Interdependence between Structural Engineering and Construction Management
Edited by Ozevin, D., Ataei, H., Modares, M., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-6-2

SEMI-COMPOSITE STRUCTURES FOR SEWER RENOVATION

MASAAKI NAKANO[1], ZIHAI SHI[1], YUKARI NAKAMURA[1], YUKITOSHI IWASA[2], and KIMITAKA UJI[3]

[1]*Research and Development Centre, Nippon Koei Co., Ltd., Ibaraki, Japan*
[2]*Tokyo Sewerage Service Co., Ltd., Tokyo, Japan*
[3]*Dept of Civil and Environmental Engineering, Tokyo Metropolitan University, Tokyo, Japan*

In the composite pipe construction method defined in the Japan Sewage Works Association's Design and Construction Guidelines for Sewer Pipe Rehabilitation, a liner pipe is constructed inside an existing sewer and the annular space behind the liner is filled with cementitious grout under pressure to form a highly integrated structure. The Guidelines for sewer renovation in Japan define a composite pipe as a composite structure that requires complete integration between liner materials and an existing pipe. However, in general, owing to the refinement of the small and enclosed working space inside sewers and the significant extension of the pipe to be renovated, mechanical shear connectors are not used to rigidly connect a renovation layer with an existing pipe. To fully explore the advantages of the composite pipe method in sewer renovation while maintaining safe design, a semi-composite structure has been applied in the renovation design of aging sewers using nonlinear FEM analysis for more than 50 sewers (over a total length of 300 km), primarily in big cities in Japan. This paper focuses on the mechanics of the structure.

Keywords: Nonlinear FEM, No-tension interface, Limit state design, Damage indices, SPR method.

1 INTRODUCTION

The general practice of sewer renovation in Japan, from site survey and structural design to renovation construction, is subject to Design and Construction Guidelines for Sewer Pipe Rehabilitation stipulated by the Japan Sewage Works Association (2017). According to the Guidelines, a renovated sewer pipe must be structurally comparable with or superior to a newly constructed sewer pipe in terms of its load-carrying capacity, material and structural endurance, and hydraulic capacity.

In this provisional code, renovation methods are classified into two categories, i.e., the composite pipe method and independent (or stand-alone) pipe method. The concept of the composite pipe method is to construct a composite structure by rigidly attaching an inner lining, i.e., a renovation layer, to an existing pipe. The renovated sewer is expected to bear external loads using the combined resistance of the two structural components. On the contrary, in the independent pipe method, a new pipe is constructed inside an existing pipe, and the new pipe is designed to fully resist external forces without relying on the existing pipe.

The SPR method is one of the typical composite pipe renovation methods put into practical use in Japan (Figure 1). It involves the spiral formations of an inner lining by polyvinyl chloride profiles with steel reinforcement in existing pipes and the filling of the annular gap between a lining and a pipe with cementitious grout. The method can be implemented while water is running through a sewer. A pipe-manufacturing machine is developed to fit the shape of the pipe, and the method is applicable to all types of cross sections. The mortar is mixed with emulsion to increase bond strength, and different specifications are available to produce different levels of strength. The steel reinforcement of a specific shape can be installed in the profile (Figure 2).

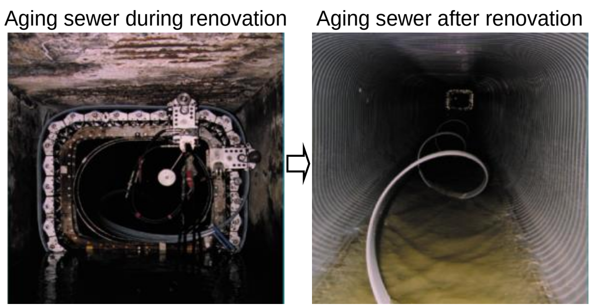


Figure 1. Sewer renovation by the SPR method.

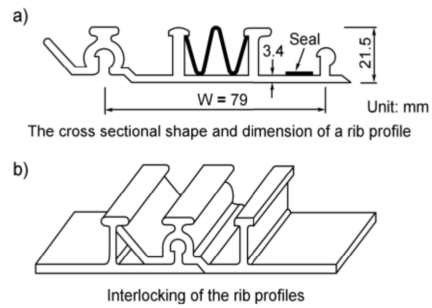


Figure 2. PVC rib profiles used in the SPR renovation method.

2 NO-TENSION INTERFACE MODELING AND THE SEMI-COMPOSITE STRUCTURE

Even though the Guidelines require a direct tension test to be performed on concrete-mortar test specimens to ensure no occurrence of interfacial debonding at the ultimate failure of test specimens, debonding has been reported during fracture tests at the interface of pipe specimens renovated by employing various pipe-reforming methods. Figure 3 shows two typical examples of fractured circular and box-culvert pipe specimens renovated using different pipe-reforming methods. In each case, the localized debonding of the interface between the original pipe and renovation layer has occurred at high loads. This type of interfacial debonding in renovated pipe specimens shows that the requirement for complete integration in the composite pipe method may not always be satisfied.

Numerical studies on these test specimens under the rigid bond condition at the interface showed that the maximum tensile stress could reach approximately 3.0 MPa or higher at peak load. Compared with the typical tensile strength of 2.0 MPa for various types of cementitious grout, debonding at the interface of a composite pipe appears to be inevitable at high loads. To fully explore the advantages of the composite pipe method in sewer renovation while maintaining safe design, a semi-composite structure is proposed for this method based on the following assumptions (Shi *et al.* 2016):

1) Perfect bond after construction: The complete integration of the original pipe and renovation layer is achieved at the completion of renovation construction.
2) No-tension interface: When tensile stress occurs at the interface under external loads, the perfect bond is replaced by free surface modeling to terminate stress transfer.
3) Perfect bond under compression: A perfect bond for the interface is assumed in the compression zones of the renovation layer. This allows for the continuous transfer of shear and compressive stresses between the original pipe and renovation layer.

The perfect integration of the original pipe and renovation layer in the compression zones maximizes the strength of the renovated pipe, and the free interface deformation of the structural components in the no-tension zones compromises the integration effect of a composite structure in these regions. This potential debonding of the interface in the tension zones of the renovation layer in an otherwise fully-integrated composite pipe leads to the unique semi-composite structure of the composite pipe method. No-tension interface modeling in numerical analysis is illustrated in Figure 4, where the interface is modeled using dummy elements and dual nodes with the same coordinates. The spring coefficients connecting the dual nodes are assumed to be infinite for the rigid bond condition. When tensile stress occurs, the spring connections in the vertical and horizontal directions are removed to allow for the free deformation of the interfaces.

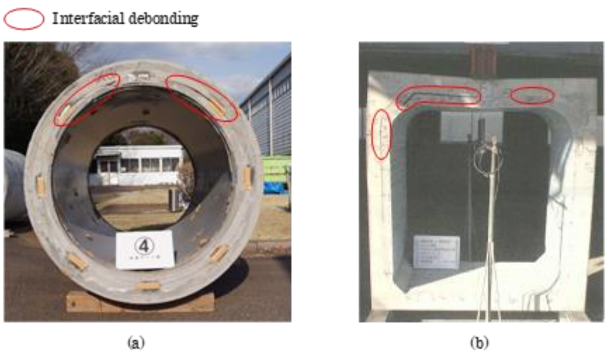


Figure 3. Interfacial debonding of renovated pipe specimens at failure loads.

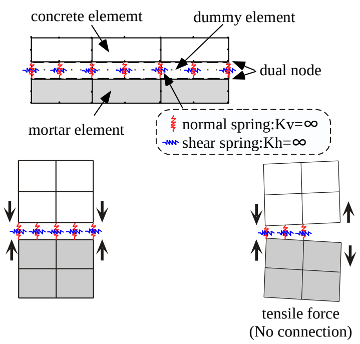


Figure 4. No-tension interface modeling in numerical analysis.

3 NUMERICAL ANALYSES OF FRACTURE IN RENOVATED PIPE SPECIMENS

3.1 Case Studied

For developing the SPR renovation method, a large number of fracture tests have been carried out on renovated pipe specimens to verify the effectiveness of the method in restoring the structural integrity of aging pipes (Nakano *et al.* 2013). Figure 5 shows a 1500 × 1500 mm rectangular pipe, which was selected from the fracture tests performed on renovated pipe specimens. Two cases are examined. One is the standard renovation of an original pipe with a standard doubly-reinforced cross section. The other is a double-layered pipe with no bond strength between the original pipe and renovation layer. This pipe is prepared by placing a thin film on the inner surface of the original pipe before renovation.

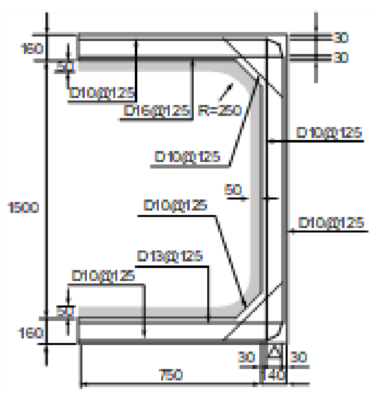


Figure 5. Structural dimensions and rebar arrangement of rectangular pipe.

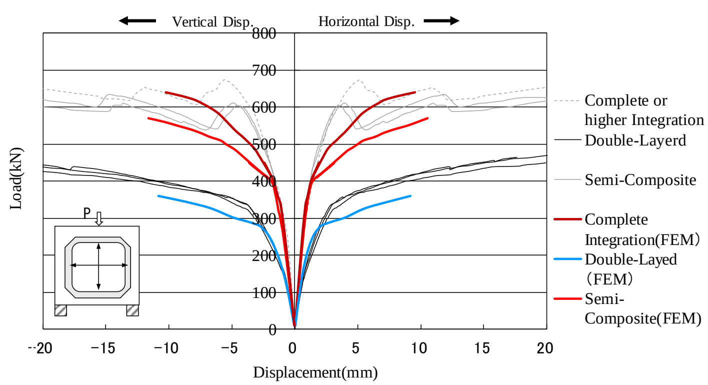


Figure 6. Numerical and test results.

Table 1 and Figure 6 show the results of the fracture tests. The maximum load of the double-layered pipe is approximately 30% smaller than that of the standard renovated pipe. This clearly shows that the bond behavior at the interface significantly affects the load carrying capacity of the renovated pipe. Even though composite pipes should not be modeled in actual design based on the assumption of perfect connection to the end of structural failure, the double-layered no-bond interface model clearly underestimates the load carrying capacity of the renovated pipe. The maximum load of one of the standard renovated pipes is higher than that of the other two specimens because the integration between the renovation materials and original pipe is higher for this pipe.

Table 1. Comparison between test and numerical results on load carrying capacity of rectangular pipe.

Cases		Maaximum Load(kN/m)			FEM/Test
		Test	**Test(Ave.)**	**FEM**	
Case1	Complete or higher	673.7	673.7	640	95%
Case2	Double-layered renovated	488.1	478.4	390	82%
		473.1			
		474			
Case3	Semi-composite	622.1	628.3	570	91%
		634.4			

3.2 Numerical Results

Numerical studies on these fracture tests are carried out in three different conditions at the interface using the active crack approach, in which all microscopic mechanical states (cracking, yielding, crack shear, and remaining stiffness of fractured materials) are integrated for macroscopic constitutive modeling (Maekawa *et al.* 2003). Case 1 is a renovated pipe under the rigid bond condition at the interface (complete integration), case 2 is a double-layered renovated pipe in which the transmission of shear stress is neglected from the beginning of loading, and case 3 is a semi-composite renovated pipe modeled with the no-tension interface model.

Figure 6 shows the numerical results of the load–displacement relations for cases 1 to 3. The test results of the load–displacement relations are also shown for comparison. The discrepancy between the numerical and test results is less than 18%, which is considered accurate in predicting the load-carrying capacity of reinforced concrete structures even though the adhesion strength and frictional resistance of the material in the actual test specimens are not considered in cases 2 and 3.

The damage indices of the second strain invariant of the deviatoric strain tensor are calculated based on the local strain at each integration point of the finite elements, as shown in Eq. (1) to Eq. (3). The scalar values are averaged over a certain region and used for studying the mechanics aspects of the semi-composite structure. Here, εx and εy are two-dimensional tensors, D is the averaged damage index, $\overline{D}$ is the local damage index ($\sqrt{J_2'}$), w(x) is the weight function according to the distance from the target integration point, and L is the averaged length (according to previous research, L = 150 mm). The damage indices of the general concrete material of the openings of bending cracks due to the yield of axial rebars or oblique cracks when the averaged region is set as 150 mm are evaluated by exceeding 0.0010 to 0.0015 (Saito *et al.* 2011) and (Tsuchiya *et al.* 2012).

$$\sqrt{J_2{}'} = \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \quad (1)$$

$$\bar{D} = \frac{\int_A D \cdot w(x) dA}{\int_A w(x) dA} \tag{2}$$

$$w(x) = \begin{cases} 1 - x/L & x \le L \\ 0 & x > L \end{cases} \tag{3}$$

In each case, the damage indices at the loads where vertical displacement sharply increases and at the maximum loads are shown in Figure 7 and Figure 8, respectively. Large deformation occurs when $\sqrt{J_2'}$ exceeds 0.001 at the top plate of the original pipe and outside the side wall at a haunch in the complete integration pipe (case 1) and double-layered pipe (case 2) and at the top plate close to the haunch in the semi-composite structure (case 3). As the shear stress at the interface is not transmitted from the beginning in case 2, the stresses at the top plate of the original pipe are higher and cracks are propagated because of its higher stiffness. In case 1, as the strain continuity at the cross section is maintained, the strains at the top plate in the renovated portion are high. On the contrary, the abrupt increase in the displacement in the semi-composite structure is at the same level as case 1, but the damage condition is different, and debonding occurs close to the haunch. At the maximum load in the complete integration pipe, the damage of the renovated portion is large based on the strain distribution in the midspan of the top plate. In the double-layered pipe, crack propagation in the original pipe is larger than that in the renovated portion. In the semi-composite structure, owing to the influence of the negative bending of the top plate close to the haunch, the damaged area is broader compared to the other two cases.

Load becomes the maximum when the averaged $\sqrt{J_2'}$ in the top plate and the side wall of the original pipe reaches approximately 0.004 and 0.003, respectively, for all cases. This shows that the effect of renovation appears in the suppression of the above two damage stages occurring in the original pipe.

Figure 9 shows the relationship between the vertical displacement and damage index ($\sqrt{J_2'}$) at the midspan of the top plate of the original pipe and the renovated portion for each case. The damage at the top plate of the original pipe is dominant in case 2, which is almost the same as the behaviors of the original pipe before renovation. In case 1, it can be seen that damage indices increase similarly in the renovated portion and original pipe portion, leading to fracture. In contrast, in case 3, the damage index of the original pipe increases in the early stage, but the damage index of the renovated portion increases rapidly when displacement exceeds 5 mm. Cracks occur even in the midspan of the top plate of the renovated portion in addition to the damage at the end of haunch due to negative bending.

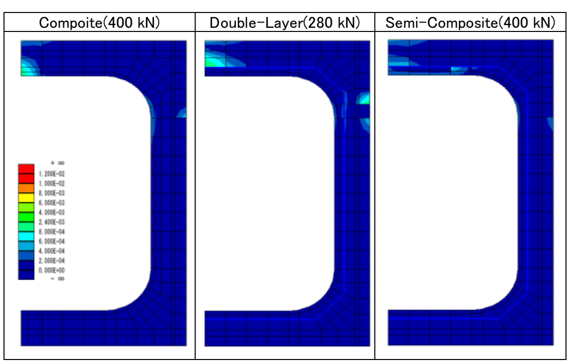


Figure 7. Distribution of damage index ($\sqrt{J_2'}$).

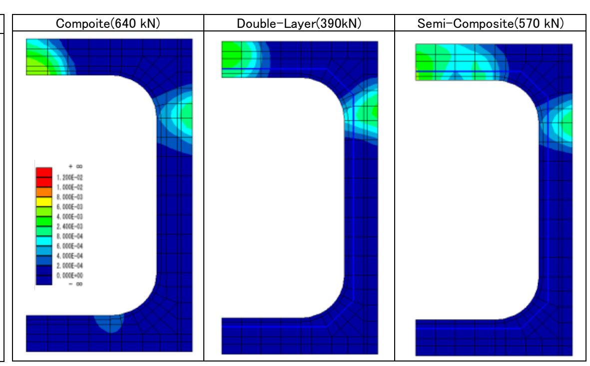
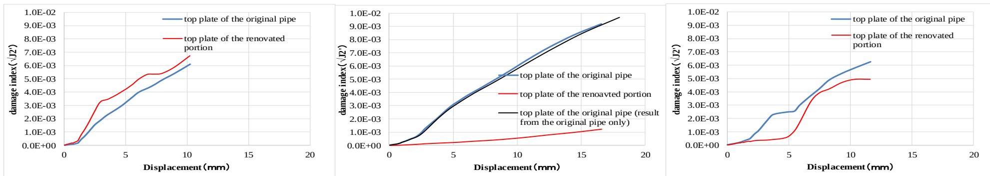


Figure 8. Distribution of damage index (averaged $\sqrt{J_2'}$).



Composite Double Layered Semi-Composite

Figure 9. Relation between the vertical displacement and damage index (averaged $\sqrt{J_2'}$).

In case 1, ideal reinforcement is possible where the renovated portion and original pipe portion resist external force. However, in case 2, as the original pipe part resists external force with its normal renovation thickness, the renovation effect is not fully demonstrated. On the contrary, in case 3, the boundary condition changes depending on the stage of deformation or damage because debonding occurs in the portion where the tensile stress occurs at the interface and the degrees of resistance between the original pipe and renovated portion change.

4 CONCLUSIONS

Based on the results of the numerical analysis, it can be concluded that the no-tension interface model and semi-composite structure combined with the fracture-mechanics-based modeling theories accurately predict the maximum loads of composite sewer pipes. By utilizing the damage indices of the second strain invariant of the deviatoric strain tensor, the characteristics and effectiveness of the semi-composite structure are discussed and compared with the renovated pipe under the rigid bond condition and the double-layered pipe at the concrete-mortar interface.

The no-tension interface model is a conservative modeling approach for evaluating the bonding strength of a composite pipe based on safe-design consideration. Even though it may not reflect the actual debonding process in a renovated pipe under loading, the abovementioned accuracy assessment indicates that the final semi-composite structure agreed reasonably well with the actual structural state of a test specimen at its maximum load.

Acknowledgments

The test data were provided by Sekisui Chemical Co., Ltd. and Adachi Construction and Industry Co., Ltd. Their contributions to this study are sincerely acknowledged.

References

Japan Sewage Works Association, Design and Construction Guidelines for Sewer Pipe Rehabilitation, Tokyo, 2017.

Maekawa, K., Pimanmas, A., and Okamura, H., *Nonlinear Mechanics of Reinforced Concrete*, CRC Press, London, 2003.

Nakano, M., Shi, Z., Shi, Z., Nakamura, Y., Nakamura, Y., Takahashi, Y., and Haibara., T., Renovation Design of Aging RC Sewers as Semi-Composite Structures Based on Non-Linear Response Analysis, *VIII International Conference on Fracture Mechanics of Concrete and Concrete Structures,* Van Mier, J. G. M., Ruiz, G., Andrade, C. Yu, R. C., and Zhang, X. X. (eds.), 2013.

Saito, S., Maki, T., Tsuchiya, S., and Watanabe, T., Damage Assessment of Beams by Nonlinear Finite Element Analysis, *Journal of JSCE, Materials and Concrete Structures*, 67(2), 166-180, April, 2011.

Shi, Z., Nakano, M., and Takahashi, Y., *Structural Analysis and Renovation Design of Ageing Sewers: Design Theories and Case Studies*, De Gruyter Open, 2016.

Tsuchiya, S., Maki, T., Saito, S., Watanabe, T., and Maekawa, K., Damage Assessment and Load-Carrying Capacity of RC Planar Members by Nonlinear Finite Element Analysis, *Journal of Materials and Concrete Structures*, 68(3), 209-224, September, 2012.