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Original Research Article

Fracture of laminated woven GFRP composite pressure vessels under combined low-velocity impact and internal pressure

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ABSTRACT

Dome curvatures of pressure vessels often sustain highest level of stresses when subjected to various loading conditions. This research is aimed at investigating the effect of dome geometrical shape (hemispherical, torispherical, and ellipsoidal domes) on mechanical deformation and crack length of laminated woven reinforced polymer (GRP) composite pressure vessels under low-velocity impact (LVI) (case one) or combination of LVI and internal pressure (case two). The study is based on finite element (FE) simulations with laboratory-based experimental validation studies. It was observed that the maximum vertical displacements (U_1^*) and crack length along the diameter of deformation (a) are both of lower magnitude in case one. Damage intensity and fracture differ for different combinations of loading. Only matrix breakage and debonding occurs in case one and fiber breakage occurs in case two. The dome geometric shapes used in this study were found to be invariant to both damage intensity and failure modes. Irrespective of the type of load applied, the magnitude of U_1^* and crack length correlate with dome geometric shape as the maximum and the minimum U_1^* occur in torispherical and hemispherical domes, respectively. The maximum and the minimum crack lengths also take place in torispherical and hemispherical domes, respectively.

1. Introduction

Fiber-reinforced polymers are increasingly used in many engineering fields such as aerospace, transportation, sports, and manufacture body armors and helmets. Thus, understanding their impact behavior is crucial in order to assess their reliability [1]. Numerous studies have been reported on impact behavior of flat composite laminates while composite laminates with curved geometries have been disregarded [2].

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Several studies were recently conducted on the effect of various loading modes on composite structures, for example, impact, internal and external pressure, static and quasi-static loads. Katunin [3] demonstrated that LVI is an important problem faced during the machine's operations of composite structures. Bienias et al. [4] showed the complexity of damage mechanism in CFRP composite laminates under low energy impact load. This paper reports on research into the performance of pressure vessels manufactured from composite material when subjected to impact loads with differing energy levels. In particular, manufacturing and design technique is crucial in order to protect vessels against low energy impacts, for example, from dropped tools during operation and maintenance activities, and intermediate energy impacts due to accidental strikes by other equipment [5].

As the use of composite pressure vessels increases, certainty of critical mechanical properties must be available to the designer. Pressure vessels are usually designed to withstand high pressure that leads to increased stresses in these vessels. Additionally, an internally pressurized vessel may encounter an accidental contact, which results to sudden mechanical deformation and possible failure due to the abrupt impact load in combination with internal pressure. Domes are the most critical part of a pressure vessel as they tend to undergo a higher level of stress when subjected to diverse loading conditions than other vessel geometries. Therefore, their in-depth failure and fracture inspection when considering geometry and material properties can result in an improvement, if not optimization, of performance [6,7]. Several examples of dome-shaped pressure vessel parts that would be assembled to cylindrical parts are shown in Fig. 1.

Numerous research outcomes has been reported in the available literature on damage mechanisms, the impact behaviours and residual strengths of laminated composite shells. Curved laminate composite panels under LVI were studied by Kistler and Waas experimentally [8]. Krishnamurthy et al. [9] investigated the impact response and damage in a laminated composite cylindrical shell using numerical and analytical methods. The results showed that for a specific kinetic energy the impact-induced damage increases with a higher-impact velocity. The decrease of curvature leads to an increase in time of contact and deflections, and curvature effects are noticeable when the curvature is high. Damage of shell panels is significantly higher compared to cylindrical shells. Layers orientation of laminas has a major effect on the impact response change of ply orientation. Kumar et al. [10] used a 3D FE method to study the impact-induced damage and the impact response in a curved composite laminate under transverse impact using a metal impactor. It was observed that by modifying the failed region stiffness, the peak contact force decreases while shell deflection increases. A considerable change was also observed in the extent of critical delamination and matrix cracking. Gupta [11] investigated about the effect of impact loading on hemispherical composite shells. The result illustrated indicated that shells of smaller thickness collapse by fragmentation, but collapse for those of greater thickness is by splaying inwards. The average collapse load for the hemispherical composite shells is more affected by the thickness than the radius. Xu and Chen [12] investigated the damage of two different laminate composites made of carbon/epoxy under LVI by employing ABAQUS software for damage identification. Zabala et al. [13] examined the behavior of a woven carbon fiber epoxy composite structure manufactured by the infusion method subjected to LVI loadings and submitted to drop weight tests. The results indicated 45% increase in the delaminated area. However, increasing impact velocity, which resulted in delamination growth, can lead to 20% reduction of the residual stiffness. Arifin et al. [14] investigated the behavior of laminated composite structures, whose winding angles vary when impact load is applied. The results demonstrated the effectiveness of matrix types on sustaining impact load. Alderson and Evans [15] studied failure mechanisms during the transverse loading of filament wound glass/epoxy resin pipes subjected to static and LVI loads. A video camera and strain gauge were exploited during the study. The most severe damage took place on the floor-supported impacted pipes. Tuğcu [16] studied the instability and failure of thin cylindrical tubes subjected to both continued pressure and impact load by using numerical approach. Strain localization and dynamic instability were investigated with respect to time and deformation. Gning et al. [17] studied the response of thick composite cylinders made of glass/epoxy and subjected to quasi-static and impact loading proposed for underwater usage. The step stone of their research was the experimental analysis. At higher energies, delamination propagates and is accompanied by the multiplication of interlaminar cracks. Damage in static indentation is same as the mentioned damages of impact tests, but the damage dimensions are not similar.

This review of salient literature demonstrates that significant prior research has been conducted into the effect of LVI on mechanical deformation of laminated composite structures,

Fig. 1 – Schematic of various types of laminated woven GFRP dome-shaped pressure vessels.