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Experimental and numerical study on structural performance of reinforced concrete box sewer with localized extreme defect

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Abstract

An experimental and numerical investigation into the structural performance of reinforced concrete box sewers with typical corrosion-related extreme defects localized at the ceiling was conducted. Firstly, during the large-scale laboratory test, some key structural responses were captured and evaluated, including the crack width development process (via digital image correlation measurement), ceiling deflection, and material strains of both complete and typical defective boxes. The failure modes and load-carrying mechanism throughout the specimen loading phases were analyzed. Furthermore, the specimen failure process was simulated using a damage-based finite element method, and a related parameter sensitivity analysis was performed. The results indicate that the defective ceiling cracked at mid-span under a low load value, but the bending capacity loss can be substituted by two shoulders and carry three to five times more load before completely collapsing. The simulation matched the lab test qualitatively, and with the suggested set strategy of material parameters, the load-deflection feature curve could provide a practical prediction of the ultimate bearing capacity of the defective sewers, with a 10–15% error on the safe side.

Keywords: Defective reinforced concrete box sewer; Corrosion; Structural performance; Large-scale model test; Digital image correlation measurement; Failure simulation

Introduction

Aged municipal sewers subjected to aggressive sewage environments generally suffer from structural defects due to long-term corrosion, increasing the risk of emergencies such as sewage leakage and surface collapse, which bring hazards not only to the drainage service itself, but also to the surrounding infrastructure and city functions, e.g., other buried pipes, traffic, environment, and business. Generally, the larger the pipe is, the worse the consequence could be. Although recovering structural properties by proactive rehabilitation is a more economical and less troublesome solution than a reactive remedy, the operation could be difficult for some large-diameter sewers due to the unacceptable impacts of cutting off flow. Thus, it's a vital issue to evaluate the structural performance of such defective large-diameter sewers and avoid a systemic catastrophe before a proper solution can be reached.

Reinforced concrete (RC) is a widely-used material for large diameter sewers due to its fine balance between structural performance and cost, but defect-related situations regarding such sewers are causing concerns worldwide. In Toronto (2008), a 60 m-long and centimeters-wide crack was spotted at the crown of a 50 year-old, 2.6 m diameter trunk sewer during a routine inspection, and a bypass

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tunnel costing $30 million was built to substitute the defective old sewer (Aulakh, 2010; Morrison, 2013). In Macomb County, Michigan (2016), a 43 year-old, 3.4 m diameter sewer interceptor collapsed due to corrosion, the sink area reached up to 30 × 90 m and it cost $70 million to repair, after which an $80 million anti-corrosion relining plan for the whole 6.9 km sewer was proposed (Paint Square, 2017). In Shanghai (2015), a survey of a 30 year-old, 3.2 × 2.6 m box sewer demonstrated extreme corrosion localized at the ceiling, that is, a total loss of the underlying rebar layer and 17–35% concrete thickness loss, depending on specific service conditions such as covering depth, traffic intensity, and hydraulic characteristics.

The rapid corrosion of sewage facilities and other infrastructure serving under harsh environments has been a worldwide engineering issue, as seen from the saline engineering case (Carvajal, Vera, Corvo, & Castañeda, 2012; Costa & Appleton, 2002), chemical plant case (Niu, Lin, & Li, 2014), and mine case (Yang, Marshall, Wanatowski, & Stace, 2017). Experimental and computational research studies on the structural performance of such defective structures have been conducted over the past several decades.

In an experimental study, Almusallam, Al-Gahtani, Aziz, Dakhil, and Rasheeduzzafar (1996) investigated the structural effects of reinforcement corrosion by testing the flexural response of simply supported RC slabs subjected to a certain period of rebar electrolysis. The results indicated that the bending capacity decreases sharply when the corrosion rate reaches 29%, and the slab performance was equivalent to that of plain concrete after 60%. Lv, Wu, Fang, and Zhou (2015) studied the mechanical performance of RC beams subjected to acid-salt mist and carbon dioxide using four-point bending tests. The results indicated a change in failure mode from compressive crushing to tensile fracturing as corrosion progressed, which was attributed to the bending strength deterioration between the concrete and tensile rebar.

In terms of qualitative research, Bairaktaris et al. (2007) computationally studied the typical "ring failure" failure mode of round pipes and proposed a key section model to evaluate their stability, namely, dividing the pipe ring into 12 pieces and connecting them with 12 key sections, where the structure fails if the number of failed sections reaches a certain threshold due to physical cracking and computation. Furthermore, there have been practices that modeled defective sewers with solid elements and simulated nonlinear structural behavior by incorporating the material criteria of Drucker-Prager (Alani & Faramarzi, 2015) and fracture mechanisms (Řoutil, Chromá, Teplý, & Novák, 2015). In terms of quantitative research, relevant codes, guidelines (Water Research Centre (Kensington)., 2001), and certain advanced assessment systems (Kirkham, Kearney, Rogers, & Mashford, 2000) have been applied to diagnose the pipe condition by grading key indexes such as residual thickness, concrete strength, and crack distribution, which were usually captured by detection techniques including CCTV, laser, sonar, and ground penetrating radar.

The existing experimental and computational research studies have offered useful clues for the structural property assessment of corroded sewers and similar RC structures. However, experimental research has focused mainly on round pipes and simply supported beams, while computational research was applicable mostly to round pipes. The Shanghai case is a box structure with localized extreme corrosion defects at the ceiling, which is unique in both the geometric character and load-carrying mechanism compared with most existing literature.

In this study, a laboratory test and numerical simulation were carried out to investigate the extremely nonlinear working state and evaluate the structural reliability of such a defective box sewer. Through a large-scale laboratory experiment on three model specimens with different degrees of ceiling defects, the structural response development process and load-carrying mechanism of a typically defective sewer were captured and uncovered. Furthermore, the specimen failure process was simulated using a damage-based finite element method (FEM) model, based on which a parameter sensitivity analysis was performed, and a practical parameter determination strategy was concluded in predicting the load-carrying performance of defective sewers.

Experimental program

Prototype field condition

The Shanghai South Trunk is a box-shaped sewer that was built in the mid-1980s and is serving 1.3 million residents by conveying 300–400 million liters of sewage per day. After 30 years of service, a field survey was conducted on this aged sewer in 2015. According to the investigation report, the 30 year-old box had suffered severe localized corrosion, as illustrated in Fig. 1: (1) the ceiling slab had completely lost its underlying rebar layer and the concrete

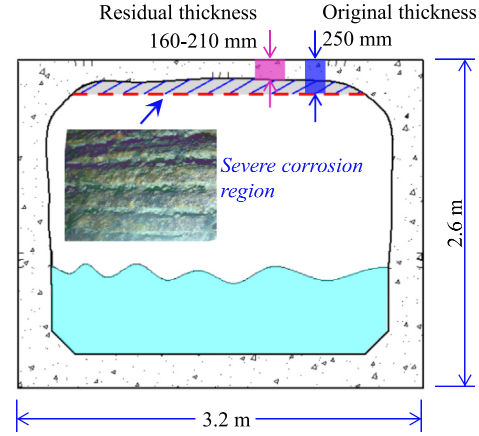

Fig. 1. Illustration of localized sewer corrosion.

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