3-D Longitudinal Performance of Rehabilitated Sewer Pipelines Based on Experiments of Actual Pipes and Finite Elements Analysis

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SUMMARY:
Reinforced concrete cylindrical pipes (RCCPs) are one of the most widely used sewer conduits all over the world. These pipelines are very vulnerable to the corrosion and accident due to traffic loads, and other hazards such as earthquakes. One of the methods for rehabilitation of these old pipelines is rebirth method, in which a new plastic pipe is inserted into the old pipe to build up a new composite, layered pipe. In order to assess the strength and ductility properties of this composite pipe, a typical setup is analysed experimentally and numerically. In this paper, longitudinal behaviour of a typical rehabilitated jointed RC pipe is examined. The results showed a meaningful consistency between finite elements simulations and experimentations, also verified the data for using in seismic design procedure of similar rehabilitated pipes.

Keywords: Reinforced concrete pipes, pipeline rehabilitation, nonlinear finite elements, pipe joints pull-out test

1. INTRODUCTION

Sewer system is a very important lifeline system for citizen's daily life. However, the history of construction of sewer pipelines started on 1960s and passed more than 60 years in Japan and other developed countries. The accidents of the buried sewer pipe due to corrosion have been occurred at many locations under traffic loads causing the settlement of surface ground. For example, the total length of sewer pipe in Japan is about 400,000km (in 2006), of which 7000 km age 30 to 50. So the rehabilitation of those corroded pipes is an urgent important strategy under heavy traffic loads, internal corrosion and various hazards including earthquakes.

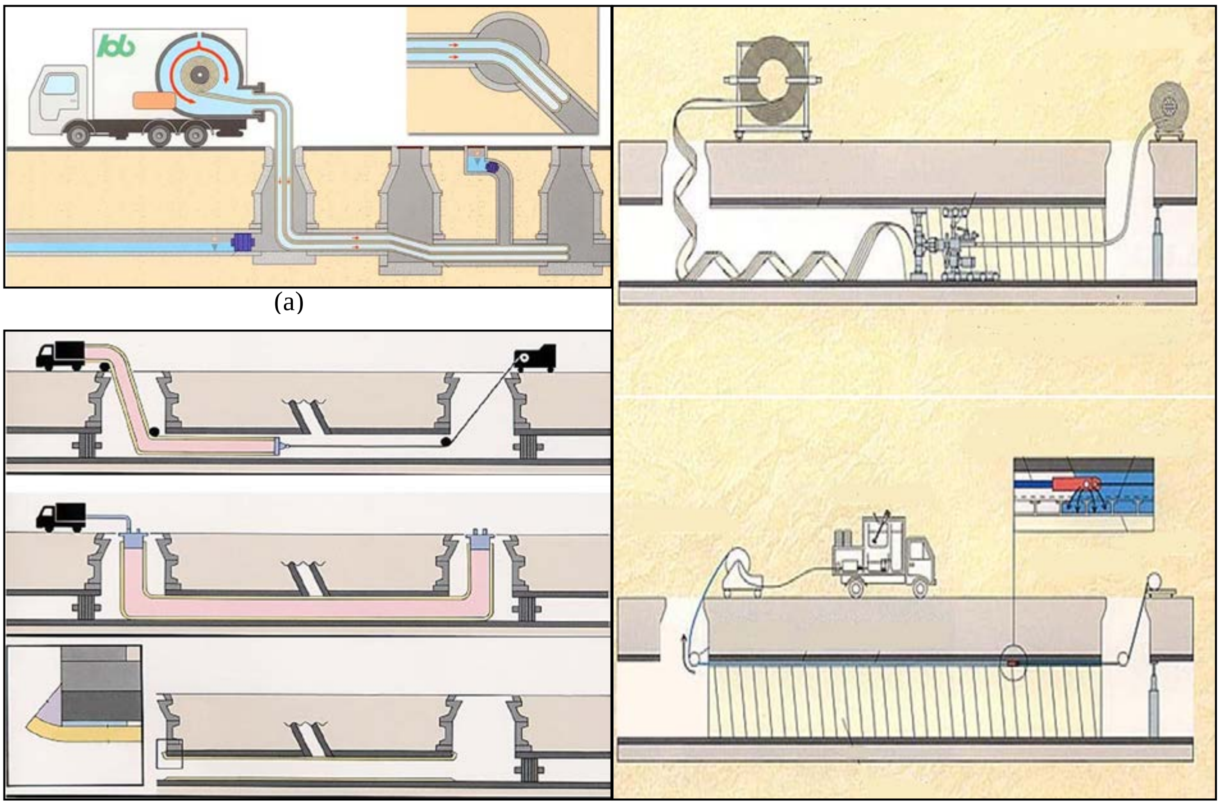
The concept of rehabilitation of lifelines specially buried pipelines is not as old as buildings. In 1997, the first guidelines for rehabilitation of oil and petrochemical facilities were published in USA [ASCE, 1997], however it lacked so many practical aspects of pipeline rehabilitations. The methods for rehabilitation of pipelines are mostly locally patented by the pipeline companies, and there is still not a verified and robust instruction for designing retrofit plans for lifeline facilities. In 2008, Japan's Sewer and Waste Water Association published the guidelines for rehabilitation of current sewer pipelines [JSWWA, 2008]. In addition to this useful guideline, there should be enough experimental and numerical analyses performed on the rehabilitated pipes for development and improvement of the seismic design and retrofit process.

Present paper investigates the longitudinal performance of a composite rehabilitated pipe. The examined composite pipe is an 800mm diameter reinforced concrete old pipe inserted PVC pipe which is formed by a thin strip of PVC plate wound up in spiral configuration by strip joint. The experiment is done for two segments of the old RC pipes of 2.45m jointed together, measuring joint separation, strain of the strip and new inner pipe deformation under the forced displacement at the centre of two old pipes. The numerical 3D model handles all the geometrical complexities of the tests, along with the nonlinear elasto-plastic model of concrete and filler mortar with their damage and cracking properties, highly nonlinear asymmetric behaviour of the joints both in the plastic inserted pipes and old concrete pipes and also interactions between each part of the composite structure. The simulations are carried out using FE code “Abaqus” and the results are compared to the experiments in order to get a better understanding of the behaviour of rehabilitated jointed pipes.

2. OUTILNE OF REHABILITATION METHOD

The rehabilitation of sewer pipes is divided into a new construction and rebirth or retrofit of pipes. The new construction needs a lot of investments compared with the rebirth method which is easier for construction under heavy traffic passing. The rebirth methods basically attempt to insert a new pipe into the existing old pipe, which is classified into (a) independent pipe and (b) two-layered pipe, which are constructed by a reverse method or formation of pipe, and (c) composite pipe, which is making one body of pipes.

In the Independent pipe method, the strength of the old pipe (generally reinforced concrete pipe) is not considered in the load carrying capacity of the assembly; in contrast, in the two-layered pipe, the partial strengths of both the old and new inserted pipe (generally PE or PVC pipe) are expected. This class of rehabilitation could be applied by either reverse method, in which a roll of plastic pipe is simply inserted to the main pipeline or pipe formation method, in which the inserted roll of plastic tube is pulled from other end of the pipeline to form a new pipe. At last, the composite pipe is considered as a structure with combined rigidity from the old and new pipes. This type of rehabilitation is performed by a special method. In this method, a roll of plastic is wound up in the form of spirals in the old RC pipe. The spacing between the spirals and old pipe body is filled with high strength mortar, and the spirals are jointed together by a special machine afterwards. The schematic outline of various rehabilitation methods are shown in Fig. 2.1.



(a)

(b) (c)

Figure 2.1. Rehabilitation of sewer pipelines by **(a)** reverse pipe method, **(b)** pipe formation method and **(c)** composite pipe method

The composite pipe rehabilitation method has several advantages over other methods. In this method, the strength and flexibility of old RC pipe is not omitted, unlike the independent pipe method in which obviously excludes a very important source of strength and flexibility from the total performance of pipeline. Moreover, this retrofit method could be applied in a specific region of the pipe, and it is not necessary to use it along the whole pipe. Also the experimentations have shown that this method would increase the flow volume in the pipe. Because of these advantages, this method is selected to be analysed in this paper as a new but robust method of sewer pipe rehabilitation.

3. EXPERIMENTAL SETUP

The experimentation conducted includes two segments of RC pipes. The length of each segment is 2.45m and the two parts are jointed together with the typical mechanical joints used in the current sewer system of Japan. The PVC strips are inserted in the pipe and connected together. The spacing between the two parts is filled with a specially mixed high strength mortar. The dimensions of the composite pipe generated are shown in Fig. 3.1.

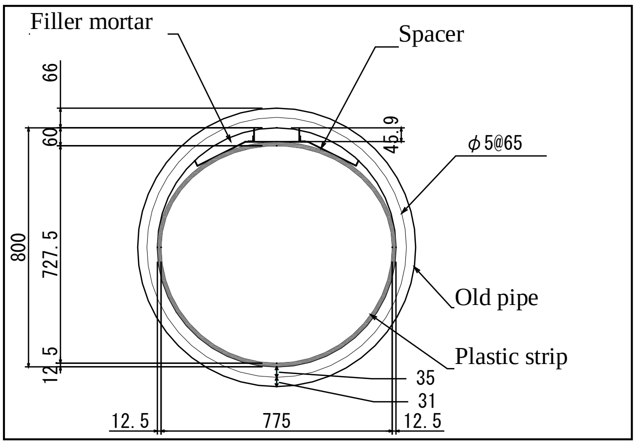


Figure 3.1. Section view of the composite pipe

The generated composite pipes are fixed at one end of the segments with restraints of a hydraulic jack, and another jack is attached to the other segment in the inner end. The loading condition is about pulling the joints to a maximum opening of 35-50 mm with a displacement controlled procedure. The total process of loading is done in 400 seconds to maintain the quasi-static condition. Strain gauges and actuators are connected to various points around the pipe joints in 3 points (at spring line, crown and bottom) in the inner perimeter of old pipe and 3 points in the outer perimeter of the plastic pipe. The outline of the experimental setup is shown in Fig. 3.2.

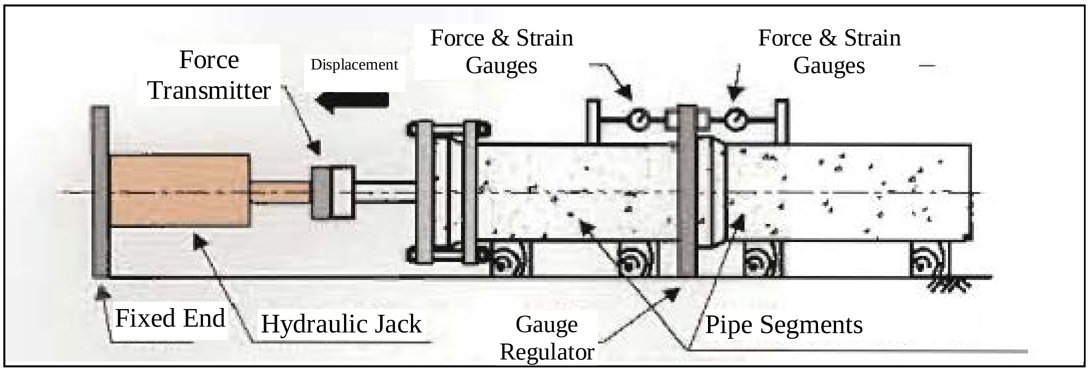


Figure 3.2. Schematic outline of the experimental setup [Takada & Kuwata, 2010]

4. NUMERICAL MODEL

The numerical model is generated based on the specifications of the experimental setup for the composite pipe. The model consists of different parts connected to each other with various contact and interaction laws, which are assumed and precisely introduced in the finite element code. The selected code for this simulation was Abaqus v.6.10-1, and the generated model was solved by a parallel set of 10 3.2 GHz CPUs with a total RAM of almost 20 Gigabytes in the High Performance Computing Lab. (HPCL) of University of Tehran.

The simulation included 100 second runtime in smooth-step [DS Simulia, 2010] loading type for considering the quasi-static state for the problem. The time-step for running the simulation was defined by the software mainly based on the finest mesh size of the parts and the distortions in every step of analysis, which was introduced shorter than 3×10^{-6} seconds. For this reason double precision was used in the calculations to avoid the round off errors in the accumulations and processing of the results. Needless to say, these assumptions and controls resulted to a very precise, yet time consuming and expensive computation with a big output dataset and a large runtime (clock) time.

The different aspects and attributes of the FE model from the geometrical properties to constitutive models of materials and contact rules are introduced in the following. The constitutive models of materials and also the interactions between individual parts are either obtained from prior experiments, or assumed based on logical judgments of the experts.

4.1. Inner Plastic Pipe

As explained before, in this retrofit plan a plastic spiral pipe is wound into the old RC pipeline. This spiral pipe is mostly made of Poly Vinyl Chloride (PVC), which is a ductile plastic material commonly used in the water and sewerage systems. In this simulation, the behaviour of this material is assumed to be isotropic elastic with the parameters defined in the table 4.1. The geometrical dimensions and the generated model for this part are shown in Fig. 4.1(a) and (b) respectively.

Table 4.1. Mechanical Specifications of PVC Pipe

Density ρ (kg/m^3)	Elasticity Modulus E (MPa)	Poisson's Ratio υ
1000	2100	0.3

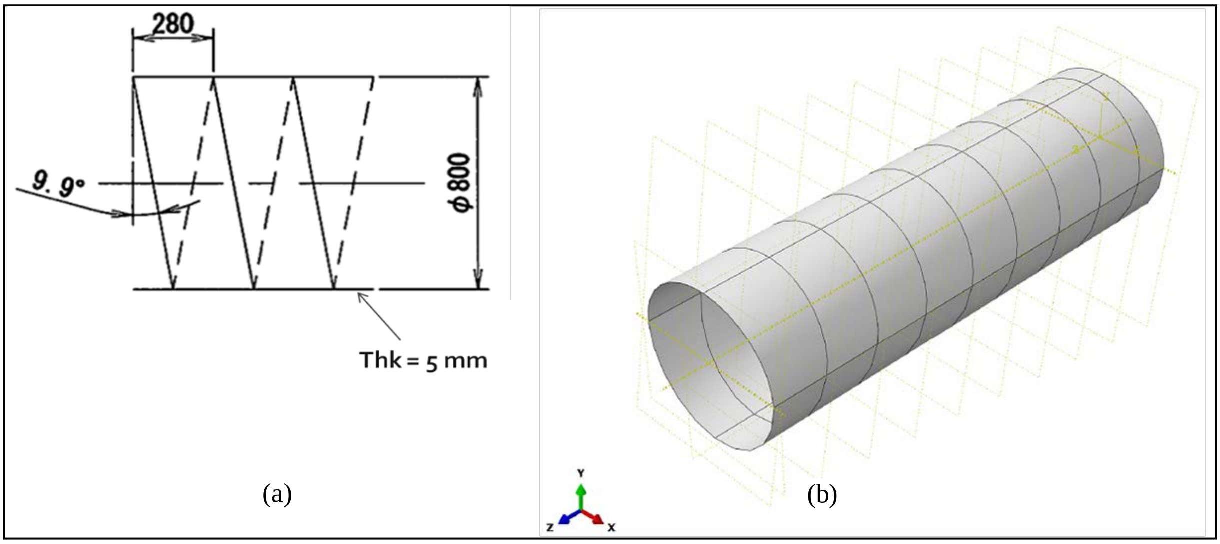
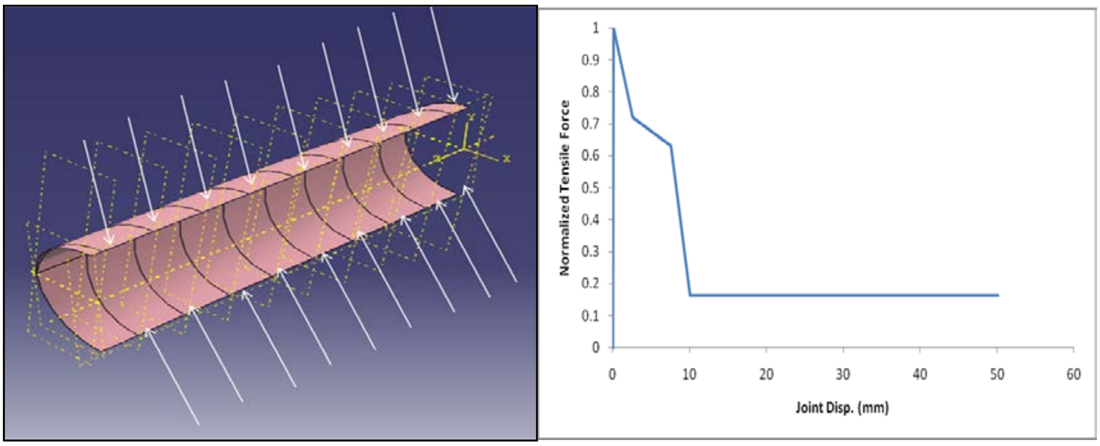


Figure 4.1. (a) Geometrical dimensions, **(b)** physical model of the jointed inserted pipe

This part is modelled as a thin shell with the thickness of 5mm using quadrilateral (4-noded) elements, and the each segment of the pipe is jointed to the other segment in the next pitch with two nonlinear joints at top and bottom points in the section (see Fig. 4.2.(a)). The tensile strength of these joints are shown in Fig. 4.2.(b), while the joints do not have any free space for compression and hard contact condition is applied.

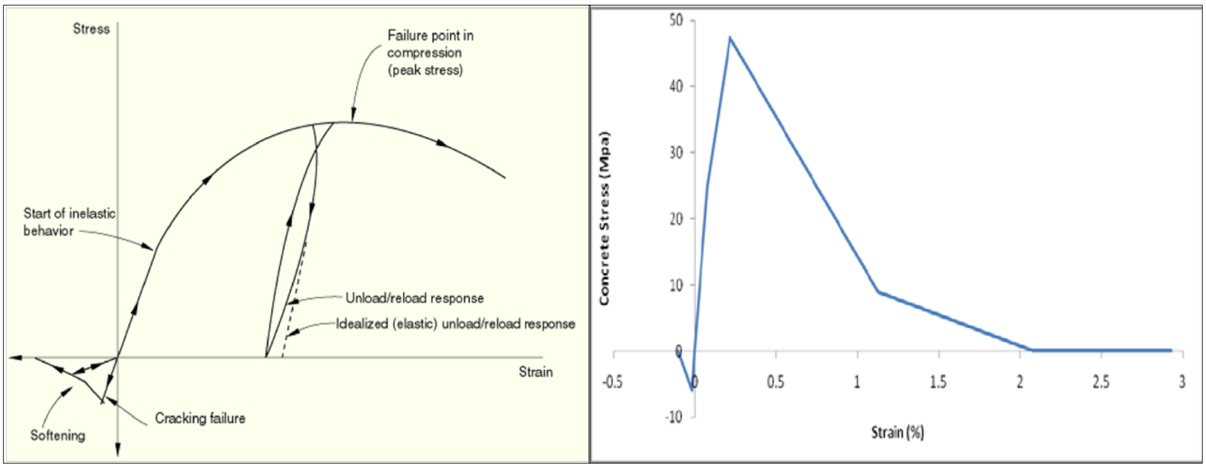


(a) (b)

Figure 4.2. (a) Joint locations of the inserted pipe, **(b)** Normalized tensile strength of inner pipe joints

4.2. Old Reinforced Concrete Pipe

The old RC pipe includes a spiral wound up steel rebar embedded in the concrete cylindrical pipe. The interaction between these two objects does not consider the slippage, which in the case of spiral reinforcement is not so inaccurate. Nonlinear behaviour of the concrete is modelled by concrete damage model enabling tension softening for better coverage of the experimental data on tensile and compressive strength of the used concrete (see Fig. 4.3.(a)). The nonlinear strength behaviour of the concrete used in building of RC pipes is introduced in Fig. 4.3.(b).



(a) (b)

Figure 4.3. (a) Conceptual hysteretic model and **(b)** nonlinear behaviour of concrete

The strength model for the rebar steel is a common elastic perfect plastic model with yield stress of 360 MPa and no hardening and Poisson's ratio of 0.3 based on the specifications obtained from the tests. Also the Poisson's ratio for the concrete part was considered 0.21, and both concrete and steel rebar are modelled by solid 8-noded elements.

According to the experimental setup, the end of the pipe segments are tapered or widened for a bell and spigot like arrangement and installation. Here, this type of geometry is not modelled as the exact results from the mechanical testing of the joints are used in the simulation, in which the effect of the shape of the joints is certainly considered. As the experimental setup included two segments of rehabilitated RC pipe, the mechanical joint between the pipes should be considered. In this regards, the mechanical behaviour of the joint is considered in axial tension and compression and also rotation for consideration of the possible tilting and rotation of the pipes because of absence of symmetry in the arrangement of inner pipes. The nonlinear behaviour of the pipe joints in axial and rotational direction are shown in Fig. 4.4. The method for application of these joint behaviours is to apply them to a nonlinear spring in every direction and connect the spring ends to the point in which the end section points of the pipe constrain together by multipoint point constraint (see Fig. 4.5) [Nourzadeh, 2011, Takada et al, 2001].

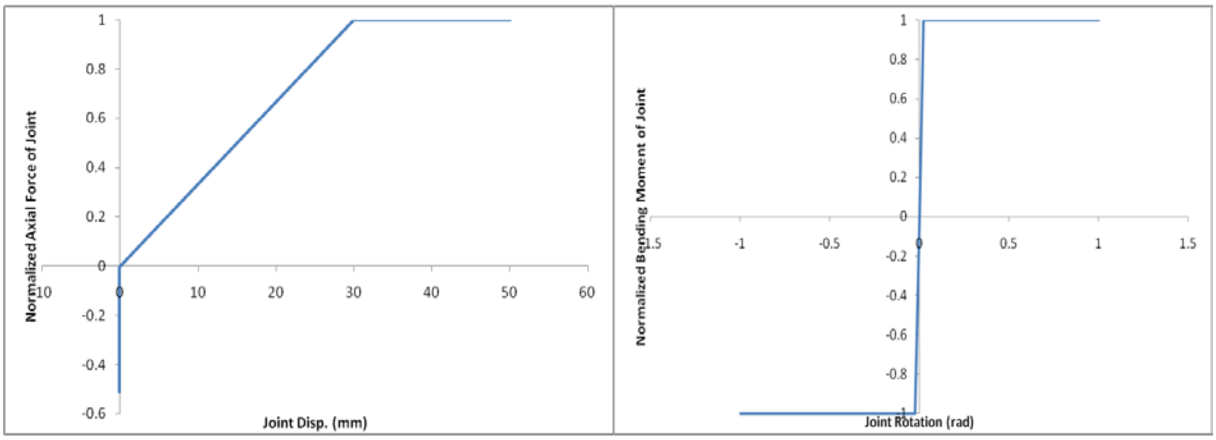


Figure 4.4. Joint behaviour of RC pipes (normalized values)

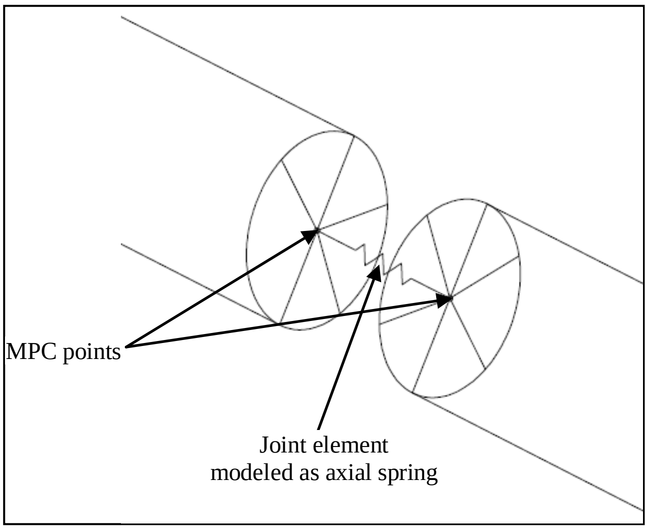


Figure 4.5. Concept of proposed model for pipe joint (the spacing scale is exaggerated)

4.3. Filler Mortar

As explained in the experimental setup, the spacing between the new pipe and the old RC pipe is filled with high strength mortar. This filler is modelled just like the concrete part, however nonlinear strength behaviour of the materials are different. The stress-strain curve of the mortar is derived based on experimental data and is shown in Fig 4.6.

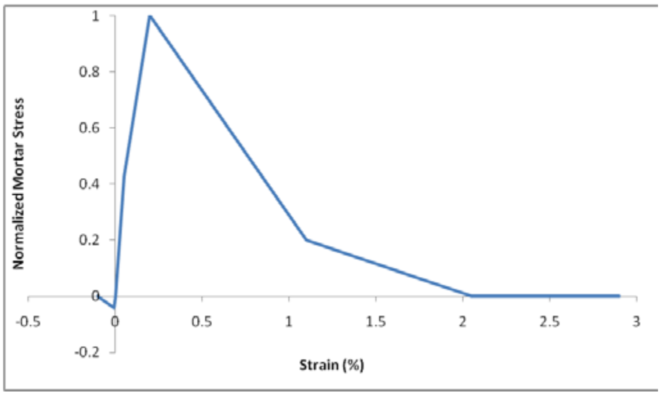


Figure 4.6. Nonlinear behaviour of high strength mortar

The interaction of filler and the RC pipe was modelled using penalty method with allowance of finite sliding in the code. The normal contact of these two parts is limited to hard contact condition preventing the penetration of parts, but allowing the separation after contact, as these phenomena were observed during experimental tests. On the other hand, the tangential interaction of the parts, frictional contact was used with a frictional coefficient of 0.6 and shear stress limit of 0.1 MPa, and also elastic slip of up to 0.1 mm was allowed with the elastic stiffness of 1kN/mm. In the contrast, the interaction between filler and inserted plastic pipe was also modelled using rough contact condition for tangential direction and hard contact condition with allowance of separation.

5. RESULTS AND DISCUSSION

The numerical model was generated and assembled based on the experimental setup. The joint pull-out displacement was the only loading in this analysis, in which 50 mm displacement is applied linearly to one of the segments of the rehabilitated pipe during 100 seconds, as a boundary condition. This condition was applied to the outer edge of the RC pipe in the contact with other pipe, as the exact modelling of the experimental test was desired. The other pipe segment is fixed at the far end in the edge. The boundary conditions for the assembled model and the test setup is shown in Fig. 5.1.

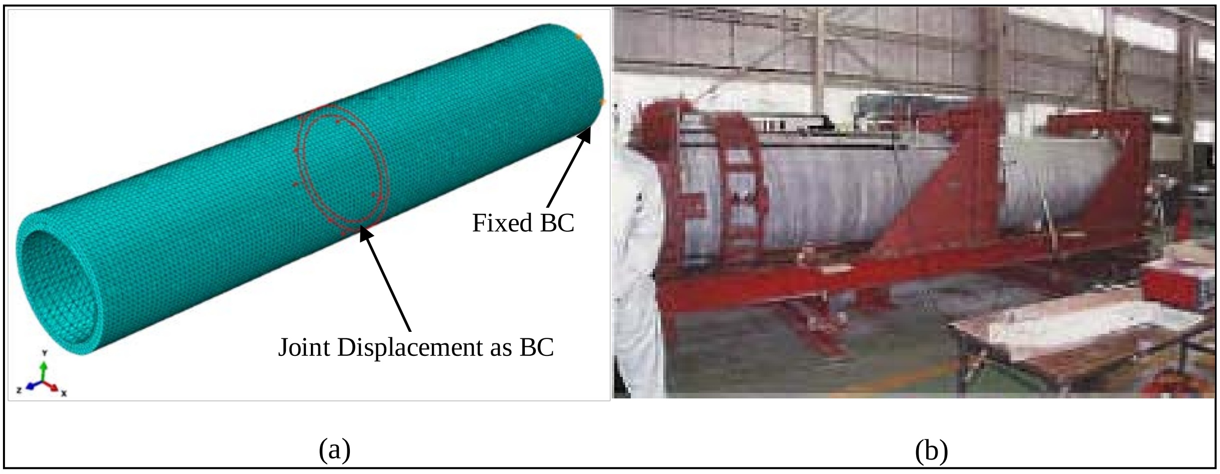
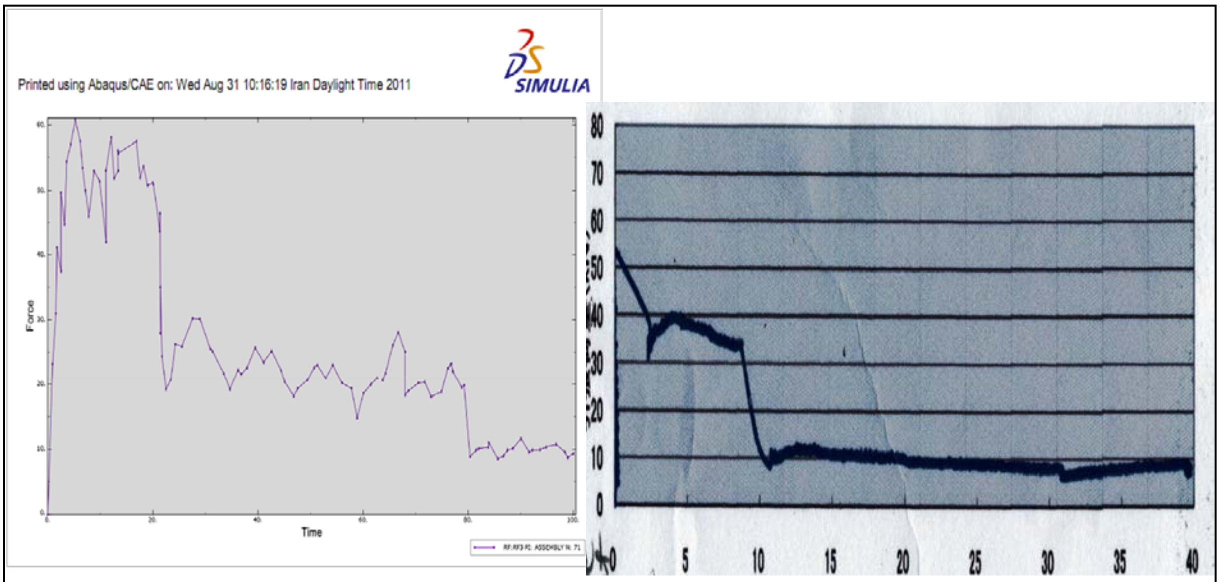


Figure 5.1. (a) Boundary conditions applied to the FE model, **(b)** Loading conditions in the experimentation [*Takada & Kuwata, 2010*]

The important results obtained from the experimentation and the simulation were the total applied force, the strain of RC pipe and the plastic strip near the pipe joint in 3 points in the perimeter of the section. In Fig. 5.2, the comparison with the experimental and numerical results for the total force during the test is shown. As it is clear in this figure, the results are in a very good consistency, however the numerical results have fluctuations over the mean values which are very close to the experimental values. These fluctuations are believed to happen because of the type of the simulation which is dynamic explicit, but with some measures to incline the model to quasi-static simulation. The other results were compared the same to the experimental values, as like as the final joint opening of a little more than 15 mm for the plastic joints and 44 mm for the RC pipe joint which are less than 10% more than the exact experimental results.



(a) (b)

Figure 5.2. Total applied pull-out force by **(a)** simulation and **(b)** experimentation

By this comparison, it is implied that the proposed simulation model best reflexes the exact behaviour in the real problem. This model is sensitive to a wide range of different parameters, assumptions and constitutive models for behaviours and interactions of different parts and materials, thus when the results are this much comparable to the exact results it could arguably be seen that all the parameters are gathered and modelled with sufficient degree of preciseness. This fact could lead to acquiring this verified model to the next steps of the analysis which could be the vertical or seismic assessment of the composite rehabilitated pipes.

6- CONCLUSION

A new method of rehabilitation for RC pipelines was analysed by experimental and numerical methods. In the simulations, the complexities of the problem including the nonlinear behaviour of materials, interactions and joints were modelled for the first time using a well gathered set of data from experimental tests. In the return, the simulations had a satisfying consistency to the tests, implying the preciseness and adequacy of the proposed models. This helps the retrofit designers use the same verified conceptual model and assumptions for analysis of the rehabilitated pipelines. The discussed rehabilitated pipe by this method is proposed to perform water proof in the high levels of seismic actions, thus the same model for seismic analysis could be used with minimum adjustments for the dynamic behaviour.

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