



Collapse loading and energy absorption of fiber-reinforced conical shells



J.S. Lin^a, X. Wang^{a,*}, C.Q. Fang^a, X. Huang^b

^a School of Naval Architecture, Ocean and Civil Engineering (State Key Laboratory of Ocean Engineering), Shanghai Jiaotong University, Shanghai 200240, PR China

^b Centre for Innovative Structures and Materials, School of Civil, Environmental and Chemical Engineering, RMIT University, GPO Box 2476, Melbourne 3001, Australia

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ABSTRACT

Background/Purpose: An analytical solution is presented to predict the mean axial collapse forces of fiber reinforced conical shells under thermal loading, in which the fibers wrapped orientation is arbitrary;

Methods: Analytical method and finite element simulate;

Results: The influences of thermal loading, fibers wrapped orientations, geometrical eccentricity factor and proportionality coefficient on the axial collapse force of fiber reinforced conical shells are given.

Conclusion: The collapse loading P_m of fiber-reinforced conical shells appears in the maximum value under different thermal environment when the fibers wrapped direction equals 45° . By optimizing the wrapping orientation of fiber layers, the capability of energy absorption of fiber-reinforced conical shells can be enhanced.

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1. Introduction

It is significant to study the crashworthy behaviors of structures composed of different materials and geometrical shapes, under various loads [1–3]. Thin-walled structures, such as tubes and shells, have considerable potential as energy-absorbing devices, which have been widely applied to design the crashworthy structures of vehicles, aircraft and missile delivery [4]. Theoretical and experimental researches on efficient crashworthy structures have been performed by the plastic collapse of thin-walled tubes under axial compression [5–7]. Fiber-reinforced metal tubes and various composite structures have an excellent crashworthy performance and a high ratio of strength to weight [8–14]. Conical shells as efficient crashworthy structures have been widely used in various fields to dissipate impact energy. Some experimental researches on energy absorption capability of metal conical shell and composite conical shell have been presented in Refs. [15–19], but corresponding theoretical analyses are few reported in previous literature.

One of early studies on crashworthy characteristics of conical shell was carried by Postlethwaite and Mills [15], where Alexander's

extensible collapse analysis for rigid-perfectly material cones was presented. Axial collapse models and energy absorption characteristics of conical shells have been reported in Refs. [16–24]. Mamalis [17] applied the explicit FE code LS-DYNA to simulate the axial collapse of steel and aluminum conical shells, in which the FE simulation and the actual experimental data from small-scale models appeared in a good agreement.

From previous investigations [15–24], it is seen that experiment study and FE simulation for the axial collapse of structures are limited to fixed experimental conditions and calculation parameters. Thus, it is difficult to describe the generalizations of collapse characteristics of structures or to enhance the energy absorption capability of structures by optimizing some key parameters due to the complexity of the results in the individual situations. To date, no analytical solution for axial collapse of conical sandwich shells with fiber-reinforced layer has been presented. Therefore, it is significant to develop some analytical solutions to predict the collapse load and energy absorption capability of structures according to a reasonable collapse model. Based on the crumpling mechanism proposed by Alexander [4] and the collapse model of conical shell simulated by the explicit finite element code LS-DYNA, an analytical model is proposed in this paper to solve the collapse load of fiber-reinforced conical shells under thermal environment. According to the analytical model for the collapse ring folds introduced by Wierzbicki et al. [25], the eccentricity factor of fiber-

* Corresponding author.

E-mail address: xwang@sjtu.edu.cn (X. Wang).

reinforced conical shells is taken into account to improve the accuracy of solution further. The novelty of this paper is to present an analytical solution for axial collapse of conical sandwich shells with fiber-reinforced layer under thermal environment, where the capability of energy absorption of fiber-reinforced conical shells can be enhanced by optimizing the wrapping orientation and thickness of fiber layers, the collapse loading of fiber-reinforced conical shells may be accurately predicted by choosing appropriate geometric eccentricity m and the proportionality coefficient λ , and the effects of thermal loading and geometric shape of fiber-reinforced conical shells on the collapse loads are detailedly described.

2. Analytical method

Figs. 1 and 2 show a fiber-reinforced conical shell and an axisymmetrical collapse model respectively, which is from FEM simulation described in Section 3.2. It is seen from Fig. 2 that the ring folds of the fiber-reinforced conical shell under axial compression loading are developed. Based on the analytical model of fiber-reinforced circular tubes presented by Hanafi [6], the collapse mechanism of instantaneous formation of five static plastic hinges corresponding to two folds simplified with four elements is taken as the axial collapse model of fiber-reinforced conical tubes, as shown in Fig. 3. The lengths of fold elements are assumed not equal, that is, the length of the first fold element is equal to H and the length of the second fold element is equal to λH , where λ is the ratio coefficient of fold lengths dependent on the folds order. The collapse mechanism permits both the inward and outward radial displacements of the fold plastic hinges, where the inward radial displacements of internal hinges are equal, and the geometric eccentricity factor m [25] of fold length is introduced to describe a difference between inward and outward radial displacements.

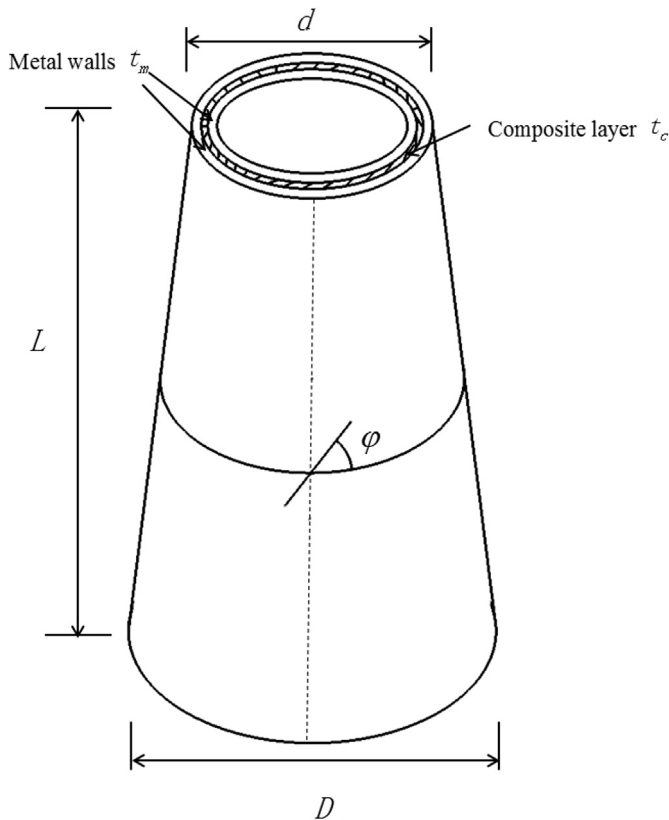


Fig. 1. Calculating model of fiber-reinforced conical shells.

Based on the conversation of energy, the mean collapse load is solved by making the external work equal the dissipated energy for a given crushing distance [5], as follows:

$$P_m = W/[2(1 + \lambda)H \sin \alpha] \quad (1a)$$

where $2(1 + \lambda)H \sin \alpha$ is the crushing distance of the four fold elements and α is the base angle between generatrix of fiber-reinforced conical shell and level.

W is the dissipated energy of fiber-reinforced conical shell, which is composed of the bending strain energy at five hinges and the circumferential stretching and compression strain energies between the hinges [7], as follows:

$$W = W_b + W_{met} + W_{mec} + W_{mct} + W_{cc} \quad (1b)$$

where W_b is the bending strain energy, W_{met} and W_{mec} are the circumferential stretching and compression strain energies of metal layer respectively, and W_{mct} and W_{cc} are the circumferential stretching and compression strain energies of fiber layer respectively.

2.1. Bending strain energy

When the angle θ of plastic hinge has an increment $d\theta$, the increment of bending strain energy at the second hinge of fiber reinforced conical metal shells is written as [7]

$$dW_{b2} = 4M_{10} \cdot d\theta \cdot \pi[2(a + H \cos \theta \cos \alpha)(1 + \beta_m \Delta T) + 2mH \sin \theta \sin \alpha] \quad (2a)$$

$$\text{where } a = a(\theta) = r + 2(1 + \lambda)H(1 - \cos \theta) \cos \alpha \quad (2b)$$

The increment of bending strain energy at the fourth hinge is written as [7]

$$dW_{b4} = 4M_{10} \cdot d\theta \cdot \pi[a + (2 + \lambda)H \cos \theta \cos \alpha)(1 + \beta_m \Delta T) + 2(\lambda - (1 - m))H \sin \theta \sin \alpha] \quad (3)$$

where M_{10} is the bending moment of the section of metal layer at outward plastic hinges 2 and 4, in which the fiber-reinforced layers are subjected to tension. β_m denotes the thermal expansion coefficient of metal wall and ΔT denotes the temperature change.

From Ref. [26], the metal layers of fiber-reinforced conical shells obey Von Mises yield criterion, the yielding stress of the metal layer in bending deformation is taken as a function of temperature change as follows:

$$\sigma_Y = \frac{2}{\sqrt{3}} \sigma_0 (1 - 0.005 \Delta T) \quad (4)$$

and M_{10} is written as

$$M_{10} = \frac{1}{2\sqrt{3}} \sigma_0 (1 - 0.005 \Delta T) t_m^2 C_T \quad (5)$$

In the above formula, C_T is the function of material properties of metal wall and composite layer, as follows [6]:

$$C_T = 1 + \frac{\sigma_{fxt}}{\sigma_0} \cdot \frac{t_c}{t_m} + 0.5 \cdot \frac{\sigma_{fxt}}{\sigma_0} \cdot \left(\frac{t_c}{t_m}\right)^2 - 0.25 \left(\frac{\sigma_{fxt}}{\sigma_0}\right)^2 \left(\frac{t_c}{t_m}\right)^2 \quad (6)$$

where t_m , t_c and σ_{fxt} denote the thickness of metal walls, the thickness of fiber-reinforced layer and the axial tensile strength of the fiber layer, respectively.

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