peak load exerted in the structural response. Bitubal or concentric tubes are also a feasible alternative to enhance the performance of energy absorbers [12], in most cases foam-filled arrangements [13–15] are used to modify the deformation mode of the individual members. Searching for innovative configurations, circular tube segments transversally loaded have also been employed for crashworthy applications in Refs. [16,17]. The advantage of using these type of tubes is the possibility of nesting an array of tubes of various diameters reducing the occupied space, in some cases the tubes are deformed additionally to obtain oblong configurations [18], which allow larger crushing displacements.

In a search for new materials and possible geometries for energy absorption applications, expanded metal sheets appear as a suitable option as found in several international patents [19]. Expanded metal sheets are manufactured in a single process upon in-line expansion of partially slit metal sheets, producing diamond like patterns as shown in Fig. 1. The final sheet is more likely a lightweight mesh with openings that are composed of nodes and strands, which exhibit a beam like structural behaviour [20].

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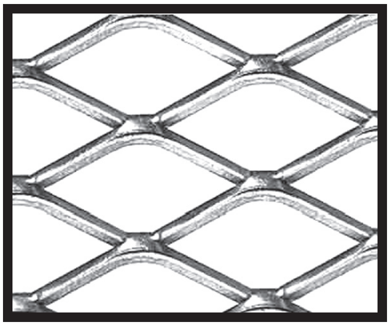

**Fig. 1.** Typical expanded metal pattern.

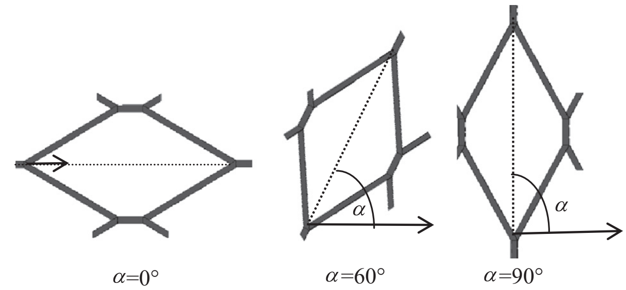


**Fig. 2.** Orientations of the expanded metal cells.

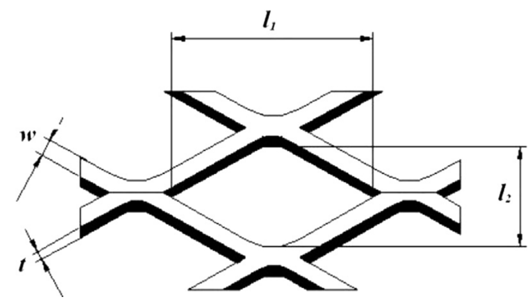


**Fig. 3.** Schematic view of an expanded metal cell.

Regarding the use of expanded metal sheets in energy absorption systems, very little information can be found in the corresponding literature. Kooistra and Wadley [21] investigated the use of flattened expanded metal sheets as core replacements for closed cell honeycombs used in sandwich panel structures. Pyramidal lattice trusses were fabricated and tested to shear and through thickness compression, the results showed improvements in collapse strength of these modified lattices. Dung [22,23] conducted an investigation aimed at finding an application for expanded metal meshes for seismically retrofitting of reinforced concrete moment resisting frames. A complete study was conducted on pure shear behaviour of expanded metal meshes subjected to monotonic and quasi-static cyclic loading, using experimental, theoretical and numerical approaches. Rambo-Roddenberry et al. [24] investigated a roofing system made of expanded metal panels, capable to mitigate hurricane effects such as windborne debris impact from high-speed winds. The results showed that the roofing system was able to resist penetration by heavy objects through the winds.

Graciano et al. [25] conducted an experimental investigation on the axial collapse of expanded metal tubes. From the test results, it was observed that the collapse mechanism depends on the orientation of the expanded metal cells (Fig. 2). Accordingly, three types of deformations patterns were observed: one characterised by a plastic collapse mechanism ($\theta=0°$); a second, in which local buckling of the individual strands lead to global buckling ($\theta=60°$); and a third, in which the tube wall buckled globally ($\theta=90°$). Martínez et al. [26] demonstrated numerically that the energy absorbing properties of the expanded metal tubes are enhanced by using various tubes configured concentrically with the same cell orientation. Nevertheless, a combination of geometries in concentrically placed tubes may lead to a greater increase in the energy absorbed when subjected to axial compression.

As seen above, expanded metal sheets are capable to absorb energy in different ways (*e.g.*, by bending, shear and axial compression), making of this a versatile material for crashworthiness applications. This paper gives a better insight into the possible mechanisms and energy absorption performance that can be achieved combining expanded metal tubes with different cell orientations *via* experimentation. Combinations of expanded metal tubes under quasi-static axial compression were tested. The results show a significant enhancement in both energy absorbing capacity and mean force for the concentric tubes, due to the interaction between the outer and inner tubes.

## 2. Experimental setup

Expanded metal sheets are basically manufactured in two basic types: standard and flattened [27]. These two sheets are quite different in geometry and mechanical properties. The flattened type undergoes additional cold-work, in which the standard sheet is passed through a cold-roll reducing mill.

**Table 1**
Dimensions of the expanded metal sheets used.

| Mesh | $l_1$ (mm) | $l_2$ (mm) | $t$ (mm) | $w$ (mm) |
|---|---|---|---|---|
| A | 90.00 | 44.70 | 1.90 | 2.80 |
| B | 68.60 | 34.50 | 1.90 | 2.80 |

Fig. 3 shows a schematic view of an expanded metal cell, the pattern is characterized by two orthogonal axes, a minor one ($l_2$) in the slitting direction and a major one ($l_1$). Two flattened meshes were used in the experiments, Table 1 shows the two cell geometries (Mesh A and Mesh B) used for the test program. In addition to the mesh size, four combinations of cell orientation were considered in this study, namely: 90°–0° (EMS900); 0°–90° (EMS090); 0°–60° (EMS060); 90°–60° (EMS9060). The first angle corresponds to the configuration of the outer tube, and the second to the inner one.

Each tube was manufactured independently by cutting the expanded metal sheets and then folding them to form the square cross-sections with the two cell orientations. Thereafter the strands and nodes were welded together to finally form the tubes, steel plates were also welded at the ends of the concentric tubes to guarantee the load application. For each geometry combination, three specimens were fabricated in order to check the repeatability of the results, *i.e.* for $\alpha=90°–0°$ with Mesh A the following specimens were tested EMS900A-01; EMS900A-02; and EMS900A-03. Finally, a total of 24 tests were performed, 12 for Mesh A and 12 for Mesh B.

The base material used to manufacture the expanded metal sheets is an ASTM A-569 steel with yield strength 246 MPa, ultimate strength 385 MPa, Young's modulus 205 MPa and Poisson ratio 0.3 [28]. It is worth noticing that the material properties change in the expanded metal meshes, particularly after flattening, during the manufacturing process. Hence, the actual properties are difficult to quantify due to the final size of the strands and nodes in the mesh.