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Investigation of the effect of stacking sequence on low velocity impact response and damage formation in hybrid composite pipes under internal pressure. A comparative study

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ABSTRACT

Filament wound hybrid composite pipes can expose to impact loading from various causes during their service life which can cause an invisible level of damage. Thus, revealing the effect of impact damage gains great importance to design hybrid composite pipes with enhanced damage tolerance. Based on this motivation, the low velocity impact (LVI) response of carbon/glass hybrid filament wound composite pipes has been studied. Hybrid pipes were produced with the winding angle of ± 55° by using glass and carbon fiber layers in various stacking sequences by filament winding method. The stacking sequence configurations were set as Carbon/Glass/Glass (CGG), Glass/Carbon/Glass (GCG) and Glass/Glass/Carbon (GGC). Before generating impact damage, an internal pressure of 32 bar was applied to the hybrid pipes in accordance with ANSI/AWWA C950 standard and pre-stress was generated in the pipes. Following, the hybrid pipes subjected to internal pressure were subjected to low velocity impact tests at energy levels of 5, 10, 15 and 20 J. The variation of contact force versus time, contact force versus displacement and energy versus time were obtained. After the testing, the effects of stacking sequence upon damage formation and damage progression under LVI loading have been evaluated based on the obtained data and microscopic analysis. It has been found that the damage formation such as matrix cracking on outer/inner surfaces, radial cracks, delamination, transfer cracks, splitting and leakage can take place. Moreover, the hybrid pipes with CGG stacking represents higher impact resistance while the GCG stacking has a better response of damage formation since this stacking does not show leakage damage.

1. Introduction

Hybrid pipes are used in several engineering applications due to their superior properties such as high strength, high chemical resistance, weathering, resistance to UV rays. Hybrid composite pipes can be produced in different stacking sequence configurations and sizes which results in various mechanical properties. Different types of fibers such as glass and carbon can be utilized for hybridization used in different layers depending on the required material sequence.

Hybrid composite pipes, which are generally utilized to transfer pressured fluids, can be subjected to impact loading during their service life. Damage formations in composite pipes are generally invisible to naked eye which cause a decrease in the strength. More importantly, these damages may progress and eventually lead leakage damage. In the design phase, composite pipes should be designed to get the best stacking sequence in such a way that excellent impact response is obtained. Therefore, it is necessary to determine the impact damage modes which can form upon composite pipes due to low velocity impact (LVI).

Hybridization and stacking sequence play key roles for the design process of composite materials and some researchers have focused on this topic [1–18]. Hosur et al. [5] have focused on LVI response of woven glass and woven carbon reinforced composite plates. They also examined the damage formation and progression. Sevkat et al. [9] performed a drop weight test on glass-graphite/epoxy hybrid composites and compared the experimental results with a finite elements simulation. Damage mechanisms in micro and macro scale have also been investigated [19–21].

Numerous studies [22–53] have been carried out in the literature concerning the determination of residual burst strength of composite pipes damaged with after impact or in different conditions. Curtis et al. [23] investigated the burst strength of composite pipes subjected to LVI or quasi static indentation. In another study, thick filament wound composite pipes with ± 55° winding angle have been subjected to quasi static indentation and LVI tests [25]. The damage formation and progression have been examined by ultrasonic testing.

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In many studies static burst and fatigue tests have been conducted to determine the mechanical properties of hybrid and non-hybrid pipes and their damage behavior have been examined [52,54–61] and the effect of winding angle, hybridization and stacking sequence have been reported [55,62,63]. Mahdi et al. [62] investigated the compression behaviors of glass/epoxy and carbon/epoxy hybrid composite pipes with different stacking sequences. They have focused on energy absorption capacity, damage formation and hybridization. It is reported that the hybridization is the dominant factor upon damage formation and the highest energy absorption capacity have been obtained at pipes with glass-carbon-glass stacking sequence. Zuraida et al. [63] investigated the mechanical and damage behaviors of hybrid and non-hybrid glass and carbon reinforced composite pipes under quasi static lateral indentation loading. It is reported that carbon/epoxy pipes show higher resistance to lateral deformation and less damage formation. Tarfaoui et al. [27] investigated the scale and size effect on impact damage and dynamic response of glass/epoxy cylindrical structures. ± 55° E-glass epoxy samples in different sizes and scales, were used in their study. It is reported that the manufacturing parameters affected the sample's dynamic response and damage formation significantly. Damage formation and residual strengths of composite pipes subjected to low velocity impact, penetration, quasi-static indentation and conditioning have been investigated [24,28,64–72].

In recent years LVI response of filament wound pipes subjected to internal pressure [46,73–77] have been investigated by several researchers. Gemi et al. [73,78,79] investigated the LVI response under internal pressure selected in accordance with ANSI/AWWA C950 standard. It is reported that the increased internal pressure results in enhancement in the LVI response and damage formation.

It can be seen in the literature that different results have been reported for composites made of similar constituents and production methods. So, it is concluded that by using probabilistic approaches for prediction of mechanical behaviors of composite materials may yield more reliable results. Some researchers have taken into account the random parameters involve the production of composite materials. Rafiee et al. [80] proposed a progressive damage model for prediction of functional failure of GRP pipes under internal pressure. The effect of fiber volume fraction and winding angle [81] and influence of core layer incorporated for pipe stiffness [82] on the failure pressures have been also investigated. Rafiee et al. [83] studied on the prediction of burst pressure of composite pressure vessels subjected to internal pressure by taking into account the manufacturing uncertainties. It is reported that considered tubes experience burst pressure below the estimated values when taking into account manufacturing inconsistencies. Rafii et al. studied the functional failure of glass reinforced polyester pipes under internal pressure investigated [84,85], fatigue life of composite pipes subjected to internal cyclic hydrostatic pressure [86] and for creep behaviors of glass fiber reinforced plastic pipes under internal pressure [87]. Stochastic modeling is also conducted for prediction of fatigue behaviors of glass reinforced composite pipes subjected to variable amplitude loading [88].

Failure analysis in composite materials and failure predictions were studied both experimentally and analytically after quasi static indentation (QSI), low-velocity impact (LVI), compression after impact (CAI), fatigue and burst tests in the literature. Although majority of the studies are focused on destructive test analysis, non-destructive test methods such as ultrasonic, acoustic emission (AE), C-scanning and 3D X-ray computed tomography (CT) have been widely used in order to determine failure analysis [89–98]. Castellano et al. have studied on ultrasonic tests in recent years. In the last study Castellano et al. [91] have proposed a new experimental approach for the comparison between QSI damage and LVI damage in polymer composites starting from the results of ultrasonic goniometric immersion tests. They reported that ultrasonic goniometric tests are capable of getting the acoustic response of the material and proposed model can be used for the characterization of more complex damages. Al-Jumaili et al. [89] used The Delta T Mapping technique and Parameter Correction Technique (PCT) to identify and locate damage formation at carbon fiber reinforced composites subjected to fatigue loading. They reported that matrix cracking and delamination can successfully be identified via PCT approach with improved location accuracy. They also reported the PCT to be an effective tool to correct signal features. Jespersen et al. [93] investigated the tension/tension fatigue damage development in unidirectional composites by using multi-scale 3D X-ray computed tomography. They reported that fiber fractures can only be observed at the intersections of backing fiber bundles one another close to unidirectional bundles. They also comment on stiffness degradation due to fiber damage accumulation.

The aim of this study is to determine the best stacking sequence for damage formation upon hybrid composite pipes subjected to low velocity impact. Filament wound pipes with ± 55° winding angle have three different stacking sequences as Carbon/Glass/Glass (CGG), Glass/Carbon/Glass (GCG) and Glass/Glass/Carbon (GGC) from inner surface to outer surface. The produced composite pipes have been subjected to low velocity impacts under 5, 10, 15 and 20 J while the pipes internally pressurized by 32 bar. The variations of force versus time, force versus displacement and energy versus time have been obtained. After the test, damage formation has been investigated by scanning electron microscopy (SEM).

2. Experimental study

2.1. Hybrid pipes manufacturing

The filament wound hybrid pipes has winding angle of ± 55° with stacking sequences of Carbon-Glass-Glass, Glass-Carbon-Glass, Glass-Glass-Carbon starting from inner surface to outer surface. Three specimens have been produced for each stacking sequence. E glass fibers with 1200 tex (17 μm diameter) and carbon fibers with 800 tex were utilized. Momentive, Bisphenol A, Epikote 828 epoxy resin was used as matrix material while hardener agent was Epikure 875 (Modified Carboxylic Acid Anhydride). The resin bath was kept at a constant temperature of 60 °C. Curing was performed at 135 °C for 2 h and at 150 °C for another 2 h. The geometric properties of hybrid pipes are shown in Fig. 1 and properties of fiber and resin are presented in Table 1.

2.2. Low velocity impact testing under internal pressure

A drop weight impact test stand has been used for obtaining dynamic response of hybrid pipes under internal pressure. The test stand is shown in Fig. 2. The mass of impactor is 6.35 Kg and it has a semi spherical tip with diameter of 24 mm. PCB Quartz ICP Force Sensor was used for measuring the contact force during impact. The hybrid pipes were placed and fixed on a V-shaped guide. The specimens were then subjected to pre-stress by pressurized hydraulic oil at 32 bar pressure and measured by a manometer and a pressure sensor [74]. After that, hybrid pipes were subjected to low velocity impact under different energy levels as 5, 10, 15 and 20 J. During the impact, force signals have been measured versus time and signals have been transmitted to the data acquisition card mounted in a PC and evaluated by using NI Signal Express software. The sampling rate of data acquisition system is 25 kHz. The obtained force-time variations were processed in accordance with the routine described in ASTM-D-7136 standard and force versus displacement and energy versus time relations have been obtained.

When the impactor hits the specimens, the kinetic energy of the impactor is transferred to the material and the remaining kinetic energy of impactor is used for rebound of the impactor. This process continues until the kinetic energy of the impactor is fully consumed. This process generally requires 12–15 impacts. However, for a clear evaluation of damage formation under certain energy levels, it is required that only