Finite-Element Modelling of a Concrete / Carbon Plate Interface Application to Sewerage Systems

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Summary

Sewerage systems undergo many structural deteriorations. This article is concerned with the strengthening of sewers using composite plates. In order to apply this technique, finite-element analysis was required to determine the failure mechanism and therefore the areas in need of strengthening. An experimental test series was conducted to characterise the various materials (concrete, glue, and carbon plate) and to obtain their constitutive laws. A control ovoid sewer and a carbon plate-strengthened ovoid sewer were then compared using a numerical model.

Keywords: Carbon fiber Composite, Sewerage Structures, Theory of Cracking, Rate of Energy Restitution, Repair, Reinforcements.

1. Introduction

Most sewerage systems date from the early 20th century. In France, there are several tens of thousands of kilometres of man-holes sewers. These structures used to be rebuilt or replaced by opening trench, but we are now in an area of renovation. The sewers were generally designed with significant safety margin, and still provide sufficient hydraulic capacity [1]. As a result, numerous repair and strengthening techniques have been developed using a variety of products and processes.

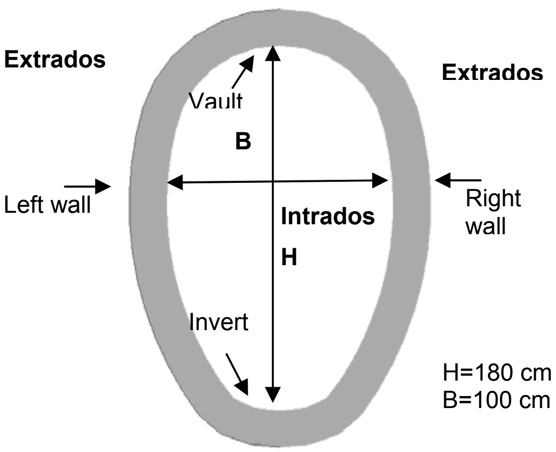


Fig. 1: Diagram of an ovoid

There are different types of sewers. They may or may not have man-holes, and are built from different materials (masonry or concrete).

They vary in shape, being circular or ovoid section. This study focuses mainly on ovoid section reinforced-concrete sewers.

Ovoids sewers consist of a vault, two abutment walls and an invert.

Man-holes sewers undergo many types of deterioration [2] that may originate inside or outside the structure. Because of their function, they suffer either chemical attack (H_2S) or surface or structural deterioration due to ground surface surcharge loadings or to design faults.

The most frequent structural deteriorations are:

- Transverse and longitudinal cracking;
- Structural deformation with associated infiltration;
- Structural damage related to the weight of ground surrounding the sewer system;
- Fractures of the vault or invert.

Deterioration may occur in specific areas or over the sewer's entire surface, i.e. from the vault to the invert via the walls, on the intrados and extrados sides. Many repair and strengthening techniques are used to restore the primary functions of deteriorated sewers, but they are costly and need to be applied over the entire structure (injection, projected-concrete or -grout lining, tubing using prefabricated sections)[2].

The construction and public works industry is now expert in selective strengthening methods using composite materials [3]. These materials come in the form of textiles or pultruded plates. The French companies Sika, Structure & Réhabilitation and Valentin Environnement et Travaux Publics, in collaboration with the LAMTI laboratory, decided to apply this technique to sewers in an extensive series of experimental tests, and to verify the results using a numerical model.

In order to transpose construction-industry methods to water-saturated environments, it was necessary to conduct a test series [4] to assess the feasibility of adhering composite plates to a damp surface without streaming water.

Numerical simulations were then performed using the URUS finite-element computation code [5] on an unstrengthened control ovoid and a composite plate-strengthened ovoid section. This numerical assessment showed us the structural functioning of the ovoid section and hence its failure mechanism. Once the structural failure mechanism was known, the areas in need of strengthening could be determined.

2. Feasibility assessment

This study comprised tests in various environments in order to characterise and assess the influence of relative humidity, present in sewers, on the concrete-glue-composite complex.

2.1. Characteristics of the materials required for test series

In this test series, the mean 28-day compressive strength of the concrete, fc28, was 46 MPa. The mean tensile strength of the concrete was 3.4 MPa. The Young's modulus of the concrete was 29 500 MPa.

The Sika Carbodur strengthening process was selected, having produced satisfactory results in construction applications.

Table 1: Mechanical characteristics of Sika Carbodur carbon plates

Characteristics	Values
Tensile strength [MPa]	2,400
Young's modulus [MPa]	150 000
Rupture elongation [%]	1.4
Relative Density	1.53

The composite carbon plates (Sika Carbodur) [6] were 1.2 mm thick and 80 mm wide (Table 1). These are unidirectional composites for which the direction of the loadings must be the same as that of the fibres (longitudinal). Carbon fibres piled up in an epoxy resin matrix represent 60% of the volume of the plates.

This glue is a solvent-free, two-part, thixotropic epoxy formulation.

Table 2: Characteristics of SIKADUR-30 glue

Characteristics	Values
Young's modulus [MPa]	12 800
Mix ratio	3/1
Relative Density (A+B)	1.8
Adhesion on concrete [MPa]	> 4
2-day compressive strength [MPa]	> 55
2-day bending strength [MPa]	> 30

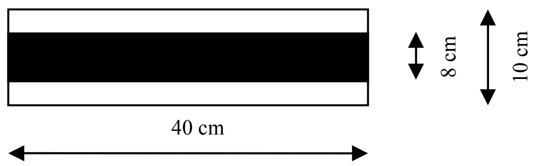
The general characteristics of the glue are:

- Very high adhesion to most surfaces;
- Impermeable to liquids and steam;
- High resistance to common chemicals;
- Overhead surface applicability;
- Fast drying;
- High mechanical strength.

The tests were performed after the strengthening plates had been glued and stored for 8 days in various environments:

- Adhesion to a dry concrete substrate in a so-called dry environment, which constituted the reference. Temperature θ was 20°C and relative humidity (HR) was 40%.
- Adhesion to a damp concrete substrate corresponding to a water-saturated environment, which characterises the general environment of sewers. Temperature θ was 20°C and HR was 90%.
- Adhesion to a damp concrete substrate extracted from the water-saturated environment, and subjected to a third environment: submersion for 8 days in 20°C water.

2.2. Four-point bending tests: results and analysis



The adhesion operation is particularly important because it conditions the success of the strengthening. Sikadur 30 glue, which was used in our study, is widely employed on construction sites and gives good results.

Fig. 2 – Plate arrangement

The four-point tests [7] allowed a comparison of the behaviour of the prisms tested in the various environments. Analysis of the tests showed good reproducibility of the results, which are hence only given for one prism.

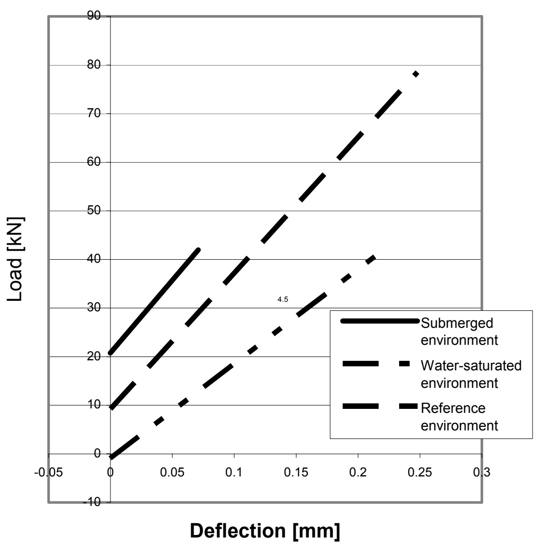


Figure 4 shows the load variations as a function of bending for the strengthened prisms in the various environments.

These curves allowed us to monitor the evolution of the behaviour of the prisms in various environments, and therefore to obtain Young's modulus for each strengthened prism.

The 28-day rupture loads recorded for the strengthened prisms were high:

- 73 kN in a reference environment;
- 45 kN in a water-saturated environment for cured prisms.

Fig. 4 – Load / bending curves in different environments

The mean rupture load of the non-strengthened prisms (control prism) was 15 kN. The gain was 356% in the reference environment and 215% in the water-saturated environment.

For the strengthened prisms, the fragile rupture of the concrete was associated with tensile rupture in the glue-plate bond in the reference environment. In the water-saturated and submerged environments, rupture occurred in the glue-concrete bond.

Table 3: Young's modulus of the prisms in the various environments

Environment	Young's modulus
Reference	27,952 MPa
Water-saturated	19,424 MPa
Submerged storage	29,688 MPa

We noted a difference in the rigidity of the respective curves, which corresponded to the modulus of elasticity values (Table 3).

For adhesion in the normal environment, Young's modulus was 27,952 MPa. This value diminished by nearly 30% in the water-saturated environment, in which we observed a reduction in the rigidity of the test specimen.

The loading gain provided by underside adhesion of the carbon plates was greater in the reference environment (356%) than in the water-saturated environment (215%). For the strengthened prisms in water-saturated environment, Young's modulus decrease by 30% (table 3). When this type of strengthening is used on a damp, trickle-free surface, a safety coefficient relative to this loss of elasticity must be applied. The process is therefore applicable to sewers dimensioned to include the relative humidity of the surfaces.

2.3. Single tensile shear tests

The purpose of these tests [9] was to determine the minimum characteristics of the concrete substrate and to verify the glue-substrate and glue-plate bond. The test highlighted the adhesion of the plate to the substrate. The two environments under study were compared to ascertain the efficiency of the glue.

For each environment, three tablets (50 mm diameter and 10 mm thickness disc) were adhered to the substrate and three to the plate. The tensile force is measured during these tests and the tear-off stress then calculated. The mean tear-off stress values are summarised in table 4.

Table 4 – 28-day shear stresses

Tear-off stress	Reference environment	Water-satur. environment
of tablets glued to support [MPa]	3.37	2.58
of tablets glued to plate [MPa]	3.48	1.68

In the reference environment, rupture occurred in the substrate and not in the glue between the tablet and concrete. The reference environment stress value corresponded to the calculate shear stress of the substrate (ft28 = 3.4 MPa). The glue therefore fully performed its role.

In the water-saturated environment, the rupture of tablets adhered directly to the concrete, occurred in the concrete. When the tablets were glued on the carbon plates, the rupture occurred in the plate carbon/concrete interface. The measured stress was lower than the concrete shear stress for the tablets glued on the plates, thus causing the glue-concrete bond to rupture.

The shear stress was 65% lower in the water-saturated environment than in the reference environment. These results confirmed that a coefficient must be applied to take account of adhesion in water-saturated environments, but also that a surface primer must be applied. However, the reference stress in sewerage systems was 1.5 MPa. Our results showed a stress slightly higher than the allowable maximum.

The tests were followed by finite-element modelling of these sewers. The constitutive laws of the materials deriving from the characterisation tests were refined [4].

3. Finite-element modelling

Modelling was performed using the URUS finite-element computation code [5]. This software allows monitoring of crack evolution to structural failure. Many conventional approaches using intensity factors k [9] and contour integrals J [10] have already been reported in the literature. We used methods for restituting energy G [11].

We modelled a reference ovoid section T180 (180 cm height) that was loaded with the equivalent of 2 metres high of silty backfill.

As the failure mechanism of the ovoid was known, the composite plates were fitted in the areas under greatest stress. Once the glue-plate complex was positioned on the concrete substrate, the calculation was continued until non-convergence of the iterative process. The results from this second modelling allowed us to obtain the strength gain and to observe whether stress redistribution occurred.

3.1. Control ovoid

The initial loading was equivalent to silty soil backfill of 2 metres in height. We incrementally increased the load until non-convergence of the iterative process. Failure occurred at the 28th incremental step, representing 2.8 times the initial loading and equivalent to 6 metres of backfill. The structural failure mechanism corresponded to the deformation mechanisms obtained during the performance of theoretical calculations based on the fundamental laws of concrete design [12]. The ovoid section failed in the keystone.

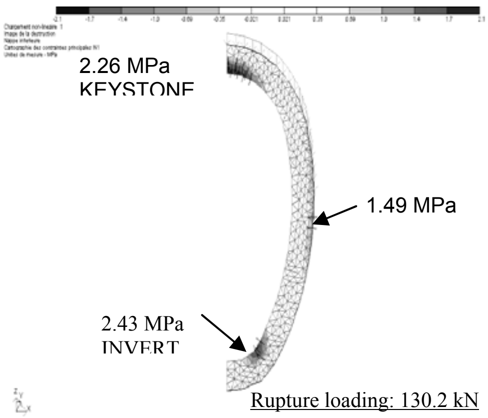


Fig. 6 – Failure mechanism of the non-strengthened ovoid

The mean value of the principal stress in the keystone was 2.26 MPa. The cracks were located on the intrados side of the keystone. In the middle of the walls, the mean value of the principal stress was 1.49 MPa. The tensioned area in this part of the structure was on the extrados side. The shear stress values did not indicate structural failure. However, some cracks were present in the tensioned area on the extrados of the structure. The mean value of the principal stress at the invert-wall junction was 2.43 MPa.

3.2. Carbon plate-strengthened ovoid

Before fitting the carbon plates, cracks should be treated and if necessary rendered leaktight.

Given the failure of the unstrengthened structure, the area in need of strengthening was the keystone. This area was optimised over a surface strengthened area of 0.75 m² per linear metre.

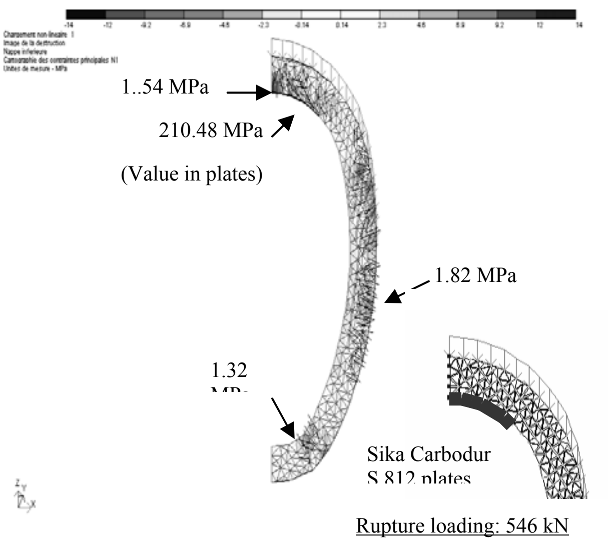


Fig. 7 – Failure mechanism of the carbon plate-strengthened ovoid

Structural failure occurred at the 42nd increment step, equivalent to 4.2 times the initial loading. Cracks spread through the structure from the intrados towards the extrados. The plates were not affected by the structural loading.

The structural failure mechanism is shown in Figure 7.

The cracks occurred mainly on the intrados of the walls. The shear stress in the structure was less than the allowable maximum. With an increase of 4.2 times the initial load, the stress in the keystone was 1.54 MPa, compared to 2.26 MPa for the control ovoid with its initial loading.

The plates therefore absorbed the forces in the keystone. The shear stress obtained in the plates was markedly lower than the allowable maximum. The keystone was therefore the most highly tensioned area of the structure.

The stresses in the glue remained well below allowable maximum values. The shear stress in the glue was 2.93 MPa. The limit of glue elasticity was defined by a maximum allowable stress of 31.87 MPa. In the strengthening plate, the mean shear stress was 210.48 MPa.

The findings of the present study prove conclusively that ovoids are strengthened by the adhesion of carbon plates

4. Conclusion

Non-linear computation enabled us to visualise the cracking areas and monitor their evolution to structural failure. In the case of vertical surcharge loading, structural strengthening achieves a considerable gain. Moreover, despite a higher loading, shear stresses in the sensitive areas were reduced. Therefore the strengthening plates absorbed the loadings, and the stresses were redistributed towards the middle of the walls on the extrados side. However, the increased stresses in the middle of the walls were not significant as they were transferred to the surrounding ground. In these repair conditions, selective renovation is a 55% less costly solution than the traditional complete renovation. Full-scale tests are currently in progress to validate this approach.

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