A systematic investigation into the effects of soil conditions and deterioration mechanisms on the failure response of unreinforced concrete sewer pipes

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Highlights

- • Full-scale experiments to determine the failure response of unreinforced concrete sewer pipes
- • FEM modelling of discrete fracture behaviour of concrete sewer pipes
- • Numerical variation study on the influence of soil conditions and deterioration mechanisms

Introduction

The service life of unreinforced concrete sewer pipes spans several decades, during which the sewer pipe system is subjected to hazardous conditions. For example, concrete sewer pipes are susceptible to biochemical degradation, ageing or a loss of soil support (Davies et al., 2001). In order to maintain the serviceability of the sewer network, sewer condition assessment has become increasingly important over the years, especially since the 1980s, when the household connectivity in the Netherlands exceeded 90%, which initiated a shift from expansion towards maintenance of the system (van Riel et al., 2015). The purpose of condition assessment is to balance between the risk of catastrophic collapse and premature, capital-intensive sewer replacement. Current inspection methods (closed-circuit television inspections) are not undisputed, due to a low accuracy and reliability of the visual inspection data, the lack of an evident correlation between visual inspection data and material properties, and the impossibility to reveal damage at the outside of the sewer pipe (Dirksen et al., 2013, Stanić et al., 2013, 2017). As a consequence, the influence of deterioration and ageing on the load bearing capacity of sewer pipes is yet not well understood. Therefore, an experimental-numerical study is conducted to provide insight into the load bearing capacity and failure response of unreinforced concrete sewer pipes. Subsequently, a numerical study is conducted to validate the experimental results, and to perform a parameter variation study. The results of this study support municipalities in the decision-making process on rehabilitation or replacement of sewer pipe systems and enhances the development of improved inspection techniques.

Methodology

In the experimental program, three different types of sewer pipes were considered, namely round sewer pipes with an inner diameter of 400 and 500 mm and egg-shaped sewer pipes with a horizontal inner diameter of 400 mm and a vertical inner diameter of 600 mm. For each of these sewer pipe types, denoted as R400, R500 and E400/600, respectively, 6 pipe specimens were subjected to full-scale destructive testing under biaxial loading conditions. The failure response of the sewer pipes was monitored by recording the load-displacement behaviour, measuring the local strain response, and by taking photographs at regular intervals of the front side of the sewer pipe. More information on the test set-up and measurement devices can be found in Scheperboer et al. (2021). The experimental results are simulated by a numerical model using the finite element method (FEM), where the geometry is discretized by continuum elements in combination with interface elements. The interface elements are located between all continuum elements and equipped with the mixed-mode damage model developed by Cid Alfaro et al. (2009). Subsequently, the model of the round R400 sewer pipe is used to analyse the sensitivity of the overall failure response of the sewer pipe to various parameters, which are i) the load contact area, ii) the ratio between the applied

horizontal and vertical loads, iii) the wall thickness of the sewer pipe, iv) the tensile strength, v) the mode I fracture toughness and vi) the Young's modulus of concrete.

Results and discussion

Load bearing capacity and fracture pattern

The vertical load versus the vertical net displacement of a round R400 sewer pipe and an egg-shaped E400/600 sewer pipe are shown in Figures 1(a) and (b), respectively. It is observed that the agreement between the experimental results (in black) and the numerical results (in red) is very good. The initial elastic stiffness response is captured well and the peak load of the numerical simulation closely approaches the experimental peak load; the overestimation by the numerical simulation is 5% for the R400 sewer pipe and 9% for the E400/600 sewer pipe. The load-displacement behaviour of the round R500 sewer pipe specimens was found to be similar to the load-displacement behaviour of the round R400 sewer pipe specimens. The failure response as obtained from photographs taken at the end of the experimental test procedure is compared against the discrete fracture pattern as simulated by the FEM model, see Figure 2. It is found that both the location of the macroscopic failure cracks and the crack sequence are in good correspondence. Four cracks typically emerge upon failure: first two cracks at the bottom-inside and the top-inside, followed by the simultaneous development of two lateral cracks at the (top-)left- and (top-)right-outside.
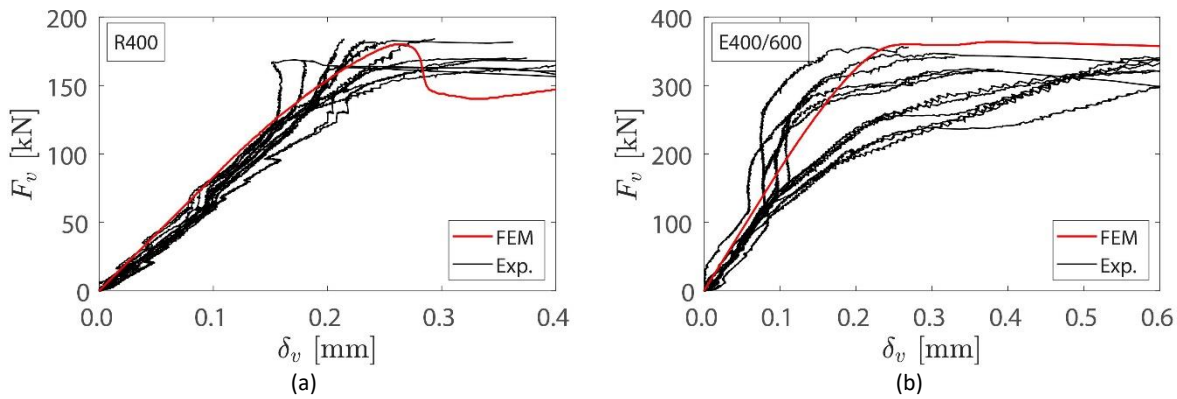

Figure 1. The vertical load F_v versus vertical net displacement δ_v of (a) a round R400 sewer pipe and (b) an egg-shaped E400/600 sewer pipe. The experimental results are presented by the black solids lines and the results from the numerical simulation are presented by the red solid line.
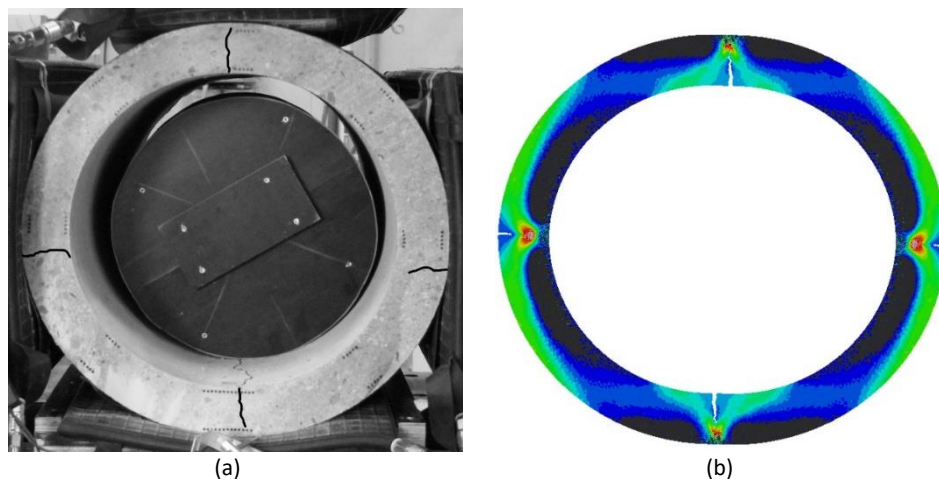

Figure 2. The failure response of the R400 sewer pipes obtained from (a) photographs taken at the end of the experimental testing procedure and (b) the numerical simulation.

Parameter variation study

As a result of the good agreement between the experimental and numerical results, the FEM model is used for studying the influence of various geometrical and material parameters on the failure response of a round R400 sewer pipe. An example of the results of the variation study is presented in Figure 3, where the

wall thickness of the sewer pipe is systematically reduced, to mimic the effect by biochemical corrosion processes. It is observed in Figure 3(a) that a reduction of the wall thickness leads to a decrease of the load bearing capacity of the sewer pipe, while at the same time the displacement at the peak load increases. The results in Figure 3(b) show that the peak load of the sewer pipe reduces significantly under a reduction of the wall thickness, i.e. a reduction of 20% already induces a decrease of the ultimate failure load of almost 40%. A degraded tensile strength also significantly decreases the ultimate failure load, whereas the influence of the Young's modulus and mode I fracture toughness on the load bearing capacity is less pronounced, see Scheperboer et al. (2021).
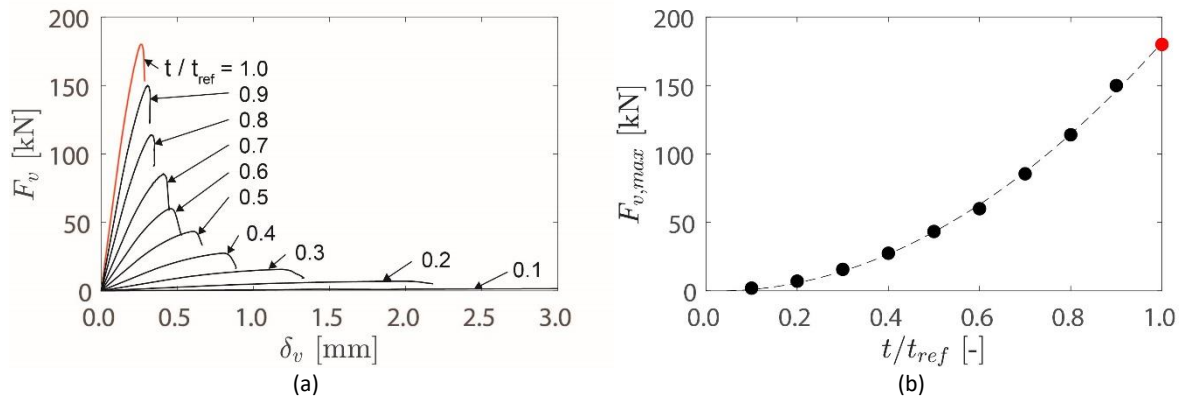

(a)   (b)

Figure 3. The influence of a relative wall thickness t/t_{ref} on the failure response of a round R400 sewer pipe, whereby the reference case is depicted in red and corresponds to the simulation shown in Figure 1(a). In (a) the load-displacement response of the simulations is presented, and (b) presents the relation between the peak load of the simulation and the relative wall thickness.

Conclusions and future work

The structural failure of concrete sewer pipes under biaxial loading conditions is characterized by four macroscopic failure cracks, which emerge at the bottom-inside, top-inside, (top-)left-outside and (top-)right-outside, respectively. Sewer asset managers benefit from this work by realizing that a failure crack at the top-inside, observed in visual inspection data, is typically accompanied by three (less visible and accessible) failure cracks. The results from the parameter variation study showed that a reduction of the wall thickness yields a severe reduction in load bearing capacity. It is therefore recommended that the degradation of the wall thickness and material parameters is monitored over time. To improve the knowledge on the influence of deterioration mechanisms on the load bearing capacity of sewer pipes, it is important to determine the type and degree of damage observed in naturally aged sewer pipes and relate these to the failure response, as presented in Luimes et al. (2021, 2021b).

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