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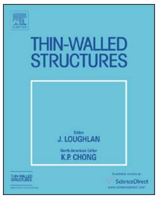

Theoretical and experimental analysis of elastic–plastic cylindrical shells under two types of axial impacts

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ABSTRACT

In this paper, the dynamic buckling of axisymmetric circular cylindrical shells subjected to axial impact is investigated theoretically and experimentally. The von Mises yield criterion is used for the elastic–plastic cylindrical shell made of linear strain hardening material in order to derive the constitutive relations between stress and strain increments. Nonlinear dynamic circular cylindrical shell equations are solved with using finite difference method for two types of loading which are stationary cylindrical shells impacted axially and traveling cylindrical shells impacted against a rigid wall. Experimental tests for two types of loading are performed by gas gun. Theoretical and experimental results for cylindrical shells under axial impact for different loading conditions are reported and it is found that there is a good agreement between them.

1. Introduction

Cylindrical shells due to their economic, low weight and efficiency have been widely used in different industries. One of the most important applications of them is in the energy absorption systems [1–3]. Thus, investigation of dynamic behavior of cylindrical shells is important. This paper aims to study the dynamic buckling of circular cylindrical shells under axial impact.

The plastic buckling of cylindrical shells under axial impact was investigated experimentally by Florence and Goodier [4]. In this study, the results of shortening, impact duration, half-wave number and buckling shape of cylindrical shells were reported. The results of axial static and dynamic loading of cylindrical shells made of steel were reported experimentally by Abramowicz and Jones [5]. In this paper, the experimental results were compared with the results of theoretical and empirical relations. This study reported a good agreement between the results of modified version of Alexander's theory with experimental ones. The experimental results of cylindrical shells with different sizes and made of aluminum and steel, under axial quasi-static and impact loading were reported by Gupta [6]. Also, circular holes were drilled on the cylindrical shells laterally. It was found that the presence of these circular holes changes the mode of collapse of cylindrical shells which decreases the Euler buckling even in relatively longer cylindrical shells. The experimental and numerical studies of aluminum cylindrical shells under quasi-static and dynamic test conditions were performed by Galib and Limam [7]. Numerical model employed in this paper predicted experimental results correctly. The experimental and numerical investigations of cylindrical shells under high velocity impact were performed by Higuchi et al. [8]. From numerical study of this paper, it was found that a large portion of impact energy is absorbed by shortening.

The axisymmetric buckling of elastic–plastic cylindrical shells under axial impact was investigated by finite element analysis [9–12]. The effects of material properties, shell geometry, boundary and loading conditions on the energy absorption and buckling shapes of cylindrical shells were investigated by Karagiozova and Jones [9]. The results of this paper revealed that the cylindrical shells made of steel material absorb the energy with the shortening mechanism, whereas the cylindrical shells made of aluminum material absorb the energy with folding mechanism. The effects of velocity and striking mass on the energy absorption and mechanism of buckling by shape were examined Karagiozova et al. [10]. It was found that the energy absorption and buckling shape of cylindrical shells are affected by velocity and striking mass. Furthermore, it was found that inertia characteristics together with material properties determines a particular stress wave propagation which determines the type of plastic or progressive buckling of cylindrical shells. In the dynamic plastic buckling "the whole length of a cylindrical shell wrinkles before the large radial displacements develop [11]", and in the dynamic progressive buckling "the folds in a cylindrical shell form consecutively [11]". The effect of approximation of strain hardening modulus on the

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type of buckling shape (plastic or progressive buckling) and also the effect of axial inertia on the initiation and development of buckling shapes of cylindrical shells under axial impact were explored by Karagiozova and Jones [11]. Dynamic buckling of cylindrical shells made of aluminum and steel under axial impact was investigated by Karagiozova and Jones [12]. In this paper, dynamic plastic and progressive buckling of cylindrical shells were investigated from the viewpoint of stress wave propagation. It was found that material properties together with shell geometry determine the type of buckling shapes (plastic or progressive) in cylindrical shells under axial impact.

Energy Absorption of thin-walled circular cylindrical shells made of metallic materials was studied using a numerical study by Xin et al. [13]. Response surface methodology (RSM) was used in this investigation. It was found that proposed RSM method can be widely used in the investigation of energy absorption characteristics for metallic thin-walled circular cylindrical shells.

Dynamic buckling behavior of aluminum cylindrical shells under high velocity impact with axial linear variable thickness, discontinuity and conical shaped was investigated with finite element program LS-DYNA3D by Gumruk [14]. This study revealed that a small change in geometry of cylindrical shell can transform the plastic and progressive buckling.

The effect of different parameters on the peak load in cylindrical shells under axial impact was investigated with finite element program MSC.DYTRAN by Chen and Ushijima [15]. In this study, an equation for calculation of peak loads in cylindrical shells under axial impact with the velocity low than 40 (m/s) was presented.

The improvement of buckling of elastic–plastic cylindrical shells under axial impact with Galerkin method was studied by Lepik [16]. Because of using many simplifications in this theory, it is impossible comparing the theoretical and experimental results with each other. Buckling of aluminum elastic–plastic cylindrical shells under axial impact was studied using a discreet model by Karagiozova and Jones [17]. The study revealed that buckling shape is strongly affected by inertia properties of striking mass and shell geometry. The plastic buckling of cylindrical shells under axial impact was investigated by Wang and Tian [18].

In the studies performed so far, the effect of different kinds of loading conditions on the shortening, energy absorption and buckling shape has not been presented clearly. In this paper, nonlinear axisymmetric dynamic circular cylindrical shell equations are derived and solved with finite difference method for two types of loading. In addition, for experimental test of two types of loading, gas gun is used. Theoretical and experimental results for two types of loading are presented. Also, the results for different kinds of loading are compared with each other.

2. Types of loading

According to Figs. 1 and 2, cylindrical shell of length L, radius R and thickness t is impacted axially in two types of loading. In the first type, as shown in Fig. 1, stationary cylindrical shell is impacted axially with a striking mass. In the second type, as shown in Fig. 2, moving shell together with attached mass is impacted against a rigid wall.

3. Governing equations

The axisymmetric nonlinear dynamic equations for cylindrical shells under axial impact are as [19]

$$N_{x,x} = \rho h u_{,tt} \tag{1}$$

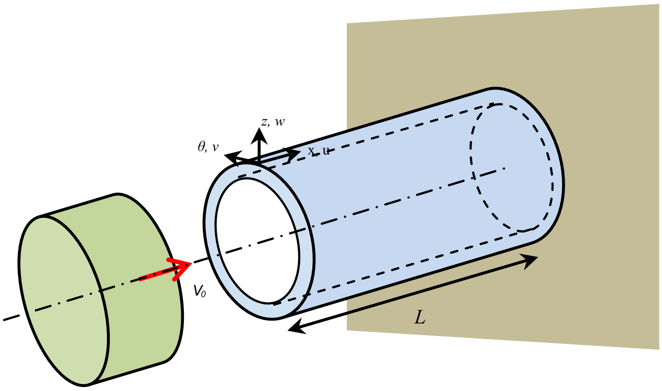

Fig. 1. Cylindrical shell is impacted with a striking mass.

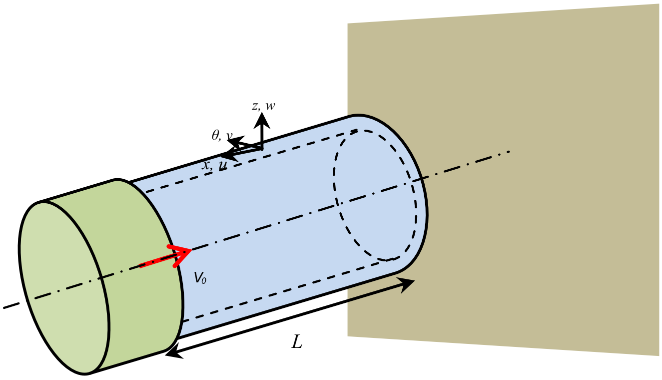

Fig. 2. Moving cylindrical shell together with attached mass is impacted against a rigid wall.

$$M_{x,xx} + \left(N_x w_{,x}\right)_{,x} - \frac{1}{R} N_\theta = \rho h w_{,tt} \tag{2}$$

In Eqs. (1) and (2), M_x is bending moment and N_x, N_θ are membrane forces. Also, u is axial displacement, w is lateral displacement and ρ is density. The elastic–plastic axial and lateral strains for axisymmetric deformation of cylindrical shells are defined by [19]

$$\varepsilon_x = \varepsilon_x^0 + z\varepsilon_x^z = u_{,x} + \frac{1}{2}\left(w_{,x}\right)^2 - zw_{,xx} \tag{3}$$

$$\varepsilon_\theta = \varepsilon_\theta^0 = \frac{1}{R} w \tag{4}$$

According to von Mises criterion, the constitutive relation between stress and strain increments for isotropic material with linear strain hardening will be derived. Total strain increment is equal to the sum of elastic and plastic strain increments as

$$d\varepsilon_x = d\varepsilon_x^p + d\varepsilon_x^e \tag{5}$$

$$d\varepsilon_\theta = d\varepsilon_\theta^p + d\varepsilon_\theta^e \tag{6}$$

According to von Mises yield criterion, plastic strain increments using Prandtl-Reuss equation is derived as [20]

$$d\varepsilon_x^p = \frac{3}{2}\frac{d\varepsilon_e^p}{\sigma_e} S_x,\ S_x = \sigma_x - \frac{\sigma_x + \sigma_\theta}{3} \tag{7}$$

$$d\varepsilon_\theta^p = \frac{3}{2}\frac{d\varepsilon_e^p}{\sigma_e} S_\theta,\ S_\theta = \sigma_\theta - \frac{\sigma_x + \sigma_\theta}{3} \tag{8}$$

The effective stress and plastic strain increments in prandtl-