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ANALYTICAL MODELING OF THE TRANSITION OF THE PROGRESSIVE FOLDING MODE OF THIN-WALLED TUBES AFTER FOAM-FILLING

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ABSTRACT

Foam-filled thin-walled tubes are widely used as energy absorbers. It is observed that the folding mode of the progressive collapse transits from non-axisymmetric (diamond) mode to axisymmetric (concertina) mode after foam-filling. In this paper, we aim to investigate this phenomenon through analytical modelling based on the kinematically admissible folding mechanisms. For the foam-filled tubes, the interaction between the foam and the outer shell is represented as a pressure applied on the inward bending proportion of the shell. Both the mean and instantaneous crushing forces are derived from the energy conservation viewpoint. Our upper-bound model predicts that for the empty tube the diamond folding mode is energy favourable, while for the foam-filled case the concertina folding mode is the energy favourable mode.

Keywords: foam-filled, kinematically admissible, folding mode, concertina, diamond.

INTRODUCTION

Cellular materials such as aluminum foams possess excellent energy absorption properties as they are lightweight and can undergo large deformation at nearly constant load. However, their relative low strengths limit their potential to be used alone. Usually, they are used as fillers in thin-walled structures for energy absorption application. As reported in the literature, the effect of foam-filling on the enhancement of energy absorption depends on a number of parameters such as the foam density and the shell thickness. For this reason, substantial efforts have been devoted to investigating the crush behaviour of foam-filled thin-walled structures. This includes the extensive experimental work contributed by Hanssen et al. (2000), Meguid *et al*. (2004), extensive numerical efforts using finite element method (Ahmad and Thambiratnam, 2009), mesh free methods (Yang *et al*., 2013), and various optimization schemes. Several analytical models were also developed to calculate the mean crushing force as well as the instantaneous crushing force of both the empty and foam-filled tubes (Meguid *et al*., 2015).

It has been found that the progressive collapse takes on different folding modes between the empty and foam-filled tubes. For the empty case, the tubes usually deform is non-axisymmetric modes, which is referred to as diamond. The local buckles take place as several lobes around the tube circumference. The number of lobes depends on the ratio of thickness to radius. While for the foam-filled case, the axisymmetric folding mode which is referred to as concertina is more commonly observed. Although it is unanimously accepted that the transition of the folding mode is attributed to the effect of foam-filling, theoretical models for quantitative explanation of the underlying mechanisms are still lack.

METHODOLOGY

In this paper, we intend to investigate the transition of the folding mode of the thin-walled tubes after foam-filling through an analytical model based on the kinematically admissible mechanisms. The derivations of the model start from the basic principle of energy conservation, i.e., the input work equals to the energy dissipation W during the progressive deformation. The dissipated energy consists of three parts: (i) work dissipated in the plastic deformation of the tube shell, (ii) work dissipated in crushing the foam itself, and (iii) for the foam-filled case only, the work dissipated due to the interaction between the foam and tube shell. The foam/shell interaction is represented by an internal pressure equal to the yield strength of the foam acting on the inward portion of the fold. For the concertina folding mode, the energy absorption contributed by the tube shell is composed of the part dissipated in bending the horizontal hinge lines in the shell, and the part dissipated in circumferential straining of the materials between horizontal hinge lines. While for the diamond folding mode, the energy absorption contributed by the tube shell is caused by the bending of three kinds of hinges, i.e., (i) the stationary horizontal hinges, (ii) the inclined hinges, and (iii) the traveling hinges. The crushing force is obtained by deriving the dissipated energy with respect to the crushing distance.

Based on the above analytical model, we can theoretically derive the crushing forces for both the empty and foam-filled tubes deformed in different folding modes. According to the upper bound theorem, the selected folding scenario should correspond to minimum mean crushing force. We can show that the diamond mode and the concertina mode are the energy favorable mode for the empty and foam-filled tubes, respectively. In this way, the transition from the folding mode of the thin-walled tubes after foam-filling can be explained.

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