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Glass reinforced epoxy tubes subjected to indentation load: A study of scaling effects

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ABSTRACT

Scaling effects in thin walled glass reinforced epoxy filament wound cylindrical tubes with [±55°] layup subjected to indentation load are presented in this work. Buckingham PI theorem is used to scale input and output parameters for four different scales (n = 1/4, 1/2, 3/4 and 1). Scaling laws are investigated for force, energy dissipation and damage propagation when tubes are resting on a flat surface. Damage propagation is captured with a video camera, by recording damage reflection on an upward facing mirror placed inside the tubes. The threshold force causing onset of delamination is identified and used for calculation of mode II energy release rate G_{IIC} with already established relation between the two. The scaling laws have been found effective in estimating quite a few parameters, including force displacement, energy displacement relation and peak load. Damage growth is found to obey scaling law and it is presented with respect to force applied, energy dissipated, indentation displacement and time.

1. Introduction

A few of the basic barriers that are holding back composite materials in oil and gas industry include lack of data base for damage mechanism and in service integrity monitoring [1]. The behaviour of cylindrical or curved structural components made of composite materials under lateral loads have been studied for a past few decades but these have received less coverage as compared to relatively simpler geometries like plates and beams. For GRE tubes under lateral load, majority of the research is carried out to understand their behaviour under impact type loading [2–13] where a few included results from static loading also. There are relatively less publications which only considered quasi static and indentation type loading on such geometries [14–17]. On the other hand there are only a few works that used a scaling technique to predict behaviour of filament wound pipes under solely impact type load, for example [11,18] where former considered thick GRE pipe and later used carbon reinforced epoxy cylinders. There is no study as such available on understanding if composite pipes subjected to indentation obey any scaling laws, at least in author's knowledge. Tarfaoui et al. [11] presented scale and size effect in glass epoxy tubular structure under impact load where only two scales were used. Thick 10 and 31 layer [±55°] layup composite tubes were tested. This work successfully showed that response parameters like contact force and displacement could be estimated for a large structure by using small model tests. It was also concluded that scaling may not be very accurate for predicting damage magnitude, which was attributed to local material variation along thickness. Tarfaoui et al. [19] in another work presented residual strength of damaged thick glass epoxy tubes. The quasi static indentation test and impact tests were carried out. Authors observed that the static damage trend was similar to that of impact but it was smaller in magnitude. Also the damage shape which was in form of cones through the thickness was very similar for static and dynamic cases. Evans and Alderson [3–7] carried out series of tests on glass epoxy tubes and presented comprehensive results for static and impact testing. This work reported load displacement curves, damage photographs, residual properties and their correlation with impact damage. Authors identified some degree of equivalence between static and impact tests for load displacement relation. Quantification of damage revealed that the floor supported impact test fails with larger delamination areas, than floor supported static test. Hence the static test was used to predict performance over a range of impact energies and velocities. It was concluded that the only other parameter which affected the value of the load was pipe thickness. The effect of curvature was not cited in this work. Though effect of curvature was shown to affect the impact induced damage in composite laminates by other researchers [20]. This theoretical work proved that as the

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curvature increased, the maximum impact force became higher for the same impact velocity and the delaminated area widened. Frost and Cervenka [8] carried out overall assessment of glass reinforced filament wound pipes. They covered a wide range of performance criteria including impact performance and damage tolerance. This work was intended to understand failure mechanisms of pipes, to provide technical input into design guidelines for the oil and gas industry. The authors concluded that impact resistance of the pipe was directly proportional to the pipe flexibility. The ply delamination was related to mode II type energy release rate. It was also concluded that peak impact force caused specific damage however it was only applicable to specific pipe geometry. Christoforou and Swanson [21] studied the strength loss in composite cylinders under impact load. Pang and Kailasam [22] presented the effect of different parameters related to impact response of composite pipe including impacter geometry, velocity, mass and material. It was concluded that the impact response was sensitive to the fibre content. Doyum and Altay [9] compared the impact response of S glass and E glass reinforced epoxy tubes. Khalili et al. [23] used finite element modelling to understand low velocity impact behaviour of different geometries, including composite cylinder [18]. Khalid et al. [12] carried out experimental and finite element analysis of glass and carbon epoxy hybrid tubes subject to quasi static indentation load. Mustafa et al. [24] presented experimental results for laterally indented thin walled GRE tubes supported by a flat plate. The tube behaviour up to the failure was observed. Force, deflection and strain were measured at various indenter displacements. This work concluded that load deflection curve was sensitive to wall thickness. A change in wall thickness of 2.6% resulted in stiffness change of 7.5% [14]. It was suggested that the change in length or end constraints of tube may change the tube behaviour; but authors did not substantiate it with any experimental results. Soden et al. [16] compared the results from quasi static indentation with low speed impact on GRE tubes, and concluded that the behaviour of tubes was the same to a certain extent. Zou et al. [17] presented values of mode II type critical energy release rate of filament wound pipes by using lateral indentation tests. This work correlated dissipated energy with the delaminated area. Critical energy release rate was related to the thickness of the tubes, i.e. 5.5 mm thick tubes had higher energy release rate than 3 mm thick tubes. G_{IIC} for former was 2.03 kJ m^{-2} and for later it was 1.54 kJ m^{-2}. Corbett and Reid [15] studied failure of GRE pipes under quasi static and impact load and compared behaviour with that of steel tubes. Authors presented an interesting direct relation between delamination area and impact energy by curve fitting. It was a simple relation which only considered number of plies and surface area of delamination on the outer surface only. Davies and Zhang [25] used simple equation relating threshold force, causing instant delamination with mode II critical energy release rate. The authors argued that it may not be very accurate, however, its effectiveness and simplification made it worth considering as compared to relatively complex computational tools.

The Purpose of this work is to study scaling effects in thin walled filament wound GRE pipes under quasi static indentation load. In this work, the authors carry out similitude study to find out relation in mechanical behaviour of scaled GRE pipe specimens subjected to indentation. There is no comparison available between mechanical properties of GRE tubes with those exhibited by smaller laboratory sized specimen. This study leads to build confidence on application of lab data to structural components in oil and gas industry including pipe lines. It should contribute to data base for damage mechanism as identified by [1] and mentioned at the beginning of this section. It has been reported in the literature that filament wound fibre reinforced tubes are susceptible to damage due to local lateral load [14]. Such local lateral loading can be caused by accidental impact [17] for example a hand tool dropped on a pipe or accidental dropping of pipe itself. To substantiate this argument it was reported that half kg hammer dropped from a height of 1 m is equivalent of 5 J impact on a structural component [8]. Moreover such incidental low velocity impact can cause a reduction of 50% in residual tensile and compressive strength [6]. It has also been reported in the past that load displacement characteristic and appearance of damaged filament wound GRE specimens loaded quasi-statically and by drop weight impacts were similar. Experimental results reported in this work may be used to establish a scaling model to estimate damage caused by accidental impact on pipes. These results can be compared with damage in these specimens subjected to drop weight impact which authors are taking up as a separate work in the future. Generally, filament wound GRE tube stands as a good candidate for studying scaling effects as discussed by Davies and Petton [26]. Experiments carried out on a filament wound tube consider the properties of separately manufactured specimens, as compared to specimen cut from the full scale structure. Also the consistency of fibre distribution in filament winding is better than the other specimen preparation techniques, for example hand layup.

2. Similitude study

Pintado and Morton [27] discussed the non dimensional relation between input and output parameters for a laminated beam under impact. Pintado and Morton represented maximum deflection during impact with δ and expressed it as a function of input variables namely geometric variables, material properties and impact conditions.

$$\frac{\delta}{L} = f(L, w, h, E, \nu, \rho, v_0, E_0) \tag{1}$$

where
L = Beam length.
w = Beam width.
h = beam thickness.
E = Young's modulus.
ν = Poisson's ratio.
ρ = Density.
v_0 = impact velocity.
E_0 = impact energy.

Now for the purpose of current work if a tube is subjected to indentation load then above expression should be valid. Geometric variables of beam can be replaced with those of a cylinder and impact loading conditions should be replaced by indentation.

Let

L = Length of the tube.
D = Internal diameter of the tube.
t = Wall thickness of the tube.
d = Indenter spherical diameter.
δ = Indentation displacement.
v_0 = Indentation speed.
E_0 = Energy absorbed.

and the variables representing material properties remain same for the current work i.e.

E = Young's modulus.
ν = Poisson's ratio.
ρ = Density.