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Applicability and accuracy of structural performance verification methods for composite renovated pipes

Masayuki ISHII[1*], Tsuguhiro NONAKA[1], Mitsuhiko WATANABE[2] and Takayoshi SUZUKI[2]

[1]*Shimane University, Japan*
[2]*Sekisui Chemical Co., LTD, Japan*
**1060, Nishikawatsu, Matsue, Shimane, 690-8504, ici@life.shimane-u.ac.jp*

ABSTRACT

Pipe system for sewage, irrigation and water supply is one of the most important infrastructures in both urban and local areas. Since pipes have been used for long period, some of them are so damaged that proper treatment is urgently needed. Renovation methods for pipes are developed to renovate existing pipes without excavation. Composite pipes with host pipes and renovating members have mechanical strength and durability, which enables extension of their service lifetime. However, the design procedure of this kind of renovated structure is not determined completely. This paper describes a method to evaluate structural performance using frame analyses, determination of cracking load, and evaluation of ultimate load. The obtained results are compared with results of numerical fracture analyses and structural experiments, and their accuracy is verified.

Keywords. Composite renovated pipes, Frame analysis, Cracking, Ultimate limit state, Performance verification

INTRODUCTION

Renovation of pipes has become one of the most important methods to extend service lifetime of sewage pipes and other kinds of pipelines. Many construction methods have already developed using different materials, as well as different designing concepts and procedures. This difference sometimes causes difficulties to compare different renovation methods and to choose the most suitable methods for a specific site or case. To compare renovation methods fairly, the common designing and evaluating procedure is essential.

Authors have been applied numerical fracture analyses to composite renovated pipes and examined the accuracy of the results. This kind of analysis is being proven to have good accuracy, but is not yet commonly used. This paper aims to develop common methods to evaluate structural performance of renovated pipes, especially for renovated composite pipes under internal water pressure. A method with frame analysis, cracking determination, and ultimate strength evaluation is investigated and its accuracy is discussed comparing with the result of numerical fracture analyses and structural experiments.

COMPOSITE PIPE BY LINING WITH SPIRALLY-WOUND PIPES

Lining with spirally wound pipes is a kind of methods to renovate a pipe as a composite pipe. In this method, an inner pipe is formed inside the host pipe by winding a strip of plastics or other methods. After making the inner pipe, the annular space between the host and inner pipes is filled with filling mortar, to make a composite pipe with the host pipe and renovation member. Some kinds of these methods can be applied to box culverts and horseshoe-shaped tunnels, other than circular pipes.

Figure 1 shows an example of construction process of SPR Method, a kind of lining with spirally wound pipes. Surface material is fed from a reel set on the ground to the winding machine located inside the host pipe. The surface material (profile, hereafter) continuously interlocks to form a spirally-wound pipe whose cross sectional shape is similar to the host pipe. By filling the annular space with filling mortar, a composite pipe is formed.

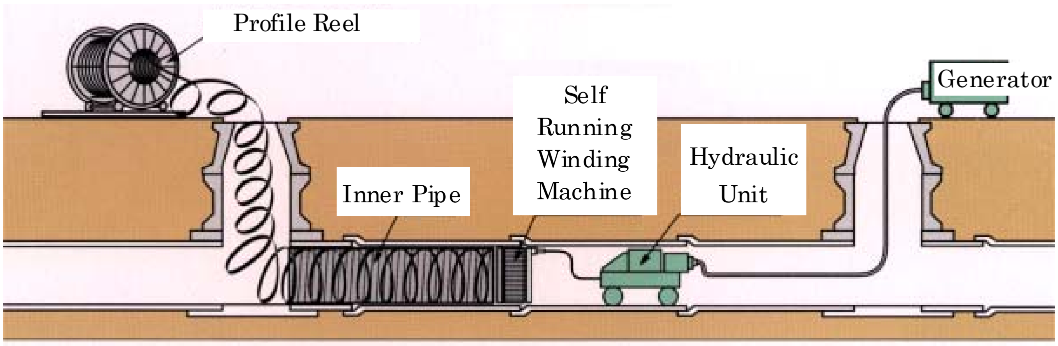
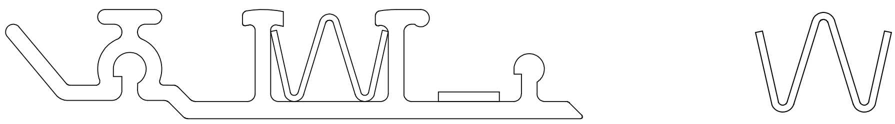


Figure 1. Construction of lining with spirally-wound pipes

Filling mortar contains polymer and has relatively large strength in tensile, but its tensile strength is not usually enough to bear bending moment by external earth pressure or axial tensile force by internal water pressure. Therefore, many of composite pipe renovation methods use tensile reinforcement and an example of surface material used in SPR Method is shown in Figure 2. Profile possesses its steel reinforcement (profile reinforcement, hereafter) and it can be considered as a kind of steel reinforcement in structural evaluation.



Profile (with “W” Shape Steel Reinforcement Material)   Steel Reinforcement

Figure 2. Profile with steel reinforcement

STRUCTURAL MODELLING WITH FRAME ANALYSIS

To evaluate the structural performance of renovated pipes, their composite features must be considered throughout the analyses. The characteristics of materials used for renovation members, as well as materials of host pipes, are necessary. The kinds of physical properties to be tested depend upon the kinds of analyses, so it is important to determine the types of analyses prior to the material tests. For frame analysis, compressive strength, tensile strength and elastic modulus are essential. Evaluation of ultimate strength does not need additional material properties, but numerical fracture analysis requires fracture energy as its essential material property.

Frame analysis is a kind of elastic structural analyses. Structural members are divided into axial elements in which material and structural properties are usually taken as constant. By applying supports and loads to modelled structure, bending moment, axial force, and share force are obtained for each element. To apply frame analyses to composite structures such as composite renovated pipes, composite structural properties are required.

Figure 3 shows a typical cross section of a composite renovated pipe. It consists of an RC section of host pipe and a renovating member. In this example, three kinds of material are used in the renovating member, profile, filling mortar, and profile reinforcement. Since the elastic modulus of profile is quite smaller than other materials, profile can be ignored in the calculations of composite structural properties.

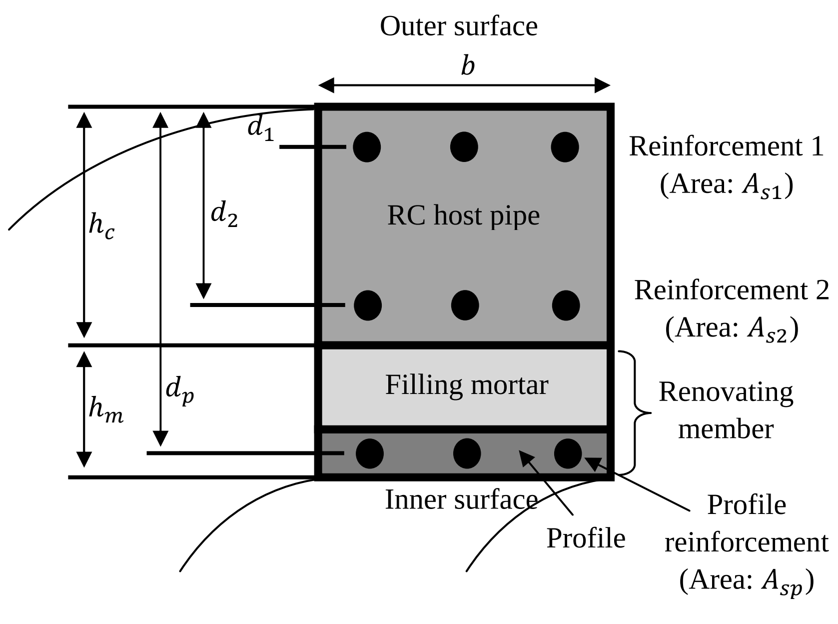


Figure 3. Cross section of renovated composite pipe

Composite structural properties required to frame analyses are composite elastic modulus E and composite bending stiffness around the centroid axis, EI. They can be obtained as:

$$E = \frac{h_c b E_c + h_m b E_m + A_{s1} E_s + A_{s2} E_s + A_{sp} E_{sp}}{h_c b + h_m b + \left(A_{s1} + A_{s2} + A_{sp}\right)} \quad (1)$$

$$EI = E_c b h_c \left(\frac{1}{3} h_c^2 - h_c y_0 + y_0^2 \right) + E_m b h_m \left\{ \frac{1}{3} h_m^2 + h_m (h_c - y_0) + (h_c - y_0)^2 \right\} + E_s \left\{ A_{s1} (d_1 - y_0)^2 + A_{s2} (d_2 - y_0)^2 \right\} + E_{sp} A_{sp} (d_p - y_0)^2 \quad (2)$$

$$y_0 = \frac{\frac{1}{2} E_c b h_c^2 + E_m b h_m \left(\frac{1}{2} h_m + h_c \right) + E_s (A_{s1} d_1 + A_{s2} d_2) + E_{sp} A_{sp} d_p}{E_c b h_c + E_m b h_m + E_s (A_{s1} + A_{s2}) + E_{sp} A_{sp}} \quad (3)$$

where E_c, E_m, E_s, E_{sp} are elastic moduli of concrete in host pipe, filling mortar, host pipe reinforcement, and profile reinforcement, and y_0 is the position of the centroid axis from the outer surface.

In some kinds of renovating method, the center of renovating member is eccentrically placed with the center of host pipes, as shown in Figure 4. This type of renovation can be called as eccentric renovation, and bearing capacity of eccentrically renovated pipes to internal water pressure is smaller than concentrically renovated pipes. The construction of concentric renovation needs supporting works to fix the inner pipe during the filling, so eccentric renovations are sometimes used to omit the supporting works. Since the thickness of filling mortar of eccentrically renovated pipes differs between the upper and lower portions, the composite structural properties also differ. Analytical methods for circular structures assuming the constant thickness cannot be applied to eccentrically renovated pipes, so frame analyses must be introduced as a common calculation method for various kinds of renovated pipes.

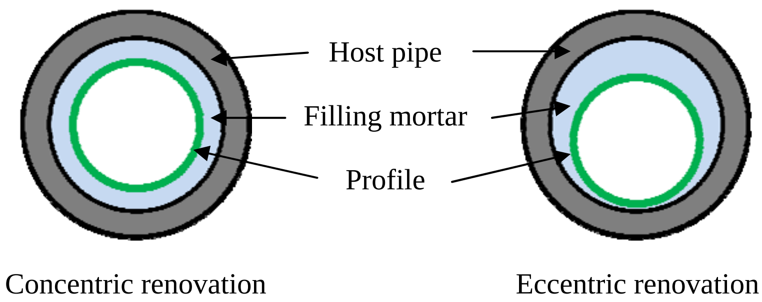


Figure 4. Concentric and eccentric renovations

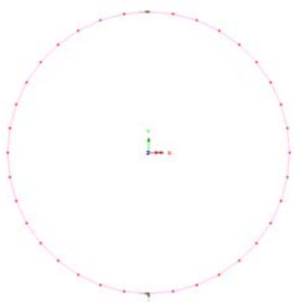


Figure 5. Frame model for circular pipe

Figure 5 shows an example of a frame model of a renovated circular pipe. Following the design standard by *Japanese Ministry of Agriculture, Forestry and Fisheries*, a circular pipe is modelled by 36-sided regular polygon with 36 axial elements. In the model for concentrically renovated pipes, every element has the identical structural properties. For eccentrically renovated cases, structural properties differ between elements and must be determined according to the thickness of filling mortar at every element.

Many of irrigation pipelines are subjected to internal water pressure, as well as external earth pressure. Since horizontal earth pressure acts as a safe load against internal pressure, it is usually ignored in structural analyses for buried pipelines. Moreover, vertical earth pressure is modelled as line loads concentrating to the top and bottom of circular pipes. Methods of structural analysis have to evaluate the combination effects of these two kinds of loads.

DETERMINATION OF CRACKING LOAD

Water-tightness is an essential performance required to pipelines. In design of pipelines, cracking load as their service limit state is quite important, especially for pressurized pipelines. Maximum tensile stress for every axial element can be calculated from axial force and bending moment. Cracking load for each element can be calculated as follows:

$$L_c = L_a \times \frac{f_t}{\sigma_a} \quad (4)$$

where L_c is cracking load, L_a is (arbitrarily) assumed load in the frame analysis, σ_a is calculated tensile stress under the assumed load, and f_t is tensile strength of material used on the tensile side. By comparing cracking loads of elements and choosing the minimum one, the initial cracking load of the pipe can be obtained.

The assumed load can be external line load, internal water pressure, or their combinations. In combined load cases, cracking external load and internal water pressure becomes smaller than solely loaded cases, and they differ according to the ratio of external and internal loads. Cracking combined loads must be calculated for different combination ratios.

Theoretically, in cases with external load only and combined loads, the maximum tensile stress is generated on the inner surface at the top and bottom of the pipe. However, composite renovated pipes have different materials on their inner and outer sides, and some construction methods use filling mortar whose tensile strength is larger than that of concrete in the host pipe. In these cases, initial cracking may occur on the outside of the lateral ends and the initial cracking load becomes large.

EVALUATION OF ULTIMATE LOAD

For evaluation of the ultimate load, ultimate strength theory is used together with elastic structural analysis. Section forces under estimated loads are calculated by elastic analyses, and the results are compared to corresponding ultimate strengths. Partial safety factors are usually introduced to achieve necessary margin of safety. In the ultimate state, some portions of the structure enters plastic region, in which material and structural behaviours does not match with the behaviours assumed in elastic analyses. However, the maximum section forces in the actual ultimate state is smaller than those calculated with elastic analyses, so elastic analyses are usually used in evaluations of the ultimate load, as methods for safe side results.

Standard Specifications for Concrete Structures published by *Japan Society of Civil Engineers* proposes a process of evaluation for structural safety under ultimate conditions. It can evaluate bending strength under axial load, as well as shear strength under axial load and bending moment. However, to apply this method to composite renovated pipes, they must be modified to consider the renovating member.

Since the renovating member may be on the tensile side or on the compressive side of bending, an evaluation process must be developed for each case. In pipelines, axial compression force in cross section cannot be large, so neutral axis in the ultimate state stands near the compressive surface. Therefore, filling mortar is under tensile stress and its tensile strength should be ignored following the common practice in concrete engineering. Profile reinforcement is only to be considered in renovating member, and the evaluation process for composite renovated pipes is identical to the process for the beams with two layered tensile reinforcement. For the case with renovation member on the compressive side, the material on the compressive surface is filling mortar, so its compressive strength is to be used for the evaluation of bending strength. Detailed process and formulae for evaluation of the ultimate load are to be referred *Standard Specifications for Concrete Structures*.

RESULT OF ANALYSES AND EXPERIMENTS

Application to renovated circular pipe. To verify the accuracy of these methods, the results of analyses are compared with the result of another kind of analysis and structural experiments. The details of investigated structure are shown in Figure 6, and material properties in Table 1. Some of material properties are obtained by estimation formulae proposed in *Standard Specifications for Concrete Structure*. This is a concentrically renovated circular pipe and all of 36 axial elements in frame analysis have the identical structural properties, which are also shown in the Table 1.

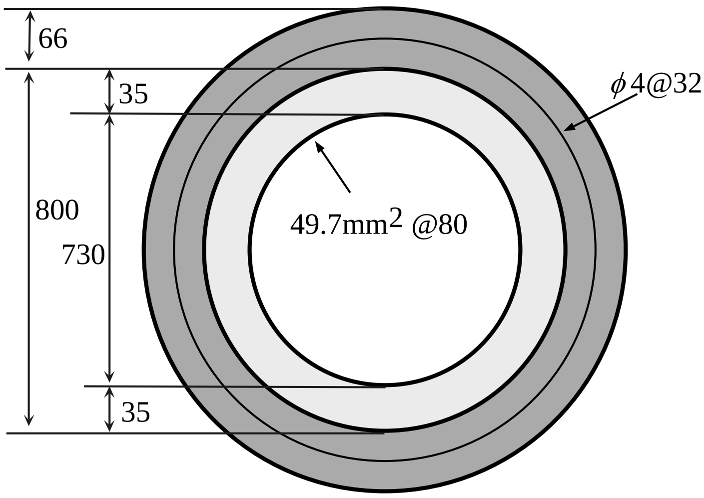


Figure 6. Dimensions of renovated circular pipe

Table 1. Material and structural properties of renovated circular pipe

Concrete and filling mortar

Material	Compressive strength	Tensile strength	Elastic modulus
Concrete	55.8MPa	3.36MPa	34.2GPa*
Filling mortar	69.8MPa	5.97MPa	24.9GPa

Reinforcement

Material	Yield strength	Elastic modulus
Host pipe reinforcement	688MPa	200GPa*
Profile reinforcement	205MPa	165GPa

Structural properties of axial elements

Composite elastic modulus	Composite bending stiffness
32.8GPa	2.73MNm^2

*: Estimated figures

External linear load and internal water pressure causing the initial cracking is calculated and compared with the result of numerical fracture analyses and experiments. Basically, the initial cracking is determined visually in experiments, but it is verified with the result of load-strain curve. No partial safety factors are introduced in the calculation of ultimate loads, so obtained results can be compared with results by other methods which do not consider safety margin. As shown in Table 2, both cracking and ultimate loads calculated by proposed method are consistent with the result by numerical fracture analyses and structural experiments.

Table 2. Cracking and ultimate loads for renovated circular pipe

External line load

Type of load	Proposed method	Numerical fracture analysis	Experiment
Cracking	78kN/m	72kN/m	80kN/m
Ultimate	131kN/m	143kN/m	144kN/m

Internal water pressure

Type of load	Proposed method	Numerical fracture analysis	Experiment
Cracking	0.95MPa	0.85MPa	----------
Ultimate	1.10MPa	0.93MPa	----------

Under internal water pressure, compressive stress is not generated in any materials, so only reinforcements are to be considered throughout the analyses. Therefore, the ultimate internal water pressure is determined as the pressure which causes yields on all of host pipe reinforcement and profile reinforcement. Both cracking and ultimate pressures is consistent with the results by numerical fracture analyses which have been proven to be accurate.

Application to renovated box culvert. This method is also applied to a renovated box culvert. As shown in Figure 7, the upper slab of the host pipe does not have its outer reinforcement, and an eccentric renovation is used to compensate it. This model structure is subjected to an internal water pressure test, and cracking pressure is obtained. Properties of the materials and structure are shown in Table 3.

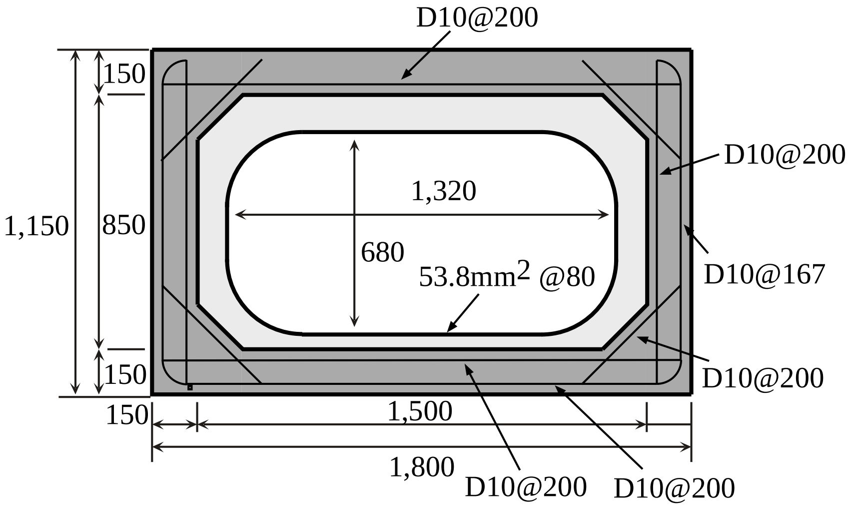


Figure 7. Dimensions of renovated box culvert

Table 3. Material and structural properties of renovated box culvert

Concrete and filling mortar

Material	Compressive strength	Tensile strength	Elastic modulus
Concrete	40.5MPa	2.71MPa*	31.1GPa*
Filling mortar	41.7MPa	3.72MPa	4.31GPa

Reinforcement

Material	Yield strength	Elastic modulus
Host pipe reinforcement	295MPa*	200GPa*
Profile reinforcement	205MPa	165GPa

Structural properties of axial elements

Member	Composite elastic modulus	Composite bending stiffness
Upper slab	19.8GPa	22.2MNm^2
Sidewall	22.2GPa	16.8MNm^2
Lower slab	26.2GPa	12.0MN m^2

*: Estimated figures

This structure is modelled as a rectangular frame model and every side is divided into four axial elements. Similarly to the experiment, internal water pressure is applied to the model, and cracking and ultimate pressures obtained by three methods as shown in Table 4. In rectangular pipe under internal water pressure, the maximum tensile force is observed in shorter sides, and the maximum bending moment at the midspans of the longer sides. The initial cracking occurs in the thin lower slab, but the ultimate state occurs in the upper slab whose effective depth is smaller. In this case, the effect of large bending moment is larger than the effect of large tensile force.

The results by proposed method almost match the results of numerical fracture analyses, but cracking pressures by them are quite smaller than that of the experiment. As shown in Figure 8, the model structure is strongly supported to keep water-tightness during the test, and it prevented deformation and cracking of the specimen, leading large cracking pressure. Since the accuracy of numerical fracture analyses is already confirmed, the proposed method can be concluded to be applicable to renovated box culverts, as well as to eccentric renovations.

Table 4. Cracking and ultimate loads for renovated box culvert

Internal water pressure

Type of load	Proposed method	Numerical fracture analysis	Experiment
Cracking	0.12MPa (Lower slab)	0.12MPa (Lower slab)	0.20MPa (Lower slab)
Ultimate	0.26MPa (Upper slab)	0.21MPa (Upper slab)	-----------

Figure 8. Supporting members to keep water tightness

CONCLUSIONS

To evaluate structural performance of composite renovated pipes, a method with frame analysis, cracking load determination, and ultimate strength theory is developed and its accuracy is verified. The results obtained by the proposed methods are consistent with the results by numerical fracture analyses and structural experiments. It is also proven that this method is applicable to concentrically renovated circular pipes, as well as eccentrically renovated box culverts. Though this method is applied to SPR Method in this study, but it is not based on special features to SPR composite pipes but common features to composite renovated pipes. The proposed method aimed and achieved to be a common method of structural performance evaluation applicable to any types of composite renovation method.

Since partial safety factors to achieve appropriate safety margin to ultimate strength are already determined, appropriate safety margin for composite renovated pipes can be obtained by introducing them. However, the safety factor for cracking is not clear and should be determined.

In the cases with renovated circular pipes, the host pipe is on the compressive side of the bending moment causing the bending fracture. The profile reinforcement is only to be considered in the renovating member and the common process for evaluations of bending strength can be applied. However, in the cases with renovated box culverts, filling mortar can be on the compressive side of bending. In the calculations of this study the equivalent stress block is also applied to the filling mortar. The result of material tests for filling mortar shows a softening nature at large strain level, similarly to concrete. However, the applicability of the equivalent stress block is not clear, and should be investigated through material and structural tests, to obtain accurate ultimate loads for renovated box culverts.

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