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Analysis of circular tubes with rectangular multi-cell insert under oblique impact loads

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ABSTRACT

The present paper is focused on the analysis of the collapse mode of circular tubes with multi-cell insert under oblique loads. The material assigned to the structures is AA6061-O thus the material strain rate sensitivity can be neglected. An analytical solution for the evaluation of the crushing force is proposed. Results obtained from extensive numerical simulation were used in order to validate the analytical solution. The analysis of buckling and bending behaviour of the structure gives an estimate of the load that produces the collapse of the structure. This set of analytical equations can used to predict the behaviour of the structure under oblique load. Results obtained from the numerical simulation are compared with the results of the parametric analysis in order to validate the procedure. In case of designing structures starting from the capable load, the available configurations were investigated using the set of analytical equations. A good agreement was found between the analytical results and numerical simulations. The proposed model can be applied to evaluate structures under oblique impact as the analytical equations can be easily solved providing a start for the investigation of these complex structures.

1. Introduction

Crashworthiness addresses the vehicle's structural response undergoing high loads during an impact. In order to improve the structural response once the functional layout has been set-up, additional structures can be added. Work on steel structures under impact loads was reported by DiPaolo and Tom [1], while Fyllingen et al. [2] investigated aluminium structures. Results for different metallic materials used to design safety structures were summarized by Hsu and Jones [3]. Composite aluminium/CFRP structures were investigated by Kim et al. [4] and glass fibre/epoxy laminated by Kathiresan et al. [5]. Beside investigating the material's mechanical properties and behaviour under dynamic load, another way to improve structural response is to design specialised structures. Structures used as energy absorbing devices are designed from generic circular or rectangular structures [6,7], triangular [8], elliptical [9] or multi-cell [10–12]. Literature also points to different structures as Song et al. [13] propose the use patterned windows in order to reduce the weight. In order to complete the investigation of some existing solution and methods for structural optimisation, foam inserts, used to improve the performances, were investigated by Kiliçaslan [14] and Azarakhsh et al. [15] for circular structures, Zhang et al. [16], Goel [17] and Niknejad et al. [18] for rectangular structures and Ahmad and Thambiratnam [19] for conical shapes. The structure's wall thickness adjustment is a solution to design for crashworthiness as well the use of graded foam filler as investigated by Zhang and Zhang [20], while the use of filler in conjunction with graded thickness was investigated by An et al. [21].

Axial impact is widely investigated and above mentioned work present the findings in this field. A more challenging situation is in the case of structures subjected to oblique impact. Oblique load of filled circular structures were investigated by Djamaluddin et al. [22] showing the influence of the filler and filler's use. Oblique rectangular structures under impact loads were investigated by [23]. Rectangular multi-cell tubes were investigated by Fang et al. [24] and a formula to evaluate the mean crushing force under oblique loading was introduced. Conical structures under inclined impact were investigated by Zhang et al. [25] and optimal solution was identified using optimisation algorithms. Rectangular tubes with calibrated windows were investigated by Song [26]. The present work is focused on the evaluation, using an analytical method, of the force causing a structure to collapse. The structures investigated are of the type of circular tubes with rectangular multi-cell insert. The study is completed by investigated the buckling and bending behaviour of the structure in order to develop a solution useful to predict the collapse mode of the structure.

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2. Circular tube with rectangular multi-cell insert

A typical section of the structure with evenly spaced rectangular multi-cell insert [27] is presented in Fig. 1. The main parameters are identified by the radius of the outer tube (R) and the number of internal walls defining the cells (W). The secondary parameters are the thickness of the tube (t) and the thickness of the insert (t_i). The structure's set of dimensions is completed by its height (H_s).

2.1. Mean crushing force

A general formulation of the mean crushing force P_m was previously derived [27]. In case of a structure with constant thickness of the walls the formula is presented in Eq. (1):

$$P_m = EC\cdot\frac{1}{\kappa\cdot\sqrt{2}}\cdot\sigma_0\cdot t\cdot\sqrt{(2\cdot\pi+4\cdot N_{CC}+\lambda\cdot N_{TC})\cdot\pi\cdot(2\cdot\pi\cdot R+L_i)\cdot t} \tag{1}$$

The terms referenced by Eq. (2) are:

- EC enhancement coefficient ($EC=1.4$).
- κ parameter that considers the actual fold development.
- σ_0 flow stress of the structural material.
- t wall thickness.
- N_{CC} the number of criss-crosses.
- N_{TC} the number of T-shape cross-sections.
- λ parameter to account for the uneven length of the third flange of the T shaped section.
- R radius of the outer tube.
- L_i length of the multi-cell insert.

The flow stress σ_0 can be calculated using σ_y as the initial yield stress and σ_u as the ultimate stress and the strain hardening exponent n from the power law definition of the stress strain curve:

$$\sigma_0 = \sqrt{\frac{\sigma_y\cdot\sigma_u}{1+n}} \tag{2}$$

A penalty coefficient, to account for the uneven length of the third flange of the T shaped section, is defined as following:

$$\lambda = \sin\frac{2\cdot\pi}{N_{TC}} \tag{3}$$

The total length of the cross section of the insert (L_i) can be evaluated using Eq. (4):

$$L_i=2\cdot(2\cdot R)\cdot\sum_{i=1}^{W}\sqrt{1-\left(1-\frac{2\cdot i}{W+1}\right)^2} \tag{4}$$

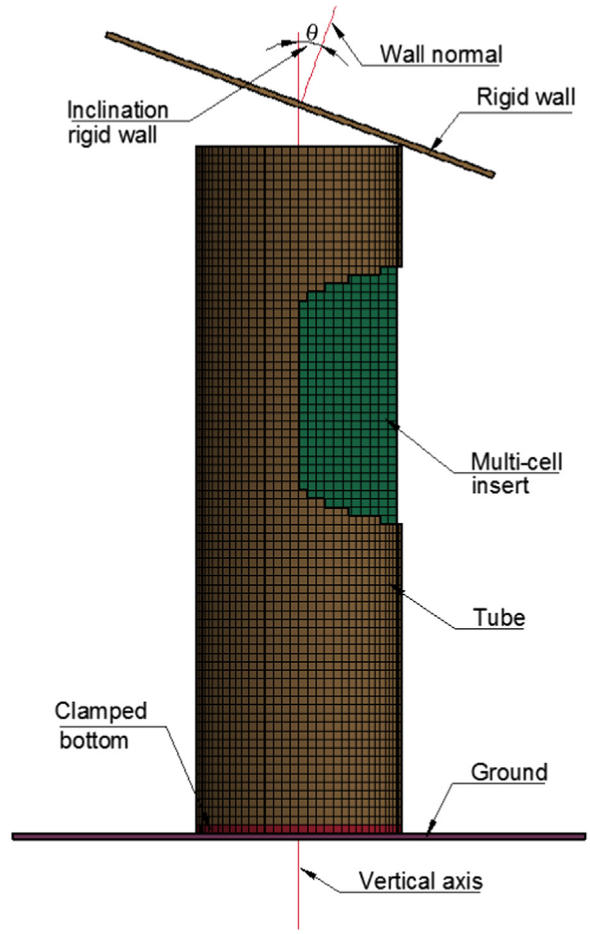

Fig. 2. Numerical model.

where W is the number of vertical walls of the rectangular insert (Fig. 1).

Investigating the structure of the formula used to determine the mean crushing force it can be noticed that it contains all the elements required to characterize the structure presented in a simplified formulation. As the equation can be adapted for various configurations and dimensions of the structure, it may be useful to investigate the crushing force developed during the oblique impact.

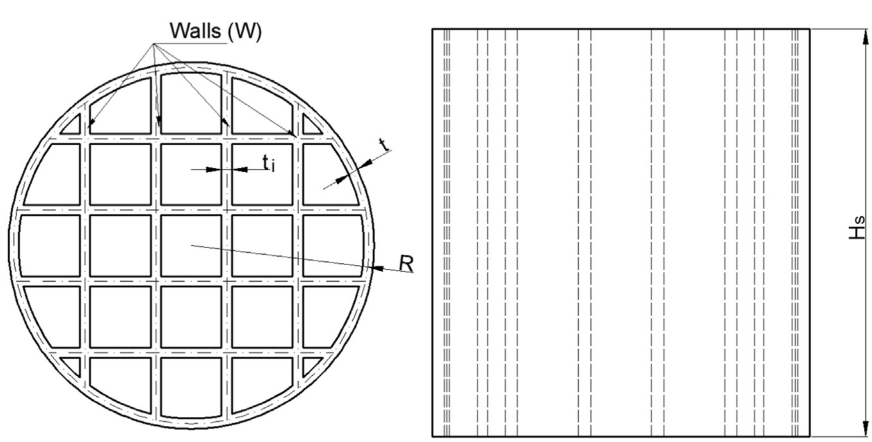

Fig. 1. Circular tube with rectangular multi-cell insert.