Composite Structures 160 (2017) 491–502

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Low-velocity impact response analysis of composite pressure vessel considering stiffness change due to cylinder stress

Ik Hyeon Choi

Aerospace Application and Materials Research Team, Korea Aerospace Research Institute, South Korea

ARTICLE INFO

Article history:
Received 6 October 2016
Accepted 8 October 2016
Available online 20 October 2016

Keywords:
Pressure vessel
Composite
Low-velocity impact
Cylinder stress
Stiffness change
Finite-element formulation

ABSTRACT

To accurately analyse the transient response and damage of pressurized vessels subjected to a drop impact or foreign object impact, we must consider the change in stiffness due to pre-stress. The pre-stress condition induces a phenomenon where thin plates with in-plane pre-stress show different stiffness during out-of-plane deflections compared to the original plate without the in-plane pre-stress. Because the cylindrical wall of a pressurized vessel is under in-plane pre-stress induced by the vessel's internal pressure, we must consider the 'change in stiffness' to accurately analyse the impact response and damage. In this study, we investigated the low-velocity impact response of a composite laminated cylinder wall of a pressure vessel with high internal pressure. The shear deformation theory of a doubly curved shell and von Karman's large deflection theory, as well as a newly proposed strain–displacement relation including initial strain terms to consider the stiffness change induced by cylinder stress due to internal pressure, were used to develop a geometrically nonlinear finite-element program. Numerical results that were calculated for the cylinder stress showed larger contact force and smaller deflection. By comparing strain values, a simple superposition of strain value calculated without considering cylinder stress and initial cylinder strain value showed 10–20% more strain than that accurately calculated with considering the stiffness change due to cylinder stress.

1. Introduction

The impact response and damage of pressure vessels manufactured using composite materials have been investigated recently [1–3]. To accurately analyse the transient response and damage of pressurized vessels subjected to a drop impact or foreign object impact, we must consider the 'change in stiffness'. The pre-stress condition induces a phenomenon where thin plates with in-plane pre-stress show different stiffness for out-of-plane deflections from the original plate without the in-plane pre-stress. As seen in Fig. 1, because the cylinder wall of such a pressurized vessel is under in-plane pre-stress induced by the vessel's internal pressure, we must consider the 'stiffness change' to accurately analyse the impact response and damage. However, no analytical result that considers the stiffness change has been identified to date.

Authors have presented certain papers on the transient response and damage prediction of composite laminated plates and shells subjected to low-velocity impacts [4–12]. Authors have developed a new finite-element formulation for composite laminates considering in-plane pre-strain, and have investigated the impact response of composite laminated flat plates with in-plane tensile and compressive pre-strain via numerical calculations and experimentations [10,11]. In those studies, the authors reported that in-plane tensile pre-strain increases the stiffness of a laminate during deflections caused by impacts and that in-plane compressive pre-strain decreases the stiffness. Recently, this author presented a paper on geometrically nonlinear transient analysis of composite laminated cylindrical shells subjected to low-velocity impact [12].

In this study the author develops a new finite-element program that considers the stiffness change of a cylindrical shell structure experiencing in-plane pre-strain. Using the finite-element program, the author presents analytical results on the impact response of a cylinder wall with in-plane pre-stress due to internal pressure.

2. Finite-element equation of a composite laminated shell considering in-plane pre-strain

A shear deformation theory of a doubly curved shell and von Karman's large deflection theory were used to develop a geometrically nonlinear finite-element program. The coordinate system used in this study can be seen in Fig. 2. In the strain–displacement

E-mail address: ihchoi@kari.re.kr

http://dx.doi.org/10.1016/j.compstruct.2016.10.023
0263-8223/

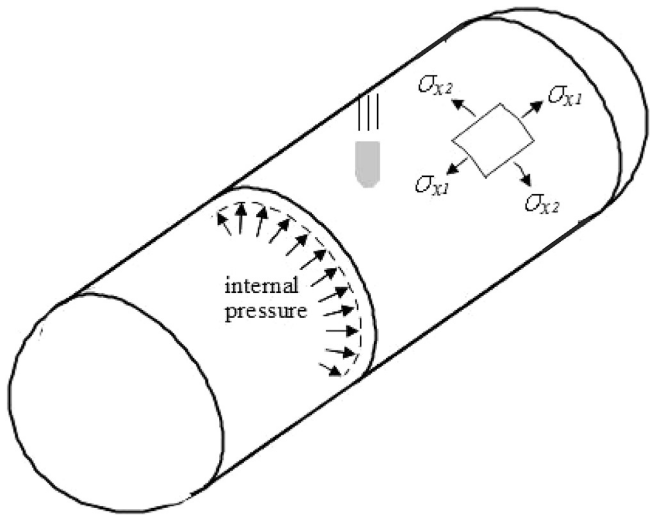

Fig. 1. Cylinder wall structure with in-plane pre-stress induced by internal pressure of pressure vessel subjected to foreign object impact.

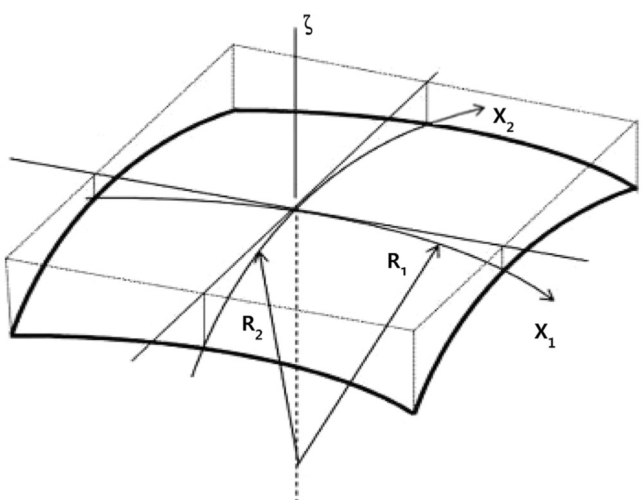

Fig. 2. Coordinate system for doubly curved shell.

relation of the shear deformation theory of a doubly curved shell and von Karman's large-deflection theory, some terms of in-plane pre-strains, $\varepsilon_1^{pre}, \varepsilon_2^{pre}, \varepsilon_6^{pre}$ are added, as shown in Eq. (1):

$$\begin{aligned}
\varepsilon_1 &= \varepsilon_1^{pre} + \varepsilon_1^0 + \zeta\kappa_1^0 = \varepsilon_1^{pre} + \tfrac{\partial u_1}{\partial x_1} + \tfrac{u_3}{R_1} + \tfrac{1}{2}\left(\tfrac{\partial u_3}{\partial x_1}\right)^2 + \zeta\tfrac{\partial \phi_1}{\partial x_1} \\
\varepsilon_2 &= \varepsilon_2^{pre} + \varepsilon_2^0 + \zeta\kappa_2^0 = \varepsilon_2^{pre} + \tfrac{\partial u_2}{\partial x_2} + \tfrac{u_3}{R_2} + \tfrac{1}{2}\left(\tfrac{\partial u_3}{\partial x_2}\right)^2 + \zeta\tfrac{\partial \phi_2}{\partial x_2} \\
\varepsilon_6 &= \varepsilon_6^{pre} + \varepsilon_6^0 + \zeta\kappa_6^0 = \varepsilon_6^{pre} + \tfrac{\partial u_2}{\partial x_1} + \tfrac{\partial u_1}{\partial x_2} + \tfrac{\partial u_3}{\partial x_1}\tfrac{\partial u_3}{\partial x_2} + \zeta\left(\tfrac{\partial \phi_2}{\partial x_1} + \tfrac{\partial \phi_1}{\partial x_2} + c_0\left(\tfrac{\partial u_2}{\partial x_1} - \tfrac{\partial u_1}{\partial x_2}\right)\right) \\
\varepsilon_4 &= \varepsilon_4^0 = \tfrac{\partial u_3}{\partial x_2} + \phi_2 - \tfrac{u_2}{R_2} \\
\varepsilon_5 &= \varepsilon_5^0 = \tfrac{\partial u_3}{\partial x_1} + \phi_1 - \tfrac{u_1}{R_1}
\end{aligned} \tag{1}$$

where:

$$c_0 = \frac{1}{2}\left(\frac{1}{R_2} - \frac{1}{R_1}\right)$$

Hamilton's principle, which is the principle of virtual work including dynamic behaviour, can be written as:

$$\begin{aligned}
0 = \int_\Omega &[N_1\delta\varepsilon_1^0 + N_2\delta\varepsilon_2^0 + N_6\delta\varepsilon_6^0 + M_1\delta\kappa_1^0 + M_2\delta\kappa_2^0 + M_6\delta\kappa_6^0 + Q_1\delta\varepsilon_5^0 \\
&+ Q_2\delta\varepsilon_4^0 + (P_1\ddot{u}_1 + P_2\ddot{\phi}_1)\delta u_1 + (\overline{P}_1\ddot{u}_2 + \overline{P}_2\ddot{\phi}_2)\delta u_2 + I_1\ddot{u}_3\delta u_3 \\
&+ (I_3\ddot{\phi}_1 + P_2\ddot{u}_1)\delta\phi_1 + (I_3\ddot{\phi}_2 + \overline{P}_2\ddot{u}_2)\delta\phi_2 - q\delta u_3]\alpha_1\alpha_2 d\xi_1 d\xi_2
\end{aligned} \tag{2}$$

where:

$$P_1 = I_1 + \frac{2I_2}{R_1},\ P_2 = I_2 + \frac{I_3}{R_1}, \overline{P}_1 = I_1 + \frac{2I_2}{R_2},\ \overline{P}_2 = I_2 + I_3R_2 \tag{3}$$

The meaning of each term and notation in Eq. (2) is described in other papers [12,13]. Eq. (2) can be used to derive the finite-element Eq. (4) below, which can be used for the dynamic analysis of a composite laminated flat plate or curved shell with in-plane pre-strain. The detailed mass and stiffness matrices can be found in the Appendix A of this paper:

$$[M]\{\ddot{U}\} + [[K_L]^{pre} + [K_L] + [K_N\{U\}]]\{U\} = \{F\} \tag{4}$$

Conversely, an impactor was assumed to be a point mass; thus, the dynamic equation for the impactor can be written as Eq. (5). The two dynamic equations for the composite shell and impactor were calculated simultaneously using the modified Hertzian contact law (6). The detailed solving procedure for the three equations and the meaning of each term and notation in Eqs. (5) and (6) can be found in previous studies [4–8]:

$$m\ddot{u}_3 + F = 0 \tag{5}$$

$$F = k\alpha^n, \text{where } k = \frac{4}{3}\frac{R^{1/2}}{(1-\nu_r^2)/E_r + 1/E_p} \tag{6}$$

Two types of pressure vessels were considered in this study as shown in Table 1. Total lengths of the vessels and internal pressure were assumed as the same at 90 cm and 350 bar. However, internal radiuses, cylinder lengths and wall thicknesses in the two types of vessels were assumed to be different, as shown in Table 1. The thickness of one ply in the two types of cylinders was assumed to be 0.303 mm for both.

Four types of fibre orientation angles in each vessel with a stacking sequence of $[\theta/-\theta]_{17T}$ or $[\theta/-\theta]_{25T}$ were considered, as shown in Table 2. The magnitude of in-plane pre-strain in geometrical coordinates induced by internal pressure varied widely according to fibre orientation angle from 45° to 56.22°, but the relative magnitude of in-plane pre-strain in material coordinates was not so varied.

As shown in Fig. 3, the cylinder was assumed to be impacted at the centre by a steel impactor with a contacting spherical cap with a radius of 0.635 cm, which was used as the value of R in the modified Hertzian contact law of Eq. (6). The stacking sequence of the laminates was constituted with θ° and $-\theta$°. Thus, the total area of the cylinder wall was meshed and calculated, as shown in Fig. 4.

As described in Figs. 3 and 4, both end lines of the cylinder and straight line at opposite side from the impact position, which means the meeting line of two edges of the cylindrically curved shell, were assumed to be in fixed boundary condition. Because this finite-element formulation was based on the curved-shell theory, the meeting line of two edges of the cylindrically curved shell should be considered with boundary conditions. In application of the shell theory, this case is that the curvature in the x_1-coordinate was zero and the curvature in the x_2-coordinate was the maximum value (i.e., a complete cylinder). The details of this description can be found in a previous paper [12].

The impact condition considered in this study is shown in Table 1. The elastic properties of a graphite/epoxy lamina were assumed to be as follows:

E_1 = 165 GPa, E_2 = 8.56 GPa, ν_{12} = 0.326, ν_{23} = 0.43,
$G_{12} = G_{13}$ = 4.39 GPa, G_{23} = 2.7 GPa, $\rho = 1.58 \times 10^{-5}$ N s^2/cm^4

The finite element used in this program is a nine-node *iso*-parametric plate element. To check for convergence on the mesh size, meshes between 8 × 8 and 24 × 24 for total area of cylinder wall were tested. A fine mesh of 24 × 24 was found to be sufficient