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Evaluating mechanical performance of GFRP pipes subjected to transverse loading

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ABSTRACT

The main objective of this research is to investigate the damage progression and the failure mechanism of Glass-Fiber Reinforced-Plastic (GFRP) pipes subjected to compressive transverse loading. An experimental study is performed to observe the level of diametric deflection where failure takes place under transverse loading and also to monitor experienced failure mode. Then, conducted experimental study is simulated in commercial finite element software taking into account both interlaminar and intralaminar failure modes, simultaneously.

The degree to which the pipe can withstand diametric deflection without experiencing any failure mode is extracted. Then, appropriate in-plane failure criteria are chosen for identifying the onset of in-plane failure mode while cohesive approach is employed for identifying the initiation of delamination as the out-of-plane failure mode. Results of numerical simulation reveal that the liner is debonded from its adjacent hoop layer at 27% diametric deflection which is in a reasonable agreement with experimentally observed 31%. Moreover, the magnitude of the reaction force at 5% diametric deflection is obtained as 1242 N which is in a good agreement with experimentally measured 1225 N. Therefore, a satisfactory level of accuracy is achieved in constructed model implying on the appropriate modeling of damage progression. Finally, a parametric study is conducted to investigate the influence of various effective parameters on the pipe resistance level against transverse loading wherein neither in-plane nor out-of-plane failure is experienced.

1. Introduction

Glass-Fiber Reinforced Polymer (GFRP) pipes are increasingly utilized in the infra-structure industries because of various benefits including but not limited to light weight, strength, corrosion resistance, extended durability against environmental issues and mechanical loadings. Moreover, the design architecture of GFRP pipes can be tailored and thus a wide range of properties suitable for various applications is achievable. The unique characteristics of GFRP pipes have inspired the confidence for their applications in various oil, gas, water and waste-water piping systems.

From installation point of view, GFRP pipes are classified into aboveground and underground or buried pipes. Dictated by normative standards, GFRP pipes are practically examined from various aspects under the quality control program. The main design constraints of GFRP pipes are categorized into internal failure pressure, longitudinal tensile strength, circumferential tensile strength and apparent pipe stiffness [1,2]. Buried pipes tend to ovalize under the effect of installation and service loads and thus the pipe stiffness parameter becomes more prominent for designing buried pipelines.

The pipe stiffness indicates the degree to which the pipe can tolerate ovality under transverse loading without experiencing any failure. Pipe stiffness defines the ability of pipe to withstand not only against external transverse loading but also negative internal pressure [3].

Classified as an structural property, the apparent pipe stiffness (K_{pipe}) is proportional to the elastic modulus of pipe along circumferential/hoop direction (E_H) and cubic power of cross section thickness and it is inversely proportional to the cubic power of the pipe diameter (D^3) [4]:

$$\frac{E_H \bar{I}}{0.14877R^3} = 53.77\frac{E_H \bar{I}}{D^3} = K_{pipe} \tag{1}$$

where $\bar{I}$ is the second moment of area in the longitudinal direction per meter length (I/L) with respect to the pipe neutral axis. The schematic presentation of pipe stiffness is presented in Fig. 1.

Revealing the resistance of the pipe against transverse loading, the pipes shall have sufficient strength to withstand certain amount of decrease in vertical diameter without any indication of structural damage as evidenced by visible damage or interlaminar separation. Consequently, as a key factor in designing buried pipes, the mechanical

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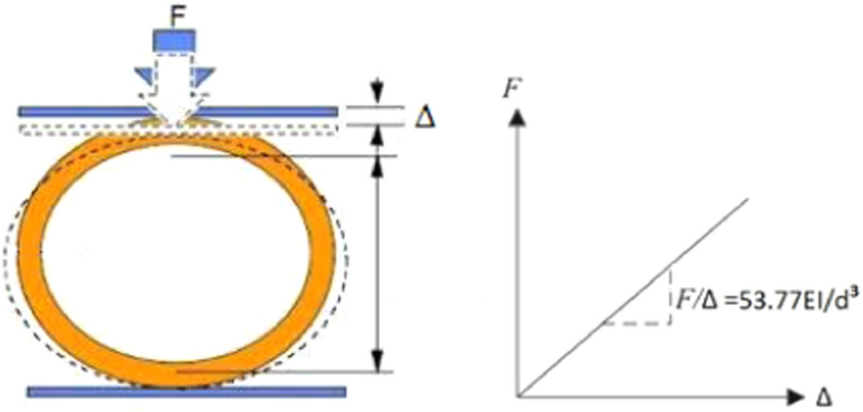

Fig. 1. Description of pipe stiffness [5].

performance of layered GFRP pipes against compressive transverse loading is required to be analyzed.

In contrast with other conducted investigations focusing on the mechanical behavior of GFRP pipes subjected to internal hydrostatic or axial loading [6–35] very limited studies have been done on analyzing the performance of GFRP pipe subjected to transverse loading [36–42].

Xia et al. [36] presented two methods to analyze the stresses and deflections of multi-ply cylindrical pipes under transverse loading conditions. They conducted an experimental investigation too and compared it to the results of theoretical calculations. They noticed that the values obtained from the experimental results fall between the values reported by theoretical calculations. Guedes [37] presented a method to analyze the stresses and deflections of transversely isotropic laminated cylindrical pipes, under transverse loading conditions. He developed an approximate 2D solution based on the assumption that the ratio of each ply thickness to its middle surface radius is negligible compared to unity. He has also analyzed underground GFRP pipe under transverse loading. He noticed that the relation between the maximum deflection and the maximum hoop strain was no longer linear as predicted by the small deformation theory. So a simple approach using deformation components based on finite deformations theory was proposed in his study [38]. Farshad and his co-worker [39,40] reported the results of long-term test on glass reinforced plastic pipe ring samples under wet conditions in their contribution. Samples were subjected to a range of diametric compression forces by series of loading devices. The creep test was carried out under constant dead weight in a submerged condition. Faria [41] focused on the experimental and numerical analyses of GFRP pipes under ring compressive loading. short- and long-term experimental tests as well as numerical simulations were performed to investigate the occurrence of delamination. Tse et al. [42] developed closed-form solutions for the spring stiffness of mid-surface symmetric, filament wound, composite circular ring under unidirectional loading. A 3D finite element analysis has also been applied to their study. Results show that FEA prediction of stiffness is always higher than the theoretical result. Furthermore, relations between the spring stiffness and the winding angles and geometry of the composite ring are considered and discussed in their study.

A lack of sufficient investigations on evaluating the mechanical performance of GFRP pipes under transverse loading is loudly noticeable in literature [43]. As a normal practice among industrial producers of GFRP pipes for the purpose of producing thicker and also economical pipes, an impregnated sand layer with resin is incorporated in between Fiber-Reinforced Polyester (FRP) layers as a core layer. These GFRP pipes are referred to as GFRP mortar pipes [1]. From installation point of view, thicker pipes are required for underground applications. On the other hand, the required layers of GFRP which can sufficiently and appropriately accommodate internal pressure, results in a thin pipe cross-section. Therefore, a sand/resin layer is incorporated into the structural layers to increase the pipe thickness as a cost-effective method for pipe stiffness enhancement.

Except theoretical studies on the stress analysis of GFRP pipes subjected to this specific load case, no study has been conducted on evaluating failure of GFRP mortar pipes. Moreover, the influence of winding angle and also the core layer on whether postponing or expediting the occurrence of delamination as the most dominant failure mechanism have not been studied.

The analysis of pipe mechanical response to transverse loading is a vital task establishing the confidence toward the safe performance of GFRP mortar pipes in underground applications. The main objective of this paper is to evaluate the influence of GFRP mortar pipe ovalisation on its structural integrity by means of finite element (FE) modeling. Firstly, an experimental study is conducted on a GFRP mortar pipe as a case study to determine the pipe resistance to diametric deflection against external transverse loading. Then, the FE model of a GFRP mortar pipe is built and subjected to the same loading condition of experimental program. Both intralayer and interlayer failure are taken into account at the same time and the damage progression is analyzed. Validating the constructed model, the obtained results from FE modeling and also experimental observation are compared. Finally, a parametric study is performed to evaluate the influence of fiber volume fraction, winding angle, core thickness and the sequence of wounded layers on both in-plane failure and also delamination of the pipe against transverse loading.

2. Experimental study

According to ASTM D2412-02 [3], the resistance of the pipe against compressive transverse loading is examined using an experimental procedure known as parallel-plate loading.

2.1. Materials and test specimens

A GFRP mortar pipe with diameter of 500 mm is chosen as a case study in this research. A small piece of pipe with the length of 300 mm was cut from the full length of a GFRP mortar pipe as the test specimen. The pipe was produced using discontinuous filament winding process. The wall construction of the investigated GFRP mortar pipe consists of liner layer and structural plies. The inner layer is called liner and it is produced on cylindrical mould. This layer comprises stitched glass fiber (450 g/m^2), surface mat (30 g/m^2) and unsaturated polyester resin with the approximate thickness of 1.51 mm. The liner prevents structural layers to be in direct contact with the fluid inside the pipe. As a GFRP mortar pipe, the structural plies contain hoop and cross FRP layers and also a core layer. A bundle of E-glass direct roving containing 42 strands with the bandwidth of 180 mm is impregnated with unsaturated polyester resin and then wound around the liner layer fabricating hoop