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Finite element method assisted stiffness design procedure for non-circular profile composite wastewater pipe linings

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ABSTRACT

The elastic behaviour of filament wound egg shape profile glass/polyester composite wastewater pipe linings was analysed with the scope of developing a simple stiffness sizing method. Ring compression tests were executed and simulated with the finite element (FE) method to verify the modelling concept. Good agreement has been confirmed, and a more realistic pipe-in-pipe type model was developed to simulate the operational loads and deformations of the liner pipes. Using the FE model outputs a 10 parameter function of the three most important material and geometric parameters was fitted to describe the defined stiffness of specific pipe cross sections. A unique design chart was developed representing the deformations of given cross section liner pipes of a wide range of stiffness values in function of the applied outer pressure.

1. Introduction

Composites made of thermosetting polymer matrix and glass fibre reinforcing materials show high tensile strength, relatively low elastic modulus, low density and high chemical resistance compared to steel. These beneficial properties have made polymer composites attractive for the piping industry, where low maintenance need of these materials is also highly appreciated [1].

Besides traditional applications such as pressure piping and large vessels, polymer composites are successfully applied for underground pipe lining with special trenchless (no-dig) technologies [2]. This is of very high interest since the main collector sewers under several cities around the world including London, Paris, Hamburg, New York, Los Angeles, Newark [3], Kolkata [4–6], Mumbai and Delhi were constructed around the end of the 19th century, more than 100 years ago using various non-circular, usually oval, egg or horseshoe shape profiles. Although a lot of the original sewers are still fully functional due to regular maintenance, they exceeded their design lifetime decades ago. Therefore hundreds of kilometres of the non-circular profile underground sewer pipe network needs urgent rehabilitation due to leakage, sedimentation and structural deterioration.

Polymer composite pipes are especially useful for trenchless pipe lining purposes which can cut down disruption to surface traffic significantly during rehabilitation of underground pipes. Various forming technologies of composites such as injecting, and prepreg technologies make them capable of being flexible during insertion into the old pipe, and they can be cured in situ. Wide spectrum of trenchless lining technologies is available for water, gas and sewerage piping, including ones for non-circular profile pipes. One of the most common lining technologies for non-circular (typically egg or oval shaped) man-accessible sewer pipes is the "short pipe" or slip-lining process [7], where prefabricated (cured) liner pipe sections usually made of fibreglass reinforced thermosetting resins are pulled or pushed into the old pipe [3–6,8]. This type of lining technology is applied in those cases, where the load bearing capacity of the old pipe is acceptable, but it is leaking due to longitudinal or other types of cracks in the rigid, usually concrete or brick pipe walls. The main load of the lining in this case is the outer hydrostatic pressure coming from the groundwater, because water can pass through the leaks and possible grouting between the old and new pipe. Researchers such as Boot and Welch [9,10], Zhao et al. [11] and Thépot [12,13] normally take the outer pressure into consideration as the only load on the lining. Analytical buckling theories published first by Timoshenko and Gere [14] and modified by numerous researchers are valid for circular profiles, and utilises the geometric and elastic constants of the pipe. In case of a non-circular lining, analytical models are too complicated and the finite element (FE) method offers accurate solutions [10,15,16], rather for elastic problems than for failure and damage analysis. Ikram and Abdennour [17] modelled various non-circular

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profiles under concentrated compressive loads and established shape factors for them. This method helps relating the elastic behaviour of irregular profiles to that of circular ones. Due to high cost only a few full scale experimental work on the buckling behaviour of flexible non-circular pipe linings has been published. Falter et al. [18] tested small and full scale polyethylene egg-shape profile liners subject to outer pressure within their comprehensive study and confirmed that German design code ATV-M 127-2 [19] is adequate for verification purposes.

It is clear from the literature survey that there is a significant demand for a simple stiffness sizing method for non-circular profile wastewater pipe linings subject to outer pressure which can take the manufacturing parameters of filament wound glass fibre reinforced composite pipes such as fibre volume fraction, winding angle and wall thickness into account. This type of quick tool could be utilised along with design codes [19,20] which usually assume given material properties and could make the design more accurate, saving material, weight and finally cutting down costs and environmental footprint of production, transportation and installation.

The aim of this study is to present a design procedure for stiffness sizing of egg shape profile sewer pipe linings subject to outer pressure loading. A finite element model was constructed to simulate the pipe-in pipe system of the rigid old pipe and the liner, and the results of the simulations were applied for the development of the stiffness sizing procedure. It is of high importance, that once the sizing method is established for a given geometry (cross-section) the finite element software is not necessary for further steps of the calculations. It is very beneficial for small companies with limited budget, that they can mandate a consultant to execute the FEM calculations for a given case (geometry and materials), and then they can use the method without subscribing for the expensive software package.

2. Materials and methods

The developed FE model was validated by comparing the results of ring compression tests to the ones obtained from the numerical model. The tests were executed on egg shape profile ring specimens (see Fig. 1) cut form a filament wound glass fibre reinforced unsaturated polyester composite pipe. The applied ring compression test method is a very basic experimental setup (see Fig. 2), which does not modify the reinforcing structure of the pipe section and for which no special equipment is needed. The ring compression tests were executed on a Zwick Z050 type universal material testing machine at 20 mm/min crosshead speed, between two rigid, flat, parallel plates. Tested specimens were compressed until fractures of the pipe walls, which happened at high crosshead displacements and low forces compared to the 50 kN capacity of the machine and therefore no compliance correction was applied to the test data.

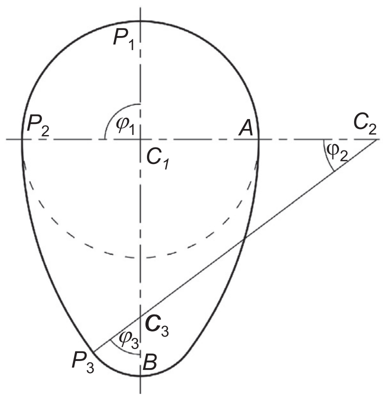

Fig. 1. Cross sectional geometry of the tested and modelled egg shape profile pipes.

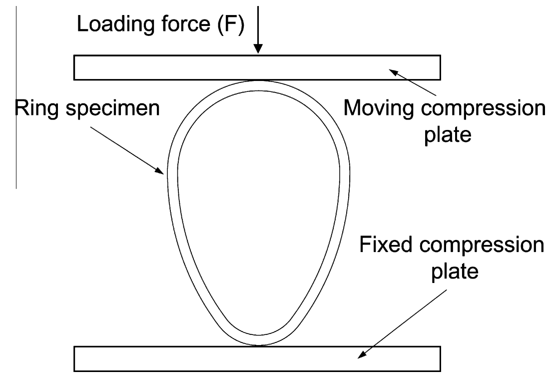

Fig. 2. Ring compression test alignment with egg shape profile ring specimen.

Nominal geometric properties of the tested rings were the following (see Fig. 1): characteristic mean radius: $R_m = |\overline{C_1P_1}| = 80$ mm, nominal wall thickness: $t = 2.4$ mm, length: $l = 20$; 40; 80; 160 mm, cross-sectional height: $h = 3R_m = 240$ mm, cross-sectional width: $b = 2R_m = 160$ mm. Three specimens were tested from each different lengths except for the longest type, where only one specimen was tested (altogether 10 pieces). Load–displacement graphs were evaluated for the specimens tested.

Matrix material of the examined composite pipe was AOC Altek H557-AEF-30 type orthophthalic acid based unsaturated polyester formulated for filament wound tanks and pipes. Applied reinforcing material was Johns Manville Star Rov PR 300 2400 907 direct E-glass roving with a linear density of 2400 tex. The roving was manufactured with silane sizing, which provides excellent adhesion to unsaturated polyester.

The tested pipes were manufactured by filament winding technology at Hodacs Composites Ltd. (Hungary) with a winding angle $\theta = 83.5 \pm 1.3°$ to the longitudinal axis of the pipe. The composite material was cured at room temperature for 24 h and postcured at 60 °C for 6 h. The fibre weight fraction of the tested composite pipes was examined with the burning method according to ISO 3451-1 and found to be $v_m = 71.4 \pm 2$ m%. As the density of reinforcing fibres is almost two times higher than that of the matrix material, the fibre content was calculated into volume fraction to give more relevant information on the material composition. The density of the composite material was examined according to ISO 1183-1 with the immersion method and found to be $\rho_c = 1.924 \pm 0.03$ g/cm^3. The glass fibre volume fraction calculated with the measured density of the composite material was $v_f = 53.9 \pm 2.2$ V%.

3. FE modelling of the ring compression tests

In this section the finite element model applied for simulating the ring compression tests is discussed in details. This setup has been chosen as a verification of the FE model developed, because experimental results were available for comparison. Initial attempts to find the most accurate modelling strategy is not presented, but as a result of assessments on several different 2D and 3D models including shell and body types, 3D body modelling has been chosen after comparison with test results.

3.1. Material definition

During the modelling phase the notable anisotropy of the filament wound pipe material was taken into account, although it