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Finite element analysis of dynamic responses of composite pressure vessels under low velocity impact by using a three-dimensional laminated media model

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ABSTRACT

This paper aims to study dynamic structural responses and failure mechanisms of composite pressure vessels subjected to low velocity impact. First, a three-dimensional laminated media model based on sub-laminate theory is introduced for intralaminar damage, where Puck's failure criteria and strain based damage evolution laws for fiber and matrix are used. The impact responses of composite pressure vessels can be calculated based on sub-laminates and the fiber and matrix damage are predicted based on each ply by using this approach. Second, the proposed laminated media model is implemented using ABAQUS/Explicit user-defined material subroutine VUMAT by the time stepping algorithm and the bilinear cohesive model is employed to simulate interlaminar delamination. Finally, numerical simulations are performed to study the impact force-time/central displacement curves and intralaminar damage and interlaminar delamination features for composite pressure vessels at three different impact energy. Detailed energy dissipation mechanisms due to intralaminar dynamic progressive failure, interlaminar delamination and deformation of liner are also discussed. By comparison, relatively good agreement is achieved between the experimental and numerical results by using the three-dimensional laminated media model.

1. Introduction

Currently, composite pressure vessel has been widely used to store compressed natural gas (CNG) and hydrogen energy source for fuel cell vehicles because of their high strength- and stiffness-to-weight ratios, good fatigue performance, excellence corrosion resistance and satisfactory durability [1,2]. The design and manufacture of the composite pressure vessel are promoted by introducing the composite filament wound technology [3]. Thus the Type III composite vessels with metal liner such as aluminium liner and the Type IV composite vessels with non-metal liner such as EPDM liner can be taken as fiber/epoxy composite laminated structures by stacking the composite layers with different thickness and different orientations [4].

Considering several causes of failure, composite pressure vessels are susceptible to low velocity impact due to weaker load-bearing capacity in the transverse direction than in the longitudinal direction [5,6]. Besides, the damage due to low velocity impact reduces the load capacity and burst strength of the pressure vessel, which may cause a potential hazard [7]. Therefore, it is important to predict transverse low velocity impact behaviors for composite pressure vessels by developing theoretical and numerical methods.

During the past decades, Much work has investigated impact problems on flat composite plates such as Donadon et al. [8], Liu et al. [9], Farooq and Myler [10], Tan et al. [11] and Liao and Liu [12], etc. However, a few scientific contributions have considered the impact analysis on the curved filament wound structures. This leads to related fundamental research on the dynamic mechanical properties of them is still not mature although there are some experiments about the structural responses and damage mechanisms [13–18]. The numerical simulation of impact problem involves material, geometry and boundary nonlinearities, and the progressive failure of composite pressure vessels includes complicated intralaminar damage and interlaminar delamination. Now, there were only a few researchers explored the impact behaviors of composite pressure vessels by FEA such as Refs. [19–22]. Ganapathy and Rao [19] performed FEA on the structural impact responses of cylindrical composite shells by considering fiber breakage and matrix cracks, but did not introduce delamination. Perillo et al. [20] and Han and Chang [21] identified the damage modes for fiber and matrix by using failure criteria, which yet fail to introduce the damage evolution mechanisms. Kim et al. [22] studied the impact

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damage including intralaminar damage and interlaminar delamination simultaneously, but the energy dissipation mechanisms with respect to different failure modes including intralaminar fiber and matrix damage, delamination and friction were not discussed. In addition, these numerical researches about impact analysis of composite pressure vessels almost all used the traditional ply-by-ply model although some of them have employed three-dimensional failure criteria by considering out-plane stress effects. However, composite pressure vessels withstanding high pressure always have multiple plies, and traditional three-dimensional ply-by-ply model requires at least one element in each ply along the thickness direction. This makes multi-ply composite pressure vessels have a large number of elements with small characteristic length, which limits the explicit impact calculation efficiency because of small stable time increments. Thus a three-dimensional ply-by-ply model for exploring the impact responses of composite pressure vessels would be too time-consuming in both pre-processing and calculation.

Several three-dimensional failure criteria based on meso-mechanics [23–25] and macro-mechanics [26–29] are supplied in The Second World-Wide Failure Exercise (WWFE-II). In these analyses, most employ a ply-by-ply approach except for Bogetti's three-dimensional laminated media theory [29]. Bogetti's laminated media theory is based on sub-laminate homogenization and decomposition of sub-laminate stress and strain [29,30]. With this method, the number of elements in the thickness direction of a laminate could reduce and the computational efficiency is greatly improved. However, Bogetti [29,30] used the maximum strain failure criteria to study damage modes of composite laminates and did not study the damage evolution mechanisms for fiber and matrix, which leads to some limitations on the application of the impact analysis for the composite pressure vessels.

This paper aims to study dynamic structural responses and failure mechanisms of composite pressure vessels subjected to low velocity impact. A three-dimensional laminated media model based on sub laminate theory is first introduced for impact analysis of composites, where Puck's failure criteria and strain based damage evolution laws are used for intralaminar fiber, matrix damage and failure mechanisms. Finite element difference algorithm for composite layers is developed and implemented in ABAQUS as a user-defined material subroutine VUMAT and the bilinear cohesive model [9] is used for delamination. It should be emphasized the energy dissipation mechanisms of composite pressure vessels are closely related to the damage evolution and liner deformation. By comparing with the work reported in Refs. [19–22], another contribution of this work is to further explain the detailed energy dissipation mechanisms and damage evolution behaviors of composite pressure vessels corresponding to different intralaminar fiber breakage, matrix cracking failure modes and interlaminar delamination. Numerical results with different impact energy obtained from FEA are compared with the experimental results in terms of the impact force-time/central displacement curves and the energy dissipation.

2. Stress-strain behavior of the three-dimensional laminated media model

2.1. The three-dimensional laminated media model

The three-dimensional laminated media model establishes a computation procedure between macroscopic single ply and sub-laminate as shown in Fig. 1. In this case, an entire multi-ply laminate is divided into several sub-laminates with a number of plies in the thickness direction. For each sub-laminate, the equivalent stiffness must be firstly calculated with material mechanical properties and the layup information. After this calculation, the general response such as global displacements, stresses and strains of the entire structure based on sub-laminates can be calculated by the equivalent stiffness. Then, the local stresses and strains for each ply in the material coordinate system are obtained through coordinate transformation and decomposition of sub-laminate stresses and strains. Finally, the stresses and strains of each ply are used to predict the damage status and the corresponding stiffness reduction after damage occurs. This procedure is shown in Fig. 1(a). In order to compare the difference between the three-dimensional laminated media model and the traditional ply-by-ply model, the procedure of ply-by-ply model is also supplied as shown in Fig. 1(b).

2.2. Three-dimensional equivalent stiffness

According to Chou's 3D equivalent theory [31], a sub-laminate comprised of a number of plies with different ply angle and different thickness is equivalent to a monoclinic material with an equivalent stiffness matrix as follows:

$$[\overline{C}_{ij}^*] = \begin{bmatrix} \overline{C}_{11}^* & \overline{C}_{12}^* & \overline{C}_{13}^* & 0 & 0 & \overline{C}_{16}^* \\ & \overline{C}_{22}^* & \overline{C}_{23}^* & 0 & 0 & \overline{C}_{26}^* \\ & & \overline{C}_{33}^* & 0 & 0 & \overline{C}_{36}^* \\ & & & \overline{C}_{44}^* & \overline{C}_{45}^* & 0 \\ & sym & & & \overline{C}_{55}^* & 0 \\ & & & & & \overline{C}_{66}^* \end{bmatrix} \tag{1}$$

where the star "* " indicates that the stiffness coefficient of the sub-laminate is an equivalent value and the barred notation "‾" signifies that it is in the global coordinate system. The stress-strain constitutive relationship for the sub-laminate is described as:

$$[\overline{\boldsymbol{S}}^*] = [\overline{C}_{ij}^*][\overline{\boldsymbol{E}}^*] \tag{2}$$

where $[\overline{\boldsymbol{S}}^*]$ and $[\overline{\boldsymbol{E}}^*]$ are the global equivalent stresses and strains.

The coefficients of stiffness matrix $\overline{C}_{ij}^*$ for the sub-laminate are defined in Eqs. (3)–(6):

$$\overline{C}_{ij}^* = \sum_{k=1}^{n} V^k \left[\overline{C}_{ij}^k - \frac{\overline{C}_{i3}^k \overline{C}_{3j}^k}{\overline{C}_{33}^k} + \frac{\overline{C}_{i3}^k \sum_{l=1}^{n} \frac{V^l \overline{C}_{3j}^l}{\overline{C}_{33}^l}}{\overline{C}_{33}^k \sum_{l=1}^{n} \frac{V^l}{\overline{C}_{33}^l}} \right] \quad (i, j = 1, 2, 3, 6) \tag{3}$$

$$\overline{C}_{ij}^* = \overline{C}_{ji}^* = 0 \quad (i = 1, 2, 3, 6; j = 4, 5) \tag{4}$$

$$\overline{C}_{ij}^* = \frac{\sum_{k=1}^{n} \frac{V^k}{\Delta_k} \overline{C}_{ij}^k}{\sum_{k=1}^{n} \sum_{l=1}^{n} \frac{V^k V^l}{\Delta_k \Delta_l} (\overline{C}_{44}^k \overline{C}_{55}^l - \overline{C}_{45}^k \overline{C}_{54}^l)} \quad (i, j = 4, 5) \tag{5}$$

$$\Delta_k = \overline{C}_{44}^k \overline{C}_{55}^k - \overline{C}_{45}^k \overline{C}_{54}^k \tag{6}$$

where k refers to the k^{th} ply and n refers to the number of plies for the sub-laminate, respectively. V^k is the ratio of the original thickness of the k^{th} ply to the original total thickness of the entire sub-laminate. $\overline{C}_{ij}^k$ represents the stiffness coefficient of the k^{th} ply in the global coordinate system, which is rotated from the stiffness matrix in local material coordinate system [29,30].

2.3. Stress and strain decomposition

With the global equivalent stiffness, the general response of the entire structure such as global stresses $[\overline{\boldsymbol{S}}^*]$ and strains $[\overline{\boldsymbol{E}}^*]$ can be easily obtained based on sub-laminates. In order to get the stresses and strains of each ply, the following assumptions are introduced [29,30]:

$$\overline{E}_{ij}^k = \overline{E}_{ij}^* \quad (ij = 11, 22, 12; k = 1, 2, \ldots, n) \tag{7}$$

$$\overline{S}_{ij}^k = \overline{S}_{ij}^* \quad (ij = 33, 23, 13; k = 1, 2, \ldots, n) \tag{8}$$