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ANALYTICAL MODEL OF THE PROGRESSIVE COLLAPSE OF FOAM-FILLED FRUSTUM CONSIDERING FOAM/SHELL FRICTION

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ABSTRACT

In this paper, the progressive collapse of foam-filled conical frusta is investigated through analytical model based on the kinematically admissible folding mechanisms. For this purpose, we improved our previous model by taking into account the friction between the foam filler and the shell wall. Both the mean and instantaneous crushing forces are derived from the energy conservation viewpoint. The energy dissipation comes from (i) the plastic deformation of the frustum shell, (ii) the crushing of the foam, and (iii) the interaction between the foam and shell, which is further composed of the contributions from the indentation of the foam by the shell, and from the friction during the foam/shell sliding. Our upper-bound model gives a closed form solution for the collapse of foam-filled frusta that can be used for crashworthiness management in automobiles.

Keywords: crashworthiness, progressive collapse, foam-filled, frusta, friction.

INTRODUCTION

Vehicle crashworthiness is one of the most important considerations in car safety, especially in the current trends of new-energy engine and self-driving. Although numerous safety features exist in motor cars, proper design of effective energy absorbing structure is still the major approach to protect the occupants from the damage of shock loads during a crash event at the present stage. Thin walled metallic structures are typically used as energy absorbers due to their weight and cost effectiveness, ease of fabrication and assembly, and high specific energy absorption (SEA). For example, thin-walled columns are used in the design of crash boxes in the automotive industry to connect the bumper to the side rails to effectively improve the crashworthiness.

Numerous efforts have been made by the scientific and engineering communities on the design of thin-walled structures to maximize their energy absorption capabilities. Extensive experiments and simulations have been carried out to investigate the effects of various material, geometric, and loading parameters on the collapse behaviour of empty and foam-filled tubes. In spite of these efforts, major challenges still exist in understanding the underlying mechanisms, which is important for quantifying the energy absorption performance and further improving the design. Theoretical modeling of the progressive collapse of thin-walled tubes is still insufficient, especially for the foam-filled frustum.

Recently, Meguid et al. (2015, 2016) developed a theoretical model. The model was based on a kinematically admissible mechanism of straight folds, and was able to predict the instantaneous crushing force as well as the mean crushing force from the energy conservation principle. In this paper, we continue this work by further including the effect of friction between the shell and foam filler on the energy absorption, to give a more comprehensive description of the foam-shell interaction.

METHODOLOGY

We focus on theoretical modelling of the foam-filled thin-walled frustum collapsed in the concertina, i.e. axi-symmetric form. For this purpose, the deformation of the frustum shell is assumed to follow the kinematically admissible mechanism of three-limb repeated folding. Fig. 1 illustrates the configurations of the progressive folding mechanism.

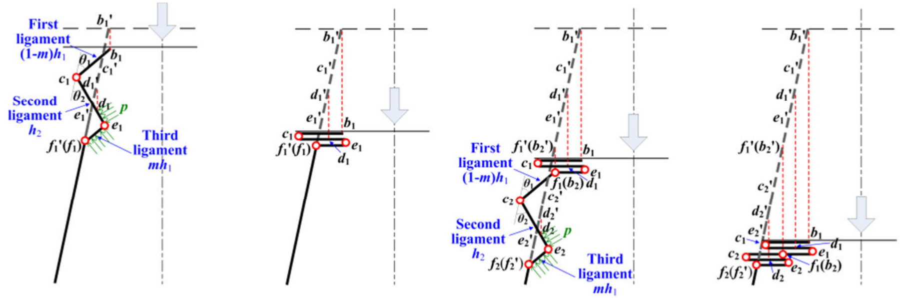

Fig. 1 - Configurations of the progressive folding mechanism

The crushing force is calculated from the basic principle of energy conservation that the plastic dissipation equals to the external work. The dissipated energy consists of three parts, (i) the part dissipated in the plastic deformation of the frustum shell, including the bending of the plastic hinges and straining along circumferential direction, (ii) the part dissipated in crushing the foam itself, and (iii) the part dissipated due to the interaction between the foam and frustum shell. The energy contributed by the foam/frustum interaction is further decomposed into two parts, one from the indentation and squeeze of the foam by the folding shell, and the other from the friction during foam/shell sliding. The indentation force of the foam by the shell is represented by a uniform pressure equalling to the foam yield stress applied on the inside part of the fold. The foam/shell friction is represented by a uniform tangential traction applied on the inside surface of the shell that slides relative to foam filler. The crushing force is obtained by deriving the dissipated energy with respect to the crushing distance. The resulted crushing load is a function of the fold length and the folding parameter defined as the length ratio of the inward part to the entire fold. It is required that the selected folding scenario should correspond to a minimum averaged crushing force, according to the upper bound theorem. The fold length and the folding parameter are thus determined.

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