#256 - Experimental-numerical study on the structural condition of naturallyaged, unreinforced, concrete sewer pipes

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Highlights

- Condition assessment: visual inspections; phenolphthalein, XRD and material properties tests
- Full-scale experiments on concrete sewer pipes that have been in service for many decades.
- FEM modelling of the discrete failure response of concrete sewer pipes .

Introduction

The structural condition of sewer pipe systems is susceptible to various factors, such as heavy surface loads, soil erosion or corrosion mechanisms. Therefore the loss of structural integrity and serviceability of these systems is a serious threat (Davies et al., 2001). To avoid sewer collapse or a premature sewer replacement, which are typically associated to high costs and large societal impact, an accurate condition assessment of in-situ sewer pipe systems is essential (Wirahadikusumah et al., 2001; Stanić et al., 2013). Currently, CCTV inspections, combined with a manual classification of the surface condition according to dedicated standards, is the governing information source based on which the condition of sewer pipe systems is assessed in The Netherlands (Wirahadikusumah et al., 2001; Dirksen et al., 2013). However, the results obtained from CCTV inspections are under discussion, and deterioration that is potentially present across the wall thickness or at the outside of the sewer pipes is not assessed (Dirksen et al., 2013; Stanić et al. 2013). This reveals that there is a need to obtain a scientific basis and practical guidelines to improve the condition assessment of sewer pipe systems. A first step towards this goal is provided by means of the comprehensive experimental-numerical study carried out at the Eindhoven University of Technology, as reported in (Scheperboer 2021 et al.; Luimes et al. (2021a, 2021b)). The results of this study support municipalities and other stakeholders to optimise their decision-making process regarding the maintenance and replacement of sewer pipe systems.

Methodology

A comprehensive experimental-numerical program has been initiated, in which the structural condition of 18 new and 35 naturally aged, unreinforced, dry-cast, concrete sewer pipes have been investigated. The round and egg-shaped sewer pipes, of which a selection is shown in Figure 1, have been provided by Dutch municipalities and production companies and varied in size, age and in-situ service conditions. All sewer pipes have been examined in the laboratory according to a systematic experimental procedure. This provided relevant information on: i) the intrinsic characteristic and environmental conditions of the sewer pipes, such as the dimensions, age, service location and soil type, ii) the type and degree of deterioration of the naturally

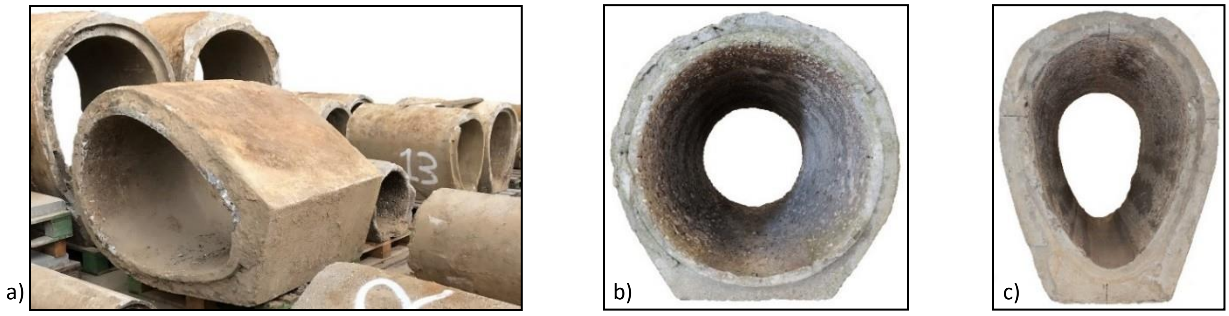

Figure 1. A selection of naturally aged unreinforced concrete sewer pipes examined in the experimental-numerical study. Excavated sewer pipes stored at the laboratory a), and surface condition at the inside of an round sewer pipe with a flat foot b) and an egg-shaped sewer pipe c).

aged sewer pipes as obtained from visual inspections, phenolphthalein tests and X-ray diffraction (XRD) analyses, iii) the concrete material properties of the sewer pipes as derived from uniaxial compression and three-point-bending tests performed on small samples sawn from the sewer pipes, and iv) the fracture response of the sewer pipes as obtained from full-scale experiments during which the pipe specimens were subjected to biaxial loading conditions. The results of the full-scale experiments have been complemented and validated by dedicated finite element method (FEM) analyses. The FEM models consisted of continuum elements that simulate the elastic behaviour of concrete, which were surrounded by interface elements endowed with a mixed-model damage model to simulate discrete fracture.

Results and discussion

Type and degree of deterioration

The type and degree of deterioration present in the naturally aged sewer pipes was investigated by combining the results obtained from visual inspections, phenolphthalein tests and XRD analyses. Relevant examples are shown in Figure 2. It was found that the sewer pipes, which had been installed in the 1920s and 1950s, showed deterioration mechanisms at the inside and outside. At the inside of the sewer pipes, the deterioration was more severe and probably induced by biogenic sulphuric acid corrosion, which is known to unfavourable affect the concrete material properties. At the outside of the sewer pipes, the deterioration found was possibly caused by carbonation, for which it is unlikely that the concrete material is affected to a large extent. From the results, no clear relation between the visual inspection data and residual alkalinity profiles could be established.

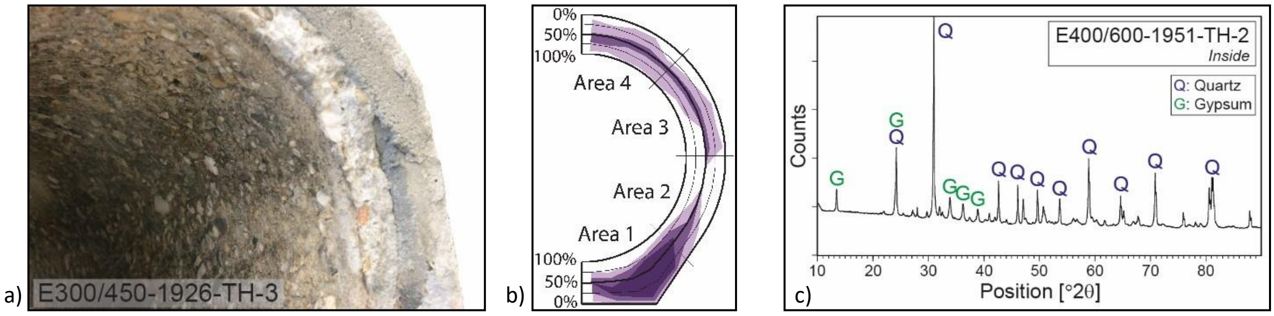

Figure 2. Examples of a) a visual inspection result showing exposed granulates at the inside of a sewer pipe, b) a contour plot of the cross-section of a sewer pipe obtained from phenolphthalein tests showing the area of alkaline, healthy concrete in purple, and c) a XRD pattern obtained from an XRD analysis showing the presence of gypsum at the inside of a sewer pipe.

Material properties

The average values and standard deviation of the compressive strength and Young's modulus were acquired for each sewer pipe type from uniaxial compression tests. For the tensile strength and mode I fracture toughness a lower bound, average and upper bound value were determined per sewer pipe type by means of a combined experimental-numerical procedure. When comparing the average results of naturally aged sewer pipes to the average results of new sewer pipes, it was concluded that the naturally aged sewer pipes had a lower compressive and tensile strength and a higher ductility compared to the new sewer pipes. The difference in elastic stiffness was less pronounced.

Structural failure response sewer pipes

The structural failure response of the new and naturally aged sewer pipes was investigated by means of full-scale experiments and FEM analyses. In the full-scale experiments, the sewer pipes were subjected to biaxial loading conditions, where the horizontal loading was set equal to 1/3 times the vertical loading, which is representative of a sewer pipe embedded in a well-graded sandy gravel that is subjected to neutral earth pressure. During testing, the load-displacement response was measured and the fracture pattern was recorded by photographs taken of the front surface of the sewer pipes. It was found that the sewer pipes failed under the development of 4 macroscopic failure cracks located at the top, bottom, (top-)left and (top-)right side of the sewer pipe, for which the exact location of the lateral cracks depended on the specific geometry of the sewer pipe, see Figure 3a. The developed FEM model was able to accurately predict the load-displacement response and discrete fracture pattern of the new sewer pipes and was therefore used to study the structural failure behaviour of the naturally aged sewer pipes in more depth. In general, the simulation results mimicked the load-displacement response and the fracture pattern of the naturally aged sewer pipes well, see Figure 3. However, the experimentally measured initial elastic stiffness and load-bearing capacity were overestimated. When incorporating in the numerical simulations the spread in concrete material properties, as obtained from the uniaxial and three-point-bending tests, a more accurate agreement between the numerical predictions and the experiments was obtained. This could however not fully explain the differences between the experimental and numerical results. Therefore, the influence of the deteriorated layer, observed at the inside of the sewer pipes, was taken into account in the numerical simulations by reducing the wall thickness of the FEM model. This resulted in a good prediction of the structural failure response of the naturally aged sewer pipes observed experimentally as shown in Figure 3c. It was concluded that a part of the deteriorated layer at the inside of the sewer pipes did not contribute to the structural capacity of the naturally aged sewer pipes.

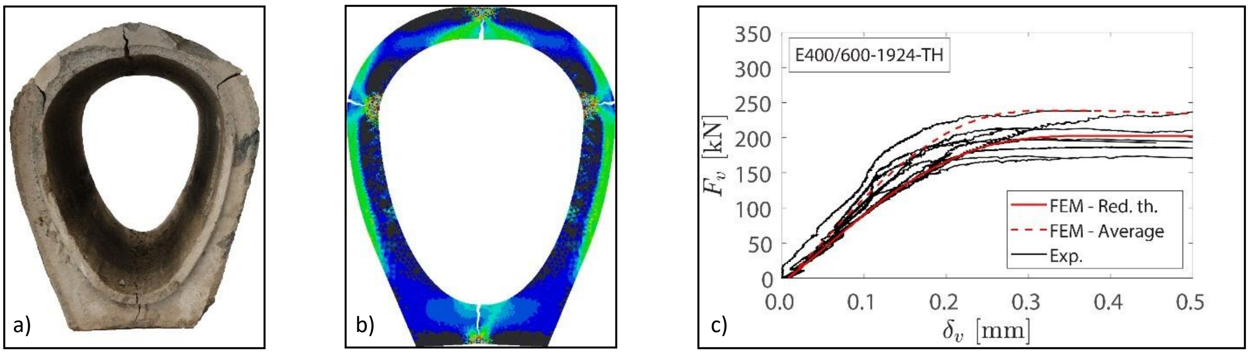

Figure 3. a) Experimentally obtained fracture pattern. b) Simulated fracture pattern. c) Influence of deterioration on the load-displacement response of an egg-shaped sewer pipe. The red solid and red dashed line represent the simulation results obtained with a model with a reduced wall thickness and original geometry, respectively. The black solid lines are the experimental results.

Conclusions and practical recommendations

The large amount of data systematically collected in the experimental-numerical study on 18 new and 35 naturally aged sewer pipes has provided in-depth information on the structural condition of the sewer pipes. It was found that the type and degree of deterioration detected at the inside of the sewer pipes was most severe. Besides, the concrete compressive and tensile strength and ductility were, respectively, lower and higher for the naturally aged sewer pipes compared to the new sewer pipes. Furthermore, it was concluded that the sewer pipes fail under the development of 4 macroscopic failure cracks. The FEM model is capable of accurately simulating the failure response of the naturally aged sewer pipes, once the geometrical dimensions, material properties and deterioration level of the sewer pipes are known. The reference case established with this study can be consulted by various stakeholders when assessing the structural condition of similar sewer pipes. In addition, monitoring the evolution of the wall thickness and deteriorated layer at the inside of the sewer pipes is essential to accurately assess the structural condition of the sewer pipes.

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