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RENOVATION DESIGN OF AGING RC SEWERS AS SEMI-COMPOSITE STRUCTURES BASED ON NON-LINEAR RESPONSE ANALYSIS

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Abstract: This paper discusses aging pipes renovated by the SPR (Sewage Pipe Renewal) method, a typical composite pipe renovation method. The structural model for this type of composite pipes as a semi-composite structure is explained, and the features of design procedures based on the limit state theories are introduced.

1 INTRODUCTION

More than 100 years have passed since the construction of the Kanda sewer system in 1884. Numerous sewer pipes, in service for more than 50 years of the legal design service life, have been aging in urban areas. Though most of the pipes are still serving their functions, many have sustained various degrees of damage due to long-term loading, material deterioration, and chemical corrosion with hydrogen sulfide. Needs have increased greatly for renovation of aging sewers by methods other than cut-and-cover because of the influence to road traffic, to the many buried utility structures in the pipe's vicinity, and cost performance. The Tokyo metropolitan government has been systematically renovating sewer pipes for the past 15 years among its huge sewerage system that extends to approximately 16000 km in total length. For aging pipes of medium to large diameter in particular, renovation methods based on a concept of composite pipe were developed in which renovation materials were attached to the inner surface of existing pipes for retrofit counting on the remaining strength of the existing pipes. This paper discusses the pipes renovated by the SPR (Sewage Pipe Renewal) method, a typical composite pipe renovation method. The structural model for this type of composite pipes as a semi-composite structure is explained, and the features of design support software developed based on the limit state design theories are introduced.

2 COMPOSITE PIPES IN SEWER PIPE RENOVATION

2.1 Characteristics of composite pipes

The composite pipe renovation method involves no cut-and-cover. Aging existing pipes are retrofitted counting on their remaining strength by attaching renovation materials to the inner surface of existing pipes to form so-called composite pipes. This type of retrofit method is expected to secure discharge capacity and prolong the service lives of existing structures. The bond between renovation materials and existing pipes are increased by using polymer cement, and the load carrying capacity can be enhanced further by inserting steel reinforcement in the renovation layers. In general, due to the refinement of the small, enclosed working space inside the sewer and the great extension of the pipe to be renovated, mechanical shear connectors are not used to rigidly connect the renovation layer with the existing pipe. Hence, bond splitting may occur at the interface during deformation of the composite pipe under the external loading. To reflect the reality of bond strength in a composite pipe, structural analysis of the pipe is based on a no-tension interface model to prevent the transfer of tensile stress at the interface. At present, five renovation methods that employ the composite pipe concept have been put into practical use in Japan. As renovation materials, spirally formed inner linings by polyvinyl chloride profile, combinations of steel ring and high-density polyethylene member, and polyvinyl chloride segments are among those that are frequently used.

2.2 Outline of SPR method

One of the typical composite pipe renovation methods put into practical use in Japan is the SPR method (Fig.1). This method involves spiral formations of the inner lining by polyvinyl chloride profiles with steel reinforcement in existing pipes and the filling of the annular gap between the lining and the pipe with resin-type mortar. The method can be implemented while water is running through the sewer. A pipe manufacturing machine is developed so as to fit the shape of the pipe, and the method is basically 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. Steel reinforcement of special shape can be installed in the profile (Fig. 2).

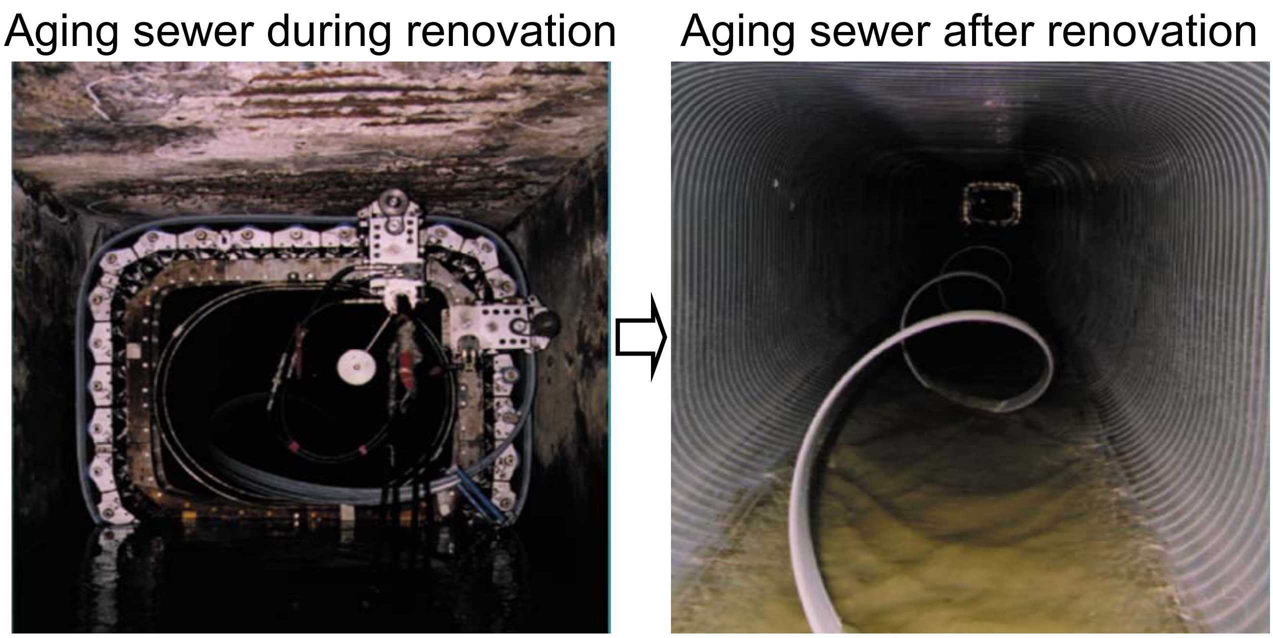

Figure 1: Sewer renovation by the SPR renovation method

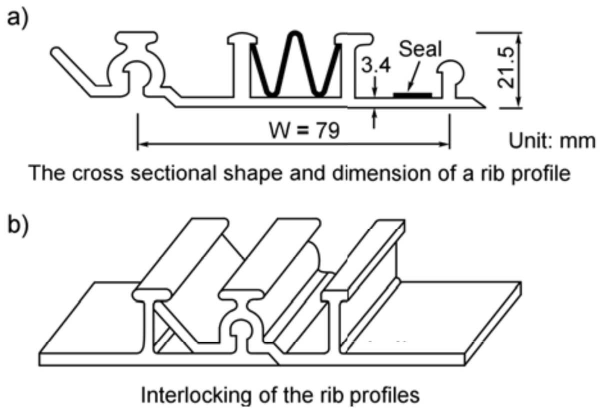

Figure 2: An example of the PVC rib profiles used in the SPR renovation method

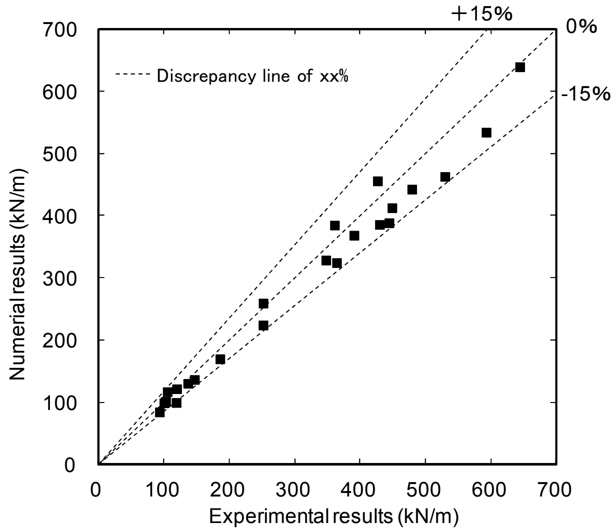

Figure 3: Discrepancy diagram between the results of numerical analysis and experiments

3 STRUCTURAL ANALYSIS OF COMPOSITE PIPE

3.1 Fracture tests on composite pipe specimens

In carrying out sewer renovation, it is required that the load-carrying capacity of the renovated pipe must be equal to or higher than that of the existing pipe at the time of its construction [1]. In developing the SPR renovation method a large number of fracture tests on renovated pipe specimens have been carried out to verify the effectiveness of the method in restoring the structural integrity of the aging pipe. These specimens included both circular pipes and rectangular pipes of different sizes and aspect ratios. To simulate aging pipes loading tests were carried out on newly-manufactured pipes with various artificial damages made to them, such as the missing of concrete cover, loss of rebar and cracking of concrete [2]. For comparison purposes, double-layered pipe specimens were also produced by attaching thin films to the original pipes before renovation. Besides the specimens with a uniform thickness of the renovation layer, specimens with a different thickness of the renovation layer at the top and bottom were also prepared to reflect the reality of in situ construction. The major test cases and results are listed in Table 1. The maximum loads in the table represent the means of results for three specimens in each case.

Though concrete structures are frequently studied using frame models, this simple method may not yet be applicable to composite pipes mainly because of the difficulty in modeling interface behavior. Finite element modeling provides an easier approach. In structural analysis of composite pipes, the state of deterioration such as the loss of concrete cover due to cracking and the corrosion of reinforcing bars was reflected in the member thickness and the cross sectional area of reinforcement in an FE model. Materials in a composite pipe are composed of concrete, rebar, mortar and the steel reinforcement inside the plastic profile. Cracking of concrete and mortar is analyzed using the smeared crack model, and the plastic behavior in compression areas is studied based on the Drucker-Prager yield criterion [3-4]. Reinforcing bars in concrete and steel reinforcement in the profile are incorporated into two-dimensional elements as one-dimensional rods of elastic-plastic materials. Numerical analyses of aforementioned fracture tests reproduced maximum loads that compared well with the test results with a precision of plus or minus 15% (Fig. 3).

3.2 No-tension interface model for composite pipes

Figure 4 shows load-displacement

Table 1: Cases and results of fracture tests on original and renovated pipe specimens

Test case	Type of pipe	State of damage in original pipe	Type of specimen	Maximum load (kN/m) Average of three tests
1	Rectangular cross section (1500mm×1500mm)	None (Standard RC cross section)	Original pipe	363.43
2			Composite pipe	643.40
3			Non-composite pipe (Double-layered structure)	478.40
4		Loss of cover concrete	Original pipe	251.13
5			Composite pipe	592.10
6		Loss of inner rebar and cover concrete	Original pipe	104.50
7			Composite pipe	360.20
8		None (Standard RC cross section)	Original pipe	390.00
9			Composite pipe (Thin-layer renovation)	425.93
10		Failed pipe (Fractured ceiling and hunches)	Composite pipte (Thin-layer renovation)	448.10
11	Rectangular cross section (2500mm×2500mm)	None (Standard RC cross section)	Original pipe	429.00
12		Loss of inner rebar and cover concrete	Original pipe	185.00
13			Non-composite pipe (Double-layered structure)	443.50
14	Rectangular cross section (3500mm×2500mm)	None (Standard RC cross section)	Original pipe	529.00
15		Loss of inner rebar and cover concrete	Original pipe	251.00
16			Non composite pipe (Double-layered structure)	347.00
17	Circular cross section (φ1000mm)	None (Standard RC cross section)	Original pipe	92.57
18			Composite pipe	146.00
19			Composite pipe (Non-reinforced profile)	99.47
20			Composite pipe (Bottom-minimum renovation)	118.90
21			Non-composite pipe (Double-layered structure)	118.07
22	Circular cross section (φ1100mm)	None (Standard RC cross section)	Original pipe	101.90
23		Failed pipe (Quadri-fracture)	Composite pipe (Thin-layer renovation)	135.97

relationships obtained in fracture tests using a box culvert of rectangular 1500-mm cross section and a circular pipe of 1000-mm-diameter of composite and double-layered types. As seen from these results, the initial rigidity is much lower in the double-layered type than in the composite type. The maximum load of the former is approximately 74% of

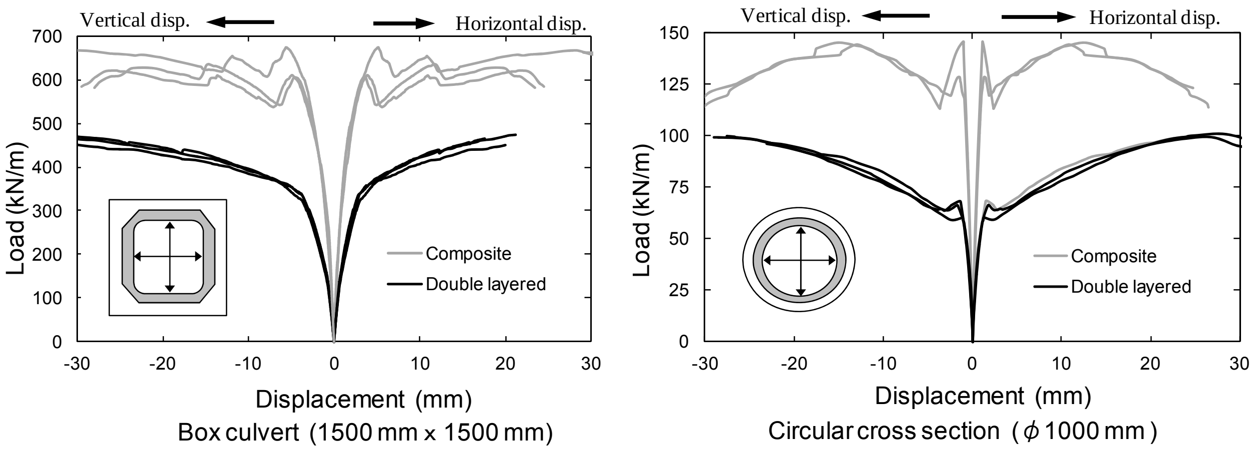

Figure 4: Load-displacement relations of capacity tests on composite and double-layered test specimens

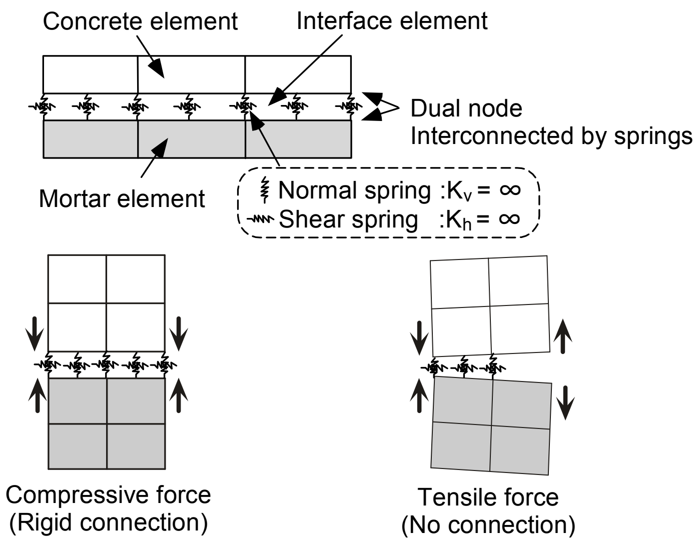

Figure 5: Interface element and modeling concept

that in the composite pipe for the box culvert, and 68% for the circular pipe. This shows clearly that the bond behavior at the interface greatly affected the deformation and load carrying capacity of the renovated pipe. Though composite pipes should not be modeled in actual design 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 authors, based on the above analysis and reasoning, employed a no-tension model at the interface for the bond behavior of composite pipes. In the no-tension model, both normal stress and shear stress are transmitted when compression acts at the interface, but the transmission of normal stress and shear stress is terminated when tension occurs. The limit of shear stress in compression at the interface is set to the value obtained by multiplying the compression by the coefficient of friction of concrete. In the FE model, an interface model of zero thickness can be easily incorporated into the interface between the existing concrete member and renovation member by employing dual nodes and spring connections, as indicated in Fig. 5.

RESPONSE ANALYSIS		
LOAD CONDITION		RESULTS OF ANALYSIS
Loading stage 1:	Dead load + Soil pressure	None
Loading stage 2: Failure analysis by incremental live loads Note: λ = Load increment coefficient of live load	Design load: $P_d = \lambda P_{ld}$ P_{ld}: Live load λ: 1.0	To calculate the cross sectional forces from the stress states: ⇒ **Design response value: S_d (= $\gamma_a \gamma_f V$; = $\gamma_a \gamma_f M$)** V, M: Shear and moment forces obtained from the response analysis under the design loads γ_a, γ_f: Structural analysis factor and load factor
	Crack initiation load: $P_{lc} = \lambda_c P_{ld}$ λ_c: Load increment coefficient at crack initiation	To obtain **the load factor for crack initiation λ_c**
	Failure load $P_u = \lambda_u P_{ld}$ λ_u: Load increment coefficient at failure	To calculate the cross sectional forces: ⇒ **Design limit value: R_d (= $\gamma_m \gamma_b V_u$; = $\gamma_m \gamma_b M_u$)** V_u, M_u: Shear and moment capacities obtained from the response analysis at structural failure γ_m, γ_b: Material factor and member factor

VERIFICATION		
Limit state of serviceability	$\lambda_c > 1.0$	λ_c : Load factor for crack initiation
Limit state of failure	$\gamma_i \dfrac{S_d}{R_d} \leq 1.0$	γ_i : Structural factor S_d : Design response value R_d : Design limit value

Figure 6: Design flow chart based on the response analysis

4 DESIGN OF COMPOSITE PIPES BASED ON LIMIT STATE THEORIES

4.1 Basic requirements

Figure 6 shows the flow chart for the response analysis and safety verification for the two limits: the limit state of serviceability and the limit state of structural failure. In analyzing structural behavior of a composite pipe at these limit states, a load increment coefficient for the design traffic loads is employed to calculate the loads needed for crack initiation and for structural failure when other design loads are present.

Under the allowable serviceability limit crack must not occur under the design load conditions. Specifically, the coefficient of incremental load at the occurrence of cracking must exceed 1.0. For the allowable limit state of failure, the design sectional force multiplied by the structure factor must not exceed the design limit value. Details of the computational procedures for limit state verification based on the response analysis are illustrated in Fig. 6.

4.2 Sample case for safety verifications

Figure 7 presents a typical case of a box-type aging sewer renovated by the SPR method as a composite pipe. The renovated cross section satisfies the design discharge capacity. Load conditions are shown in Fig. 8, where the design live load is based on the T-25 traffic load. The sewer channel was laid parallel to the road alignment. The material

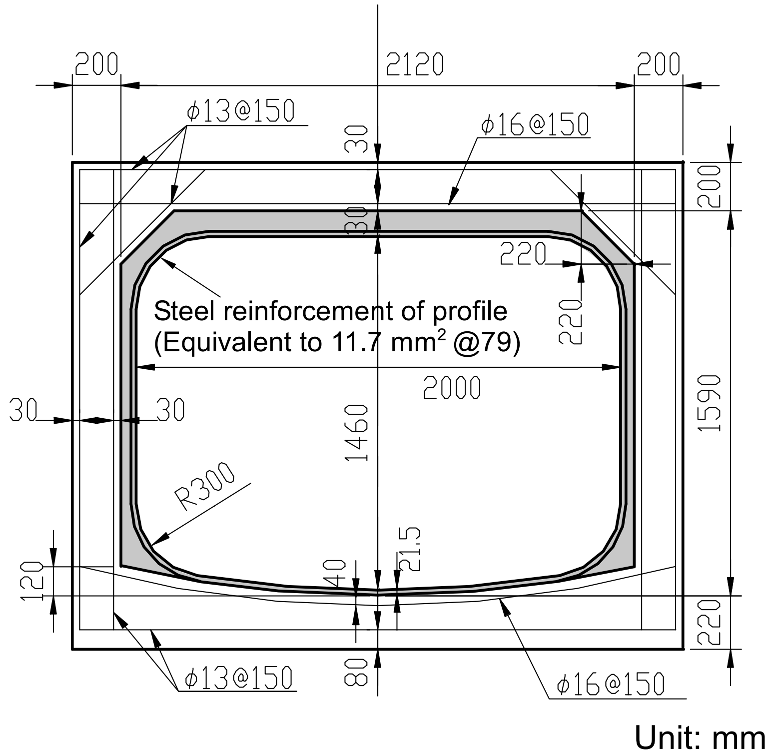

Figure 7: Dimensions of an aging sewer after renovation

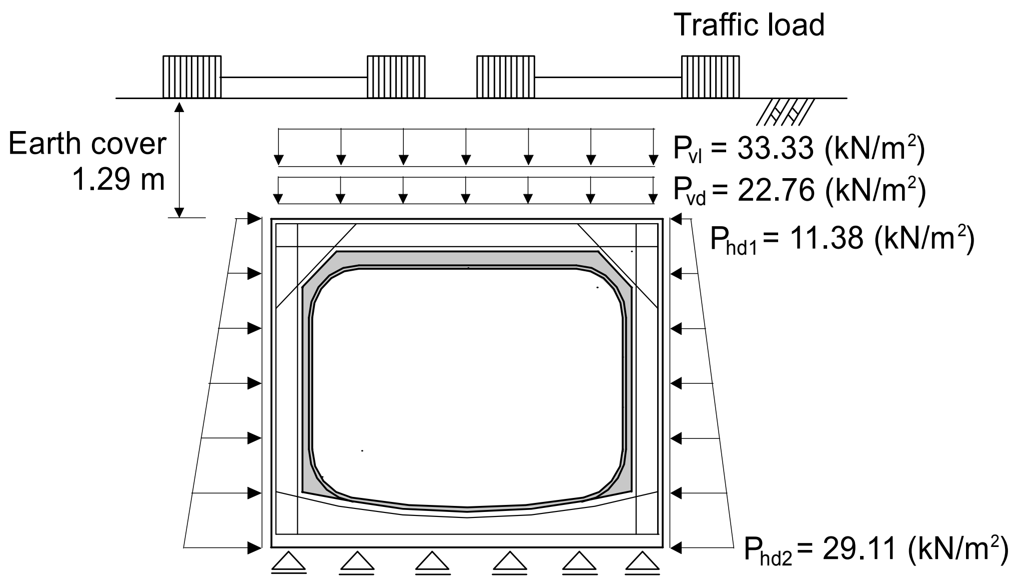

Figure 8: Load conditions

properties of the pipe are shown in Table 2, which were obtained from field investigations of the existing pipe.

Table 3 shows the results of safety verifications for this composite pipe, including all the safety factors considered for the computations. As seen from the table, the proposed renovation design of this aging sewer will ensure the renovated pipe to satisfy both requirements for the serviceability limit and the failure limit.

To facilitate the structural computation and renovation design by the SPR renovation method, specific design-aided software has been developed and the outline of the computer programs is shown in Fig. 9 [5]. The composite renovation methods have found wide applications in Japan, and in the Tokyo metropolitan areas alone the total length of the renovated man-entry aging sewers by the SPR method has reached approximately 40 km and is still extending.

Table 2: Material properties

Material	Item	Value	Material	Item	Value
Existing concrete	Compressive strength	24.6 N/mm^2	Mortar cement (Backfill material)	Compressive strength	12.0 N/mm^2
	Tensile strength	1.9 N/mm^2		Tensile strength	1.8 N/mm^2
	Elastic coefficient	25.3 kN/mm^2		Elastic coefficient	7.5 kN/mm^2
	Poisson's ratio	0.2 -		Poisson's ratio	0.2 -
	Unit weight	23.0 kN/m3		Unit weight	12.0 kN/m^3
	Fracture energy	85.0 N/m		Fracture energy	18.3 N/m
Steel	Yield stress	235 N/mm^2	Steel reinforcement in profile	Yield stress	210 N/mm^2
	Elastic coefficient	200 kN/mm^2		Elastic coefficient	170 kN/mm^2

Table 3: Results of safety verifications on two limit states

Limit state of performance				
Load increment coefficient at crack initiation (λ_c)			2.9	
Verification			λ_c > 1.0 (OK)	
Limit state at failure			Ceiling	Wall
Moment	Member force at (γ_f×design load)	M	19.4	17.9
	Structural analysis factor	γ_a	1.1	1.1
	Design member force	**Md**	**21.3**	**19.69**
	Member force capacity at failure	Mu	97.4	90.3
	Material factor	γ_m	1.3	1.3
	Member factor	γ_b	1.3	1.3
	Design member force capacity	**Mrd**	**57.6**	**53.4**
	Structural factor	γ_i	1.1	1.1
	Verification	γ_iMd/Mrd	**0.41**	**0.41**
			< 1.0 (OK)	< 1.0 (OK)
Shear	Member force at (γ_f×design load)	V	47.9	25.4
	Structural analysis factor	γ_a	1.1	1.1
	Design member force	**Vd**	**52.7**	**27.9**
	Member force capacity at failure	Vu	192.3	72.5
	Material factor	γ_m	1.3	1.3
	Member factor	γ_b	1.3	1.3
	Design member force capacity	**Vrd**	**113.8**	**42.9**
	Structural factor	γ_i	1.1	1.1
	Verification	γ_iVd/Vrd	**0.51**	**0.72**
			< 1.0 (OK)	< 1.0 (OK)

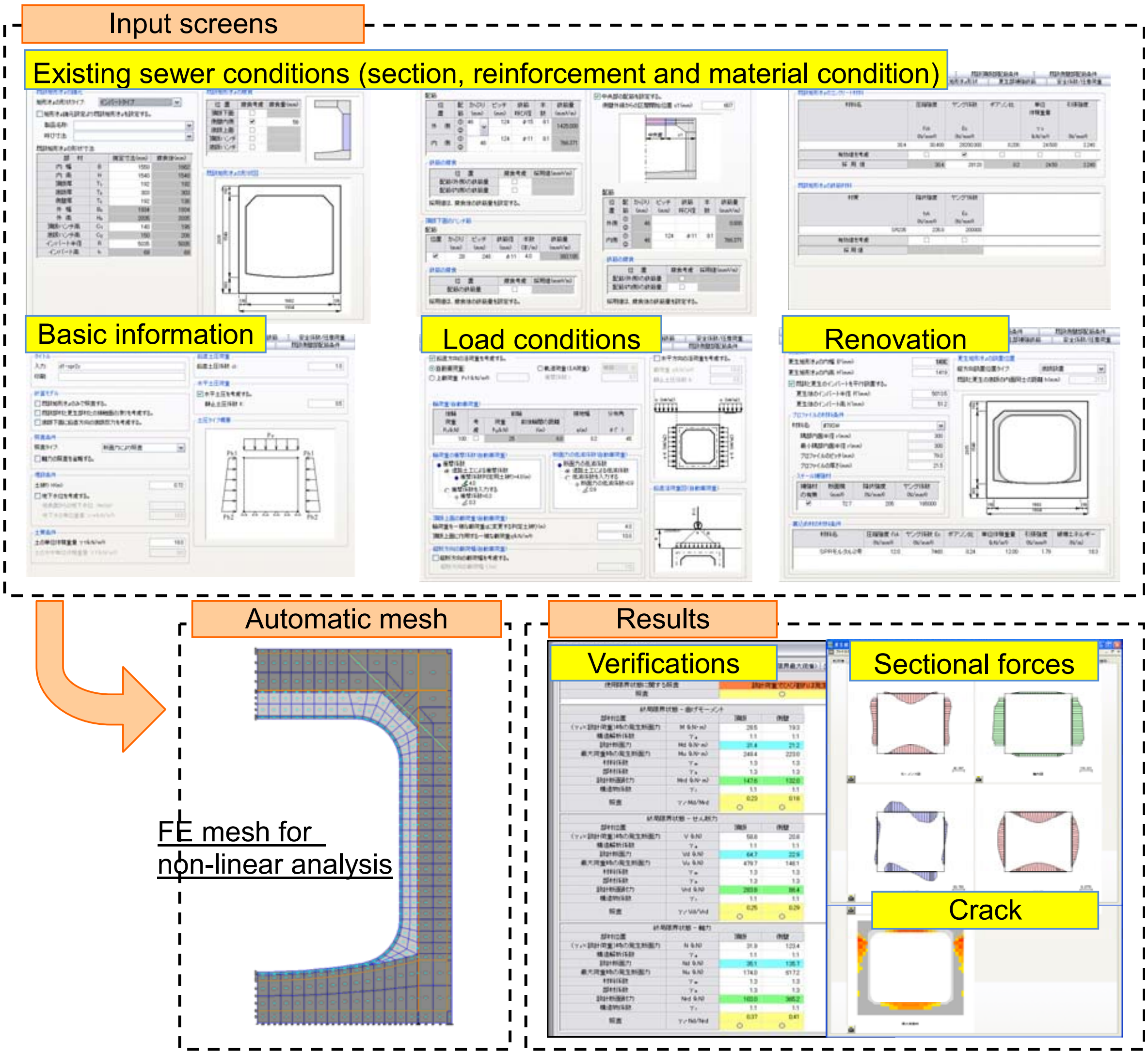

Figure 9: Outline of design-aided software for SPR renovation of aging sewers

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