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Evaluating long-term performance of Glass Fiber Reinforced Plastic pipes subjected to internal pressure

Roham Rafiee [*], Behzad Mazhari

Composites Research Laboratory, Faculty of New Sciences and Technologies, University of Tehran, North Karegar St., Tehran, Iran

HIGHLIGHTS

- An integrated procedure is developed to predict long-term behavior of GFRP pipe subjected to internal pressure.
- The developed modeling is just in need of short-term experimental data on pure resin.
- Creep evolution is simulated based on gradual and sudden degradations of mechanical properties.
- As a case study, developed modeling is executed for a commercially produced GFRP.

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ABSTRACT

A computational modeling procedure is developed for simulating long-term creep behavior of Glass Fiber Reinforced Plastic (GFRP) mortar pipes subjected to internal pressure. The modeling procedure includes creep evaluation, stress analysis, failure evaluation and degradation of mechanical properties. Different levels of internal pressure are examined to obtain sufficient data point on failure-pressure versus time-to-failure graph up to 100,000 min. At each specific pressure level, the modeling procedure continues till the functional failure is distinguished implying on weepage phenomenon. Obtained data are extended to 50 years using extrapolation technique for predicting the remaining strength of investigated GFRP pipe after 50 years.

1. Introduction

According to the international statistics, huge consumption of composites can be tracked in construction and infra-structure industries such as civil engineering, oil, gas and water piping systems. In other words infrastructural industries can be considered as the pioneer for exploiting composite materials. Preventing corrosion in chemically reactive environments and its consequent repair costs are the main reasons that different industrial segments have been encouraged to employ GFRP pipes [1]. Besides transferring service, irrigation and potable waters or municipal and industrial waste waters, GFRP pipes are also utilized for the water-intake of cooling towers, fire extinguish systems and process flow lines of factories.

GFRP pipes are expected to remain in operation for 50 years as a long-term design constraint regulated by international rules and regulations [2,3]. Thus, characterizing the mechanical performance of GFRP pipes from durability point of view is an essential step during the design process. The experimental procedure dictated by international standard [4] for evaluating residual strength of GFRP pipes after 50 years is a very cumbersome and time consuming task. A series of long-term hydrostatic tests is necessary on GFRP pipes up to 10,000 h. Pipe samples are subjected to a constant internal pressure with different levels and corresponding time-to-failures are measured accordingly. A regression analysis on the obtained experimental data is performed to estimate remaining properties of GFRP pipes after 50 years [4].

Almost all conducted studies in the literature on characterizing long-term behavior of GFRP pipes subjected to internal pressure have been carried out experimentally [5–12]. In some investigations, it was intended to develop/use alternative approaches to decrease duration of the experimental study [6–12]. Most recently, Rafiee and Mazhari [13,14] have developed an integrated procedure for creep analysis of polymeric composites and simulated the long-term behavior of industrial GFRP pipes developing a theoretical procedure as the only available computational approach. The obtained results have been compared with experimental data

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* Corresponding author.
E-mail address: Roham.Rafiee@ut.ac.ir (R. Rafiee).

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for commercial GFRP pipes produced using continuous filament winding technology. An excellent agreement between predicted results and experimental data has been reported [14]. The current research is an extension of the previously conducted study by the same authors for the purpose of simulating long-term hydrostatic tests on the GFRP pipes produced by discontinuous filament winding technology. In previous study [14], first ply failure (FPF) was taken as the failure point of the pipe. Since, in continuous filament wound GFRP pipes, stress distribution is mostly dominant in the hoop direction in all layers for the case of pure internal pressure without pipe ends, the study of creep induced failure is rather simple employing simple failure criteria. Moreover, FPF prediction was aimed in the previous study [14] and post-failure analysis of other layers after occurrence of FPF was ignored to simplify the analysis. But here, a GFRP pipe fabricated using discontinuous filament winding technique is analyzed presenting more complex stress distributions within its layers attributed to the existence of angle plies. Due to the substantial difference between the wall constructions of the GFRP pipes produced by continuous or discontinuous technology, developed modeling procedure in the previous study [14] is modified and improved for analyzing long-term creep and creep-induced failure in the GFRP pipes produced with discontinuous filament winding techniques. The wall construction of GFRP pipes produced by continuous filament winding technology consists of both continuous and chopped strands reinforcements wherein continuous fiber is just placed along circumferential directions [14]. In these pipes, sand layer is also reinforced with short fibers [14]. In contrast, FRP layers of GFRP pipes produced by discontinuous technology solely consists of continuous fibers placed either along circumferential or arbitrary directions presenting hoop and helical layers. In these pipes, sand layer consists solely of resin and silica sand.

In this study, the failure progress is monitored in all layers till the last-ply-failure (LPF) happens. This represents the functional failure (FF) of the pipe. Firstly, theoretical basis of creep/failure modeling is presented and then developed modeling is implemented to predict long-term behavior of GFRP pipes subjected to internal pressure. Since, no experimental data is available for the long-term hydrostatic performance of discontinuous filament wound GFRP pipes, developed theoretical modeling is employed to gather such data for a commercial GFRP pipe as a case study.

2. GFRP pipe wall construction

In discontinuous filament winding process for producing GFRP pipes, an innermost layer called liner is firstly produced on a rotating mandrel. The liner is the thin chemical barrier layer which is in direct contact with internal fluid and practically composed of stitched fiber glass and resin. After curing the liner, then structural layers are wound. A bundle of roving glass fiber strands with a certain bandwidth is impregnated in resin bath and then applied to the rotating mandrel via a moving feeder travelling along the length of mandrel. Customizing the relative speed of moving feeder with respect to the rotating speed of mandrel, hoop and helical plies can be wound on mandrels. Thus, structural layers in discontinuous GFRP pipes include a combination of both helical and hoop plies. Hoop plies are known as those plies wherein fiber is placed along circumferential direction of the pipe with the winding angle of 89–90°. In helical plies, balanced angle plies with [±θ] configuration are formed. After curing the structural layers, surface coat which is a top layer made of resin is produced playing the role of protective layer. For the case of GFRP mortar pipes, a core layer consisting of impregnated sand in resin is also placed between the structural layers to increase the pipe wall thickness and its flexural rigidity. A schematic presentation of filament winding process and real structural winding process at industrial scale are presented in Fig. 1.

The investigated pipe in this article has diameter of 400 mm unsaturated polyester resin and E-glass direct roving with TEX-2400 are used. The configuration of structural layer is [±55/Core/90/±55]. 20 kg of silica-based sand is firstly impregnated with polyester resin and then applied to the length of pipe in between FRP layers using cellular fabric during filament winding process. The thickness of sand layer is about 1.34 mm; while the thickness of all applied FRP layers is 2.24 mm. Following the mentioned procedure in ASTM D 3171 [15], the average fiber volume fraction of the FRP layers obtained is 57.4%, while the volume fraction of sand in the core layer is obtained about 50%. The mechanical properties of all constituents are given in Table 1.

3. Theoretical modeling

The flowchart of the whole modeling procedure developed for evaluating long-term creep in discontinuous filament wound GFRP pipes and predicting long-term creep induced failure is presented in Fig. 2. The modeling procedure analyzes stress/strain variations in each individual layer of pipe taking into account updated mechanical properties as a time evolutionary problem. This part which is shown in dashed line in Fig. 2 is considered as the core of creep modeling in developed procedure. After stress analysis, the occurrence of failure is examined. If failure occurs in a structural layer, sudden degradation rules are applied to the mechanical properties of failed layer, otherwise next time-step is analyzed. The procedure continues until all layers experience failure. Developed modeling consists of four main stages as: creep modeling, stress analysis, failure evaluation and sudden degradation of mechanical properties.

3.1. Creep modeling

As it was explained before, the creep modeling procedure has been previously developed by the same authors and explained in a companion article [13]. Thus, the main framework is briefly summarized here.

Firstly, simple short-term experiments are conducted on pure resin in accordance with the procedure outlined in ASTM D 2990 [16]. Obtained short-term compliance of pure resin is converted to the long-term compliance of resin using master curves [13]. Then, using appropriate micromechanics rules, linear long-term compliance of lamina in transverse and shear directions are calculated using linear long-term compliance of resin. As an acceptable compromise in modeling, it is assumed that elastic behavior is exhibited in longitudinal direction due to the fiber-dominated properties.

Rule of mixture is employed to obtain longitudinal Young's modulus and major Poisson's ratio of FRP layers [17]. Modified rule of mixture [17] and Chamis formulation [18] is used to obtain transverse Young's modulus and in-plane shear modulus of FRP layers, respectively.

Semi-empirical equations are employed to obtain mechanical properties of the sand layer [17,18]:

$$E_{sand/resin} = \frac{(V_S)^{0.67} E_m}{1 - (V_s)^{0.33}\left(1 - \frac{E_m}{E_s}\right)} + \left(1 - (V_s)^{0.67}\right) E_m \qquad (1)$$

$$G_{sand/resin} = \frac{(V_S)^{0.67} G_m}{1 - (V_s)^{0.33}\left(1 - \frac{G_m}{G_s}\right)} + \left(1 - (V_s)^{0.67}\right) G_m \qquad (2)$$