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On the impact-induced damage in glass fiber reinforced epoxy pipes

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ABSTRACT

The high mechanical performance of glass-fiber reinforced epoxy (GFRE) pipes and structures may be adversely affected by their low resistance to impact loadings. The low-velocity impact loads are particularly more dangerous as their damage to the structural integrity of the composite pipes often goes undetected. In the present work, a finite element (FE) model of GFRE pipe is developed and used in conjunction with failure criteria based on three-dimensional state of stress to predict layer damage under low-velocity impact. The performance of the numerical model is validated with experimental results. The load–time traces and maximum deflections estimated by FE are found to correlate with the experimentally measured ones. The validated model is then used to predict the composite pipe failure under 12 J, 35 J, 80 J and 110 J and develop damage maps for four incident impact energy levels and two pipe thicknesses. The FE results show that at low impact energy, the damage happens mainly by matrix cracking and delamination, while at intermediate to high energies, fiber breakage occurs, which is in agreement with the experimental results. The damage mechanisms and the severity of the damage under different impact energies are found to correlate well with those obtained experimentally, earlier in this research project.

1. Introduction

Because of their good corrosion resistance, durability and high strength-to-weight ratio, the use of glass-fiber reinforced epoxy (GFRE) pipes has increased in many diverse industries such as, offshore marine, chemical processing and pressure piping. However, these materials are susceptible to degradation in mechanical performance, reduction of structural integrity and fluid leakage due to incidental low velocity impacts, either in service or during handling. Low-velocity impacts can produce local indentation and delamination that are often difficult to detect and may contribute to failure during service. This highlights the need for full characterization of GFRE pipes' behavior under dynamic loading conditions by assessing the extent of such failures and the effect on mechanical properties. Several investigations have been performed to examine the impact loading of fiber reinforced composites materials using finite element (FE) analysis.

Naik et al. [1] and Khan et al. [2] experimentally studied the effect of environmental degradation on the performance and resistance to low velocity impact of the glass fiber reinforced vinyl ester and GFRE pipes. The specimen were made from filament-wound glass fiber reinforced pipes with 150 mm internal diameter and 6 mm thickness, and the winding was performed for a ply angle of ± 54.5° for 8 plies. An almost 80% reduction in the pipes' pressure performance was noted when subjected to high energy impact. Gning et al. [3] experimentally studied the damage development in filament-wound E-glass/epoxy pipes with 55 mm internal diameter and 6 mm thickness and composed of 20 plies with a ply angle of ± 55°. Different levels of energy (up to 45 J) were considered with both static and impact loading. At low impact energy, a small local indentation occurred at the contact area in the outer layers of about 0.3 mm thickness. Then with increase in the impact energy, the damage initiated at the threshold energy level in the form of delamination, which propagated through the pipe thickness. Further the transverse intra-layer cracks appeared for higher impact energy. Using numerical analysis, Li et al. [4,5] investigated the effects of various parameters such as the size of target plate, boundary conditions, impact velocity and impactor mass on the impact-induced damages. It was found that numerical modeling can capture the main features of impact phenomenon and predict various damages. Naik and Meduri [6] studied the impact behavior of polymer–matrix composite plates subjected to low velocity point impact load using a 3D transient FE analysis. Both in-plane and interlaminar failure initiation for various composite configurations were investigated and it was noted that mixing of unidirectional and woven-fabric layers results in increased impact damage resistance. Yen et al. [7] developed a progressive failure criterion for impact analysis of composite structures, which included fiber failure, matrix failure and

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delamination as contributing factors. They used adynamic FE code to determine the nonlinear behavior of the composite cylindrical shapes subjected to drop weight impact loading and the results showed good correlation with the experimental data. Aslan et al. [8] studied the low-velocity impact of cross-ply E-glass/epoxy laminated composite plates and noted a remarkable variation in the load–time curves with the impactor mass. The values of the impact forces predicted by the numerical model were found to be higher with shorter contact period compared to the experimental ones. The in-plane dimensions influenced the composite structures' mechanical behavior where the contact duration increased with the decrease of the plate width. Zhao and Cho [9] investigated the initiation of impact induced damage and its propagation in composite shell subjected to drop weight impact. They found that, for the shell, the damage propagated from the outer layers toward the inner layers but it was the reverse sequence in the case of a plate.

The main objective of this work is to quantify the damage in GFRE pipes caused by low velocity impact loading using elastic-plastic FE analysis. The numerical results are compared to the experimental observations obtained for the same problem configuration both in terms of geometry and loading.

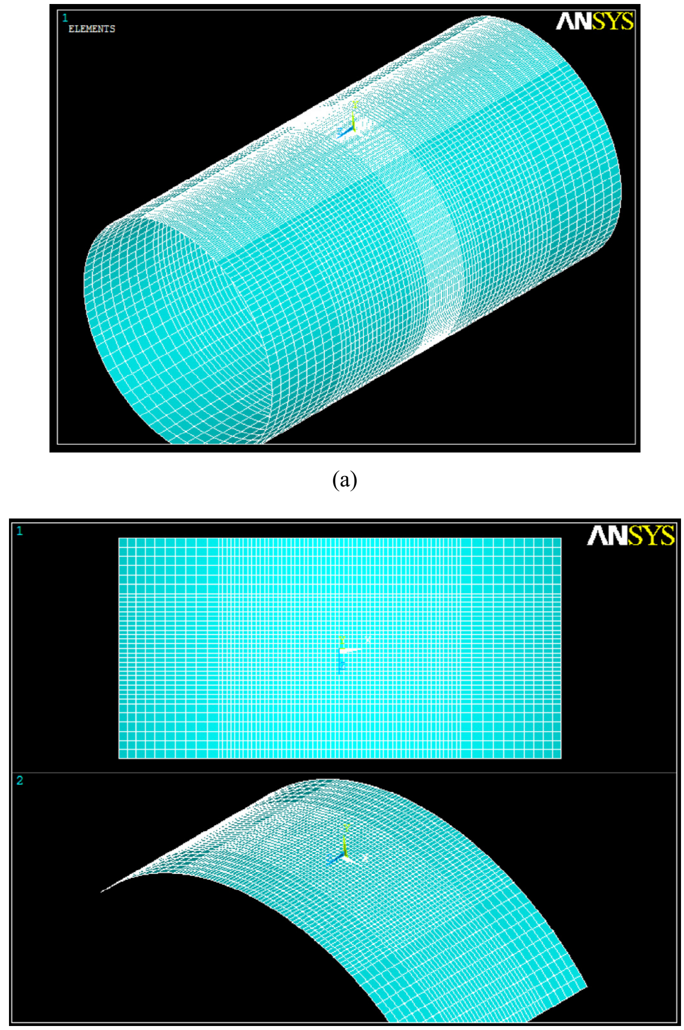
2. Development of finite element model

Low velocity impact damage of a GFRE pipe is modeled using ANSYS/LS-DYNA package. The impactor considered consists of a 12.7 mm diameter hemispherical head and a rigid body attachment of 50 mm diameter and 66 mm length. The mass of impactor is 10 kg for low impact energy and 25 kg for higher impact energies. The GFRE pipe considered is 300 mm long with 150 mm internal diameter and 6 mm thickness. It consists of a fiber volume fraction of about 65% and 8 plies with a ply angle of ± 54.5° for which the reference direction coincides with the axis of the pipe. These parameters are selected to conform to the experimental tests performed in the first of this research project by Naik et al. [1] and Khan et al. [2] in accordance with the ASTM D2444-99 [10] and ASTM D2290-08 standards [11].

2.1. Meshing, material model and boundary conditions

A full section of GFRE pipe is modeled (Fig. 1a) as, owing to the inherent nonsymmetrical nature of the geometry of laminate with a ply angle of ± 54.5°, it is not possible to use symmetry to reduce the problem size. The meshing process is performed by subdividing the pipe into distinct regions with a fine grid size applied in the regions located near the impact area, while gradually coarser grid sizes are used away from the impact area as shown in Fig. 1b. The meshing of GFRE pipe section is performed using a four-noded quadrilateral layered shell element (SHELL163 in ANSYS) whereas the nonlinear material properties and the lamina (ply) properties are specified as real constants for the chosen element. The solid steel cylindrical impactor is meshed using an eight-noded brick (SOLID164) elements. A composite material model representing an orthotropic material is used for the GFRE pipe and the input properties of the GFRE pipe and the impactor materials are listed in Tables 1 and 2, respectively [12].

The 300 mm long pipe section is considered to be simply supported with a span of 240 mm between the supports. The boundary conditions used simulate GFRE pipe resting on two V-blocks. ANSYS/LS-DYNA can define contact between surfaces efficiently through identifying the contact surfaces and then the type of contact between the surfaces. For this model, the contact algorithm required creating two components to represent the impactor (contact component) and the GFRE pipe (target component). Due to the unpredictable contact conditions for this problem, no particular contact algorithm was chosen. Instead, automatic surface to surface contact between the pipe and the impactor was selected and the program automatically adjusted for the changes that occurred during simulation. The model performance was tested by validating it using published FE results on graphite/epoxy composite and



(a)

(b)

Fig. 1. Finite element mesh for (a) full model of GFRE pipe section and (b) impact area.

Table 1
Material properties of E-GLASS/EPOXY composite [12].

Longitudinal modulus (E_1)	40.51 (GPa)
Transverse modulus (E_2)	13.96 (GPa)
In-plane shear modulus (G_{12})	3.10 (GPa)
Poisson's ratio (ν_{12})	0.32
Density (ρ)	1830 (kg/m^3)
Longitudinal tensile strength (S_1^t)	783.3 (MPa)
Transverse tensile strength (S_2^t)	64 (MPa)
Longitudinal compressive strength (S_1^c)	298 (MPa)
Transverse compressive strength (S_2^c)	124 (MPa)
In-plane shear strength (S_{12})	69 (MPa)
Interlaminar shear strength (S_{23})	38 (MPa)

Table 2
Material properties of the impactor [12].

Young's modulus (E_i)	207 (GPa)
Poisson's ratio (ν_i)	0.30
Density (ρ)	8290 (kg/m^3)