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Design of Composite Pipes with Different Fiber Orientations

Evaluation of the Internal Pressure Capacity

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***Abstract*— Fiber reinforced composites pipes provide excellent strength and stiffness characteristics and high corrosion and erosion resistance. In addition, the possibility to tailor the strength and stiffness characteristics by optimizing the winding angle gives the designer extra flexibility to design different pipe based on the different working conditions.**

In the current work, GFRP pipe designed with four different winding angles have been tested under internal pressure. Four pipes were manufactured by filament winding with winding angles of [±45/ ±45/ ±45], [±55/ ±55/ ±55], [±63/ ±63/ ±63], and [±63/ ±45/ ±55]. Each pipe has internal diameter of 110 mm, wall-thickness of 3.8 mm, and length of 450 mm. The pipes were exposed to internal pressure to determine their capacities. Under internal pressure, the maximum failure pressure recorded (60 bar) was that for the pipes with $[\pm 55]_3$ winding angles. All specimens failed in the same way of initial leakage, governed by matrix cracking, which causes a drop in the internal pressure.

Keywords—*Composite, Pipe, Winding angle, Internal pressure*

I. Introduction

Polymeric composites, composed of resin (epoxy, polyester, PEEK, etc.) and reinforcing fibers (carbon, glass, aramide, etc.) show high specific strength and stiffness, low density, and high chemical resistance. Fiber reinforced polymeric composites, as the most important category of engineering composites, are employed not only in high technology industrial applications such as aerospace, but have also penetrated low-tech industry such as sanitary ware. Indeed, the market for polymeric composites now spans the full range of industry sectors, including transport (rail, road, air and sea), military, aerospace, municipality, energy production and transmission, civil and infra-structure, sports and leisure [1]. In the pipeline industry, driven by the ever-increasing need for energy and water resources, the market is rapidly growing, with fiber reinforced pipes one of the key potential materials [3]. Composite pipes currently find applications in chemical industry, ducts, offshore, water supply and sewage systems [4].

Typically, steel has been used in piping applications, which provides good performance, especially under heavy mechanical loading (e.g. high pressure, large pipe movement). However, in aggressive environments, steel pipes undergo degradation because of internal or external corrosion, which can generate partial or total failure of the pipe [2]. For this reason, several studies have focused on the search for new resistant and non-corrosive materials and claddings [2]. Glass fiber reinforced plastic (GFRP) pipes represent an attractive alternative to steel pipelines subjected to severe internal or external environments in onshore or offshore applications due to its corrosion resistance properties, which reduces maintenance and costs and lengthens the lifetime of the pipe [5]. A service lifetime of 50 years is generally considered for civil engineering structures. GFRP pipes are also required to remain in service for 50 years as a long-term design constraint in accordance with international rules and regulations [6]. In addition to the high internal pressure capacity driven by the high strength and long lifetime, the low density of composite pipe results in reduction in construction and transportation costs [7].

Composite pipe body is usually made of three main components: an inner liner, a composite laminate, and an outer cover [8]. The liner, either metallic or polymer, serves mainly as a barrier against the inner fluid, [9]. The laminate is the load bearing component. The outer cover is a protective layer from the external environment. The inner liner, laminate and cover are all bonded or fused to the laminate. Additional outer layers may be added as special purposes layers, e.g. as local wear protection or fire protection.

Composite pipes under internal pressure are subjected to both hoop and axial stresses in the case of close-ends tubes with hoop-to-axial stress of two to one. For long open-ends, axial stress resulting from the internal pressure is zero. In addition, other stresses may result from the installation, weight, external pressure, etc. In designing composite pipes, the stress and failure analysis is generally performed without considering either the internal liner nor the outer cover [8], i.e. it is assumed they do not contribute to the resistance to deformation. The design process of the composite lay-up may include fiber and matrix material selection, overall laminate thickness, the thickness of each lamina, and the fiber orientation of each individual layer. Designers should consider that internal pressure does have an effect on the measured mechanical properties of FRP pipes when being tested under pressure and different mechanical loadings [10]. Thin wall cylinders built with multiple layers, develop a hoop stress that is higher in the internal surface than in the external one. This leads to the reasoning that the fracture would start in the inner

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layer, because this layer is the first one to exceed the strength limit of the composite, decreasing the structure capacity to stand loads. The layers, that did not fracture, will then start to be submitted to increased stress. This will lead to the fracture of the other layers [11].

For thin-walled cylindrical-pressure vessels with a ratio of applied hoop-to-axial stress of two to one, an optimum winding angle of 55° was noted. For thicker walled tubes, the optimum angle changed slightly [12]. The optimum winding angle also depends on the loading condition, [13]. Hamed et al. [14] showed that filament wound pipes should be wound at 55° for biaxial pressure loading, 75° for hoop pressure loading, while 85° is suitable for biaxial pressure with axial compressive loading. Haftchenari et al. [15] tested Kevlar/epoxy composite tube under internal pressure at different temperatures. The authors used winding angles of 25°, 55°, and 75°. The results showed that for the 55° angle, the hoop strain is a function of the temperature whereas, the hoop stress does not show any dependency. For the other winding angles, the seems to be independent of the working temperature. This result can be justified by the difference in the coefficient of thermal expansions of the three laminates.

Rafiee and Amini [16] studied the effect of stacking sequence, fiber volume fraction and winding angle on the internal pressure capacity of composite pipes using finite-element modelling. Three winding angles were examined: 52.5°, 57.5°, and 60.19°. Similarly, the numerical analysis of Sulu and Temiz [17] showed that the internal pressure capacity of GFRP pipe is a function of stacking sequence as well as wall thickness. It is worth remarking that the model presented by Rafiee and Amini [16] considered more material and damage features whereas, the study in [17] examine a wider range of winding angles.

Krishnan et al. [18] also studied the effect of winding angle on the behavior of glass/epoxy pipes under multiaxial cyclic loading. In this experimental study, winding angles of 45°, 55°, and 63° and pipes were exposed to internal pressure. The results showed that the optimum configuration depends on the loading ration (hoop to axial stress ratio). To simulate high sub-sea depths, E-glass fiber/epoxy tubes were tested to destruction by Pavlopoulou et al. [19] under hydrostatic external pressure leading to buckling or crushing. Different fiber architectures and winding angles were tested at a range of wall thicknesses highlighting the advantage that hoop reinforcement offers under external pressure.

Colombo and Vergani [20] presented a pipe-wall thickness optimization study by varying fiber volume fraction, matrix and winding angles. The algorithm uses laminate theory for the pipe stiffness an empirical formulation for strength prediction and a failure theory to be applied for each layer. The results showed that the optimum winding angles is in the range $44.5 < \theta < 52.5^\circ$ if both hoop and axial stress affects the pipe at different loading ratio. It is worth remarking that the results of this algorithm could be improved by using measured UD properties rather than calculated properties.

In the current paper, the winding angle effect is examined against internal pressure capacity. In addition to the winding angles usually addressed in the literature (a pipe of single angle), this paper examines a pipe made of different winding angles against internal pressure. For safety reasons, the pipes were not allowed to burst. Instead, a feedback system controls the pressure to stop adding any additional pressure whenever any drop appears.

II. Materials and Specimens

A. Materials

E-glass fiber and Epoxy (GFRP) is used for this study due to the highly expanded market of the GFRP in current piping applications. ARALDITE LY-1564 epoxy resin, mixed with hardener, is used as matrix material. The fiber volume fraction is measured for all the manufactured pipes as per the ignition test standard ASTM D2584-11. The average value of the measured fiber volume fraction for all the specimens is 49.8% with a coefficient of variation of 8.8%. The specifications of the fibers, epoxy material are listed in table I.

TABLE I. TABLE TYPE STYLES

Properties	Fiber	Matrix
Young’s’ Modulus (GPa)	80	3.1509
Poisson’s ratio	0.2223	0.35
Tensile strength (MPa)	2150	78
Compressive strength (MPa)	4600	130

B. Manufacturing

Several manufacturing techniques are recorded for GFRP pipes, such as centrifugal casting, hand layup, and filament winding. The latter is adopted in this work to manufacture our GFRP pipes. A five-axes computer controlled filament winding machine of maximum diameter 2 m and maximum length of 6 m is used. A PVC pipe of 110 mm external diameter is used as a mandrel. Before to start the filament processes, a releasing agent is applied to make it easier to get the GFRP out of the mandrel after curing.

In total, twelve GFRP were manufactured using filament angle machine, with $[\pm45]_3$, [±55]3, [±63]3, and [±63/±45/±55] winding angles. Three pipes for each angle were manufactured with a total length of 1 m of each pipe. The specimen was left over night on the mandrel mounted on the machine with continuous rotation to avoid any agglomeration of the matrix at one side of the pipe. After being completely cured, the edges were trimmed and the pipes were cut into specimens of 450 mm length using diamond saw. The PVC mandrel was kept inside the pipe during the whole manufacturing and cutting process. After getting the final specimen, the PVC mandrel was extracted by a very light extraction force. The final shape of the specimens is shown in Figure 1. The dimensions of the specimens after being prepared for the tests were measured and analyzed. The measurements of the length, wall thickness and internal diameters and the corresponding coefficient of variations C.O.V. are listed in Table II.

Figure 1. The four types manufactured specmens

TABLE II. DIEMSIONS OF SPECIMENS

Dimension	Average	C.O.V %
Length (mm)	448.5	9.2
Internal diameter	110.1	1.2
Wall thickness	3.8	11.2

III. Internal Pressure Tests

Pressure test was performed to determine the capacity and the mode of failure of GFRP pipe. Hydrostatic testing is the most common method employed for testing pipes and pressure vessels. The test involved filling the pipe system with a liquid, usually water or oil, which may be dyed to aid in visual leak detection. The burst test was performed using Resato high pressure technology machine.

During the test, the first step was filling the pressure pipe to 5 bars in 30 seconds. Then, pressure was set to reach 100 bars in 60 seconds, which expected for pipes to fail before reaching the maximum pressure. At that time, the machine was set to be stabilized and decrease slowly to 0 bar which allow the machine to reach ending test stage. The fixture used for pipes is made of steel. The fixture composed of two steel plates of 500 x 500 mm in-plane dimensions and 20 mm thickness. One of the two plates has a central hole to apply the internal pressure. The two end plates were connected together by 4 steel threaded rods, holding the composite pipe in-between. The steel plates were machined at the interface with the pipe edge to ensure, in addition, the pipes ware internally and externally sealed with rubber to ensure the failure away from the pipe edge. The machine control unit was prepared to stop applying the hydrostatic pressure at the first drop of the internal pressure for safety reasons. Three specimens were tested of each configuration.

IV. Results and Discussions

Pressure tests were applied to the filament-wound composite pipes in close-end condition using computer controlled hose test machine. A protection test box was confidently used for observing the failures of the specimens. During all the internal pressure tests, this test apparatus was used by satisfying the closed-end conditions of the composite pipes.

The pressure test is divided into two main stages. Stage one is filling process in this stage the machine fills the GFRP pipe with the oil at 5 bars. Stage two is pressurizing process, where the machine starts to pressure the liquid in the pipe up to the peak point. Failure of composite pipe is usually initiated by matrix cracking. Therefore, on increasing the pressure, it is seen that leakage failure has occurred at the specimen surface. The failure propagates with additional matrix failure as a result of increasing the cycles, causing a drop in the internal pressure reading which stopped the loading processes. The internal pressure history is summarized in Figure 2.

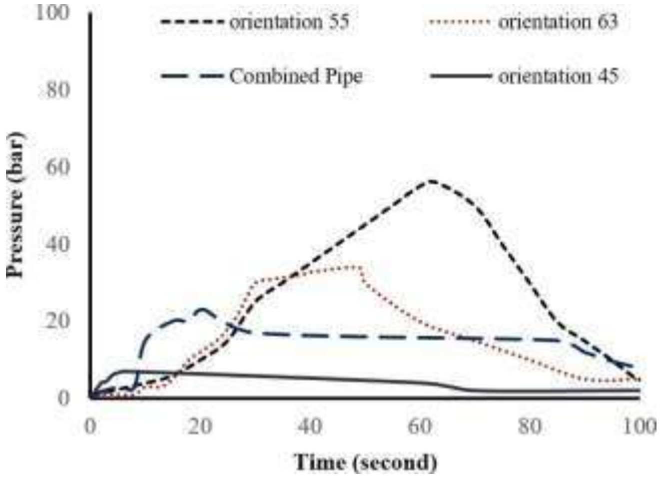

Figure 2. Loading history of the four pipes with different fillament angles.

For the pipes made of ±55° winding angles, during the filling process there was increasing in the pressure up to 5 bars. After that the pressure increased in stage two up to 56 bars. None of the three tested samples showed leakage at the specimen's mid-section. Instead, the three of them showed leakage at/near the interface with the steel plates. This results reveals that the capacity of this pipe is, mostly higher than the measurements. For the specimens made of ±63° winding angles, no leakage was observed during stage one as the pressure increased up to 5 bars. After that the pressure increase until the peak point. The failure occurs as a leakage, of few drops, on the specimen surface. After the test, the pipes were examined by naked eye, and there was no cracking, whitening or delamination.

The specimens manufactured with the ±45° were not expected to provide the best internal pressure capabilities as they are not amongst the recommended stacking sequence for internal pressure application. During the manufacturing process of such pipe, fibers were not evenly distributed throughout the length of the pipe. There was a fiber overlaps, which increase the distance between the fibers, and create gaps in the pipe. The maximum pressure that the pipe can handle is 7 bars, after that pressure the leakage start all over the pipe surface. cracking, whitening or delamination did not appear on the pipe by naked eye examination. It is worth remarking that this low capacity under internal pressure is a result of the gaps generated during the manufacturing.

The specimen manufactured with combined filament angles showed hybrid response. After filling process, the pressure increases until the failure point (23 bar). The failure is leakage weeping along the lower surface of the pipe, no crack or delamination occur on the pipe surface. It is highly believed that the result of this hybrid specimen is affected by the gabs in the 45° layer which caused major thinning in the specimen wall-thickness.

Figure 2 shows the peak point for all specimens (55,63,45 and combined) under the internal pressure test. The pipe with the staking sequence of ±55º showed highest peak point (56 bar). The ones with ±63º and combined GFRP pipe handled pressures of 34 bar and 23 bars, respectively, which were 40% and 59% less than the ±55º pipe. While the failure on ±45º pipe occurs at 7 bars.

In the oil and gas applications, different design considerations are usually taken when selecting a certain pipe configuration depending on the functions of the pipeline. In general, up to 50 mm (2 in) diameter pipe is used to for the distribution lines. These type of pipes lines are usually carrying an internal pressure up to 15 bar. Gathering pipelines, used between the source and processing, are usually of 50 – 200 mm diameter (2-8 in) and working for a typical pressure level of 45 – 50 bar. Transmission lines are of higher diameter (up to 1500 mm) and working under a higher level of pressure (up to 2000 bar) [21]. The pipes tested within this paper can suit the first and the second type of pipelines. The ones made of the ±55º and ±63° can fit for both applications whereas the hybrid ones can be recommended for the distribution lines. Although it is usually recommended for bucking design consideration, layers of 45° winding angles cannot be recommended, based on this analysis, for any of the prescribed applications.

V. Conclusions

This paper presents an experimental investigation on the composite pipe internal pressure capacity. The paper tested four specimens made with the winding angles of $[\pm45]_3$, $[\pm55]_3$, $[\pm63]_3$, and [±63/ ±45/ ±55]. All the specimens have the same nominal dimensions of 110 mm internal diameter, 3.8 mm wall thickness and 448.5 mm length. Internal pressure tests were conducted under closed loop control system to ensure safety.

The results showed the superior internal pressure capacity of the specimens manufactured using the winding angles 55°, which in agreement with the data available in the literature. The specimens made of 63 winding angles and the ones made of the hybrid angles both showed a close values of the pressure capacity, with advantages to the 63° specimens due to the gaps resulted during manufacturing of the 45° layers. Unfortunately, the specimens made of all 45° angles are not recommended for any oil and gas applications based on our current analysis and the manufacturing difficulties we faced with this configuration.

Obviously, the decision is clear in case of selecting a pipe for only the pressure capacity. Although, pipes are not only subjected to internal pressure and they might suffer from impact, bending, axial loadings, aging, etc. The response of composite part under any of these conditions is highly dependent on the winding angles. For this reason, a recommendation can be drawn to design GFRP pipes based on the satisfaction of, not only the internal pressure, but also the other expected loading and working conditions.

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References

[1] R. Rafiee, “On the mechanical performance of glass-fibre-reinforced thermosetting resin pipes: A review”, Composite Structures, vol. 143, pp. 151-164, 2016.

[2] M. Bouhafs, Z. Sereir, A. Chateauneuf, “Probabilistic analysis of the mechanical response of thick composite pipes under internal pressure”, International Journal of Pressure Vessels and Piping, vol. 95, pp. 7-15, 2012.

[3] E. Giannaros, T. Kotzakolios, V. Kostopoulos, “Blast response of composite pipeline structure using finite element techniques”’ Journal of Composite Materials, vol 50, pp. 3459-3476, 2016.

[4] H. Faria, R. Guedes, “Long-term behaviour of GFRP pipes: Reducing the prediction test duration”, Polymer Testing, vol. 29, pp. 337-345, 2012.

[5] J.M. Lees, “Behaviour of GFRP adhesive pipe joints subjected to pressure and axial loadings”, Composites: Part A, vol. 37, pp. 1171-1179, 2006.

[6] R. Rafiee, B. Mazhari, “Simulation of the long-term hydrostatic tests on glass fibre reinforced plastic pipes”, Composite Structures, vol. 136, pp. 56-63, 2016.

[7] G. Czel, T. Czigany, “A study of water absorption and mechanical properties of glass fibre/polyester composite pipes: Effects of specimen geometry and preparation”, Journal of Composite Materials, vol. 42, pp. 2815-2827, 2008.

[8] DNVGL-RP-F119, “Recommended practice for thermoplastic composite pipes”, Tech. Rep.; DNV GL, 2015.

[9] G. Wrobel, M. Szymiczek, J. Kaczmarczyk, “Influence of the structure and number of reinforcement layers on the stress state in the shells of tanks and pressure pipes”, Mechanics of Composite Materials, vol 53, pp. 165-178, 2017.

[10] P.A. Zinoviev, S.V. Tsvetkov, “Mechanical properties of unidirectional organic fibre-reinforced plastics under hydrostatic pressure”, Composites Science and Technology, vol. 58, pp. 31-39, 1998.

[11] G. Marinucci, A.H.P. de Andrade, “Microstructural analysis in asymmetric and unbalanced composite cylinders damaged by internal pressure”, Composite Structures, vol. 72, pp. 86-90, 2006.

[12] M. Xia, K. Kemmochi, H. Takayanagi, “Analysis of lament-wound fibre-reinforced sandwich pipe under combined internal pressure and thermomechanical loading”, Composite Structures, vol. 51, pp. 273-283, 2001.

[13] M.W.K. Rosenow, “Wind angle effects in glass fibre reinforced polyester filament wound pipes”, Composites, vol. 15, 144-52, 1984.

[14] A. F. Hamed, A.Y. Khalid, S.M. Sapuan, M.M. Hamdan, T.S. Younis, B.B. Sahari, "Effects of winding angles on the strength of filament wound composite tubes subjected to different loading modes" Polymers and Polymer Composites, vol. 15, pp. 199-206, 2007.

[15] H. Haftchenari, F.A.R. Al-Saleti, S.T.S. Al-Hassani, "Effect of temperature on the tensile strength and failure modes of angle ply aramid fibre (KRP) tubes under hoop loading", Applied Composite Materials, vol. 9, pp. 99-115, 2002.

[16] R. Rafiee, B. Mazhari, "Modeling and experimental evaluation of functional failure pressures in glass fibre reinforced polyester pipes", Computational Materials Science, vol. 96, pp. 579-588, 2015.

[17] I.Y. Sulu, S. Temiz, "Stress analyses of multi-layered composite pipes subjected to internal pressure", Academic Journal of Science, vol. 4, pp. 187-194, 2015.

[18] P. Krishnan, M.S. Abdul Majid, M. Afendi, A.G. Gibson, H.F.A. Marzuki, "Effects of winding angle on the behaviour of glass/epoxy pipes under multiaxial cyclic loading", Materials and Design, vol. 88, pp. 196-206, 2015.

[19] S. Pavlopoulou, S.S. Roy, M. Gautam, L. Bradshaw, P. Potluri, "Numerical and experimental investigation of the hydrostatic performance of fibre reinforced tubes", Applied Composite Materials, vol 24, pp. 417-448, 2017.

[20] C. Colombo, L. Vergani, "Optimization of filament winding parameters for the design of a composite pipe", Composites: Part B, vol. 148, pp. 207-216, 2018.

[21] A. Hilier, Types of pipeline every oil and gas engineer should know about", Mirage Machines Portable Performance Blog, Nov 14, 2017, https://blog.miragemachines.com/types-of-pipeline-every-oil-and-gas-engineer-should-know-about