Computers and Concrete, *Vol. 20, No. 4 (2017) 483-490*
DOI: https://doi.org/10.12989/cac.2017.20.4.483

FE analysis of RC pipes under three-edge-bearing test: Pocket and diameter influence

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(Received May 12, 2016, Revised June 6, 2017, Accepted June 8, 2017)

Abstract. This paper studies on the behavior of reinforced concrete (RC) pipes used in basic sanitation in the conduction of storm water and sanitary sewer. Pipes with 800 mm and 1200 mm in diameter were analyzed. The 800 mm pipes were built with simple reinforcement and the 1200 mm pipes with double reinforcement. For the two diameters of pipes the presence or absence of the pocket was evaluated, and the denomination of each one is spigot and pocket pipe (SPP) and ogee joint pipe (OJP), respectively. The 3D numerical models reproduce the three-edge-bearing test that provides information about the strength and stiffness of the reinforced concrete pipes. The validation of the computational models was carried out comparing the vertical and horizontal displacements on the springline and crown/invert and it was also evaluated the reinforcement strains and the crack pattern. As a main conclusion, the numerical models represented satisfactorily the behavior of the pipes and can be used in future studies in parametric analysis.

Keywords: reinforced concrete pipes; spigot and pocket pipe; ogee joint pipe; three-edge-bearing test; numerical analysis

1. Introduction

Concrete pipes have been used effectively as conduits for storm water and sanitary sewer in the construction of infrastructure in basic sanitation. From the point of view of durability, it is important to notice that the fluids being transported might have a high level of aggressiveness and the pipes must be designed in order to prevent cracking.

There is a standard test widely used in the evaluation of the mechanical strength of reinforced concrete pipes called three-edge-bearing test (TEBT). In this test, the load is applied as a line load along the crown of the pipe, while the pipe is supported over two closely spaced bearing strips along the invert (Fig. 1). The code that standardized the TEBT is the ASTM C497.

One way to control the crack opening in concrete structures is the use of fibres. Thus, the concrete is widely studied for application in pipes. A large number of studies on the behavior of fibre reinforced concrete pipes were found in the literature, one of them was Haktanir *et al.* (2007), which studied the effect of dosage of steel fibres on pipe strength and cracking peculiarities in a comparative way by performing the same tests both on conventional reinforced-concrete pipes and on steel-fibre concrete pipes. One of the conclusions of the authors was that the steel-fibre concrete pipes are more economical and mechanically and physically superior to reinforced-concrete pipes.

Another current study on the behavior of steel fibre concrete pipe is Mohamed *et al.* (2015). In this research, a parametric analysis was carried out and a comparison between codes was conducted. Precast pipes were tested using both the continuous and cyclic loading procedures as per the ASTM C497 and EN 1916 guidelines, respectively. It was also found that the behavior of steel fibre concrete pipes could be fully explored using the continuous three-edge-bearing test without the need of an extra loading cycle as specified in the EN 1916 code.

According to De La Fuente (2013), Peyvandi (2013) and Peyvandi (2014), although the mechanical requirements established in the standards for steel fibre concrete pipes do not allow its cracking during service life, the use of steel fiber is inadvisable due to its potential sensibility to chemical attacks, which can lead to load bearing capacity reductions as well as leakage. From a durability standpoint, such in the region with higher probability of opening of cracks, at the invert region, the steel bars could be directly exposed to the fluid conducted by the pipe, which can lead to section loss, by corrosion and mechanical failure under tension. One alternative is the use of polypropylene fibres,

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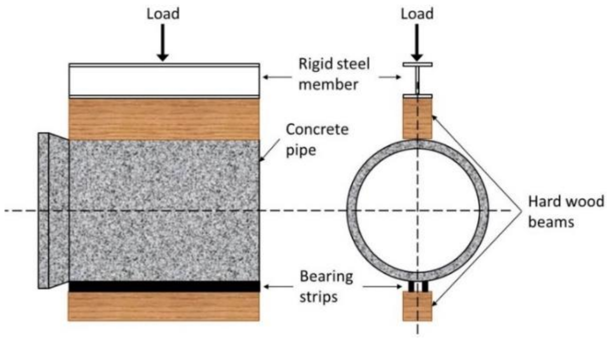
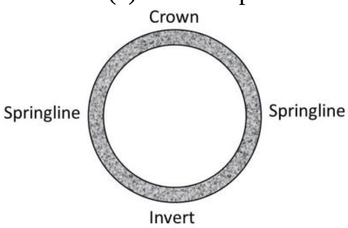
http://www.techno-press.org/?journal=cac&subpage=8
ISSN: 1598-8198 (Print), 1598-818X (Online)

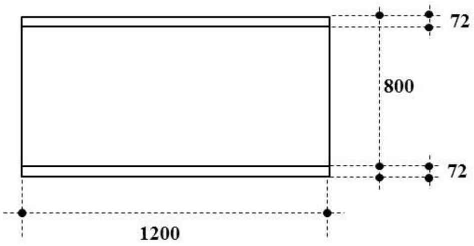


(a) Test setup

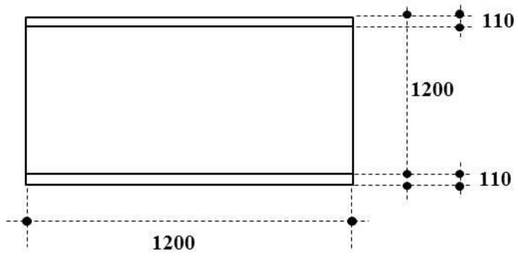


(b) Parts of the reinforced concrete pipes

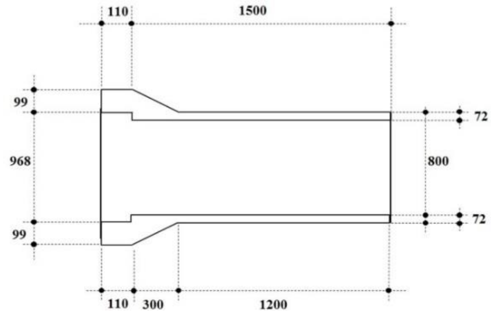
Fig. 1 Setup of the TEBT and name of the parts of the pipe



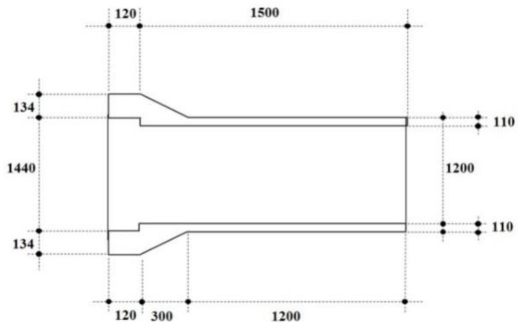
(a) OJP ND 800



(b) OJP ND 1200



(c) SSP ND 800



(d) SSP ND 1200

Fig. 2 Dimensions of the pipes (Unit: mm)

which are resistant to potential chemical attacks, and therefore improve the durability and the structural integrity throughout their service life.

In De La Fuente *et al.* (2011) and De La Fuente *et al.* (2013) was carried out a numerical and an experimental study in which concrete pipes manufactured using polypropylene fibres were analyzed. De La Fuente *et al.* (2011) verified that the numerical model is a powerful tool for the optimal design of the fibre dosages, avoiding the need of the systematic employment of the test as an indirect design method. Consequently, the use of this model would reduce the overall cost of the pipes and would give fibres a boost as a solution to this structural typology. De La Fuente *et al.* (2013) demonstrated that the use of plastic fibres is compatible with pipe production systems, and when subjected to the TEBT, plastic fibre reinforced pipes had satisfactorily behavior that are attractive in terms of the growth of this material in the concrete pipe industry.

The same way the fibres can suffer corrosion, the reinforcement must be protected against this phenomenon too. When the pipe has more than one reinforcement layer, the concrete cover tends to be thin. In Peyvandi *et al.* (2013) and Peyvandi *et al.* (2014) fibre concrete pipes were analyzed and their behavior was compared to concrete pipes. A new design which takes into account the contributions of fibers to the tensile behavior of concrete was developed. Test results confirmed that the number of steel reinforcement layers in concrete pipes can be reduced with the use of synthetic fibres. This improvement enabled reduction of welded wire fabric steel reinforcement layer in concrete pipes from two to one, thus increasing the protective concrete cover thickness over steel and durability of concrete pipes under the aggressive exposure conditions of sanitary sewers. The large-scale evaluation of concrete pipes indicated that 30% improvement in load-carrying capacity was realized with the introduction of the fibres.

The use of recycled material in the concrete pipes was another alternative to improve the performance of this element. The behavior of the concrete pipes was tested with the addition of recycled crumb rubber used to replace sand. This study was conducted by Park *et al.* (2015) with the intention to assess the enhancement of the structural performance of concrete pipes through the use of crumb rubber, steel, and synthetic fibers. Based on the three-edge-bearing tests according to ASTM C497, pipes with five different concrete mixtures were produced and tested. An important conclusion of this study was that the excessive addition of crumb rubber exhibited a significant reduction in the pipe strength but an appropriate amount of rubber can effectively improve its strength and ductility.

All the above researches used the TEBT to analyze the behavior of concrete pipes. Due to the large application of the TEBT in industry and because of design proceedings,

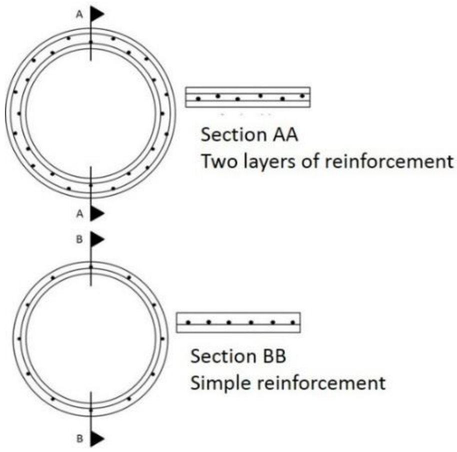


Fig. 3 Reinforcement configurations

which use bedding factors to relate in-place pipe performance to the performance obtained from this test.

Intending to show that the conventional method did not express the real behavior of the reinforced concrete pipes, MacDougall *et al.* (2016) carried out a series of shallow burial tests with surface loading, a deep burial test, and a three-edge-bearing test. Both the shallow and deep burial tests indicated that the critical cracking does not develop until the specified service load has been surpassed, suggesting that current pipe designs are overly conservative. In the burial tests, the tubes are buried in the ground.

The replacement and maintenance of concrete pipes require hard work and cause a lot of inconvenience in the urban environment. However, when the researches introduce fibres into concrete, when the reinforcement is changed and even when new methods for concrete curing are tested, as in Rostami *et al.* (2011), the intention of the researches is to build pipes with higher resistance and durability. Rostami *et al.* (2011) study the used a different type of concrete curing which combined steam and carbonation. A beneficial use of carbonation as an auxiliary curing regime for concrete pipes was studied in an attempt to reduce steam curing time, improve durability performance and explore the possibility of using concrete pipe to sequester carbon dioxide emitted from cement production.

The inspection of the tubes conditions is another concern that researchers are trying to solve with the use of ultrasound systems and non-destructive evaluation methods of cracking. In Iyer *et al.* (2012) the ultrasonic inspection and imaging system was evaluated. The results showed that the method comprising a reliable detection system, which can lead to the overcoming of many limitations of the current manual inspection practice, can also provide a more accurate assessment of buried pipe conditions. Yang *et al.* (2010) also used ultrasound in their research with tubes. This study developed a nondestructive evaluation of the depth of surface-breaking crack. The cracking affects the material and structural properties of concrete pipes, as mentioned previously. Therefore, the nondestructive evaluation of the cracks depth is very important to assess the serviceability of these pipes, which are commonly used in underground infrastructure installations.

Table 1 Characteristics of the tested pipes according to ASTM C76 and NBR 8890

Series	Diameter (mm)	Pipe	Quantity	Thickness (cm)	Welded mesh	Length (m)
1	800	SPP	12	7.2	As= 3.96 cm²/m	1.5
		OJP	4			1.2
2	1200	SPP	12	11.0	Internal reinforcement: As=3.96 cm²/m	1.5
		OJP	4		External reinforcement: As=1.96 cm²/m	1.2

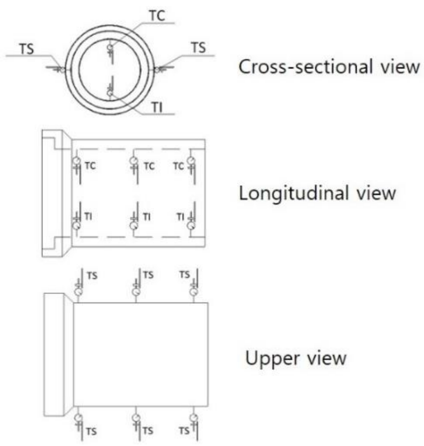
Fig. 4 Test setup

Complementing the previous studies, this paper contributes with the knowledge of this element analyzing the behavior of concrete pipes with different diameters (800 and 1200 mm) with pocket and without the pocket in one edge. Thus, it was possible to verify the influence of the pocket and the diameter on the pipe strength. For this, numerical simulations were performed to deepen the analyzes from a validated computational model to estimate the strain and stress in both the reinforcement and the concrete.

2. Summary of experimental program

The tests described in this paper were conducted in Silva (2011). The experimental program was comprised of thirty-two TEBT. In addition, half of the pipes had a nominal diameter of 800 mm (Series 1) and the remaining half had 1200 mm (Series 2). In each series, twelve pipes had the pocket (spigot and pocket) and the remaining four pipes were produced without the pocket (ogee joint pipes). The spigot and pocket pipes and the ogee joint pipes were named as SPP and OJP, respectively. The features of the pipes are presented in Table 1 and in Fig. 2.

According to prescriptions of the design of concrete pipes, which recommend that pipes with less than 1000 mm of diameter, simple reinforcement is usually used, while for diameters greater than 800 mm it is common to use two layers of reinforcement, in this experimental program, pipes with nominal diameter of 800 mm and 1200 mm were tested in order to evaluate the behavior of the pipes in these two situations. Fig. 3 illustrates the arrangement of reinforcement configurations.



TC: transducers to measure the displacement of the crown
TI: transducers to measure the displacement of the invert
TS: transducers to measure the displacement of the splingline

Fig. 5 Overview of displacement transducers (T)

The instrumentation was the same for the two types of pipes. Displacement transducers and hydraulic jack with cell load were used. A steel reaction frame was used for attaching the hydraulic jack in the three-edge-bearing tests, as presented in Fig. 4. The transducers (T) were used to measure the displacement of the crown (TC), the splingline (TS) and the invert (TI), as shown in Fig. 5. The tests were conducted according to the predictions of Brazilian code, which is similar to ASTM C497 and EN 1916. In the evaluation of the cracking load and loading versus displacement curves were used, which were plotted using the measurement of the displacement transducers.

3. Nonlinear FE analysis

The numerical analysis proposed in this paper is focused on verifying that the numerical modeling is a potential tool to satisfactorily replicate the experimental three-edge-bearing test. The numerical simulation is an inexpensive alternative to structural analysis due to the fact that replaces the physical models, which are expensive and time-consuming to be built. To validate the simulation results the numerical data will be compared with the experimental results. 3D finite element models were created for replicating the three-edge-bearing tests of the experimental program of Silva (2011). The software Midas FX+was used to construct the geometry and also to view the results (pre and post processing). The software DIANA was used to process the numerical model using the finite element method (FEM).

Just one type of finite element was used to construct the mesh, and the selected one was a four-node, three-side isoparametric solid pyramid element. Different densities of mesh were tested in order to adequate the quality of the results with the time spent in the processing. However, the selected mesh guarantees a good compromise between the size of the elements and the stability of the numerical solution. Details of the models are shown in Fig. 6.

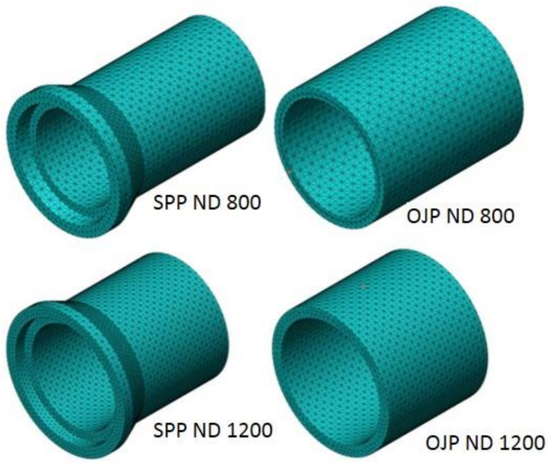


Fig. 6 Mesh of the pipes

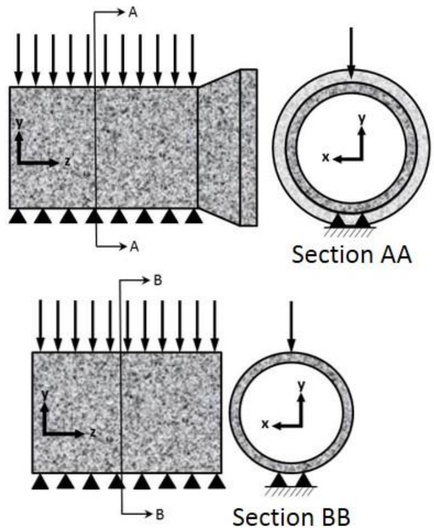


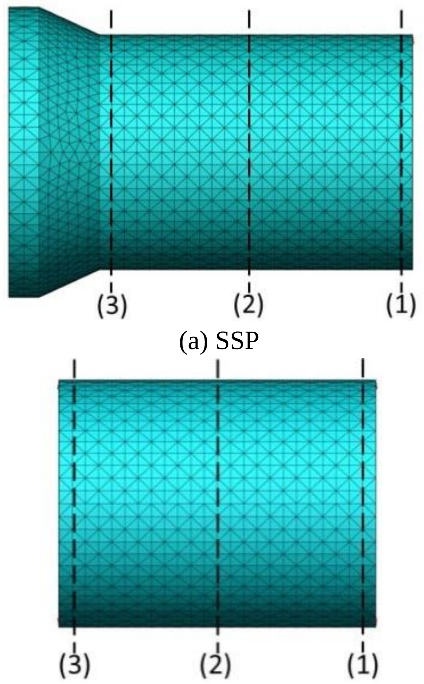
Fig. 7 FE boundary conditions

Table 2 Materials properties of the numerical models

Properties	Concrete ND 800	Concrete ND 1200	Steel bars
Young Modulus (GPa)	37.100	35.960	200.000
Compressive Strength (MPa)	51.380	46.800	-
Tensile Strength (MPa)	4.400	3.500	-
Tensile fracture energy (N.mm/mm²)	0.045	0.055	-
Compressive fracture energy (N.mm/mm²)	4.716	4.418	-
Yielding Stress (MPa)	-	-	710.000
Poison (υ)	0.200	0.200	0.300

The boundary conditions adopted for the numerical models were the restrictions of the displacements on y and z directions in two lines in the base, simulating the same conditions of the test. The loading was introduced along the pipe length (except in the pocket region when it exists). The scheme of the boundary conditions and the loading application is presented in Fig. 7.

The constitutive model adopted to describe the concrete elements was the total strain model, whose advantage is the simple concept. The steel bars were described by the plasticity models of Von Mises, which are appropriated to



(a) SSP

(b) OJP

Fig. 8 Points of measurements of the displacement in the springline (numerical model)

ductile materials. The Von Mises model of maximum energy distortion was chosen for the steel elements in this model under the assumption that the maximum energy accumulated in the distortion of the material could not be greater than or equal to the maximum distortion energy of the same material in a uniaxial tensile test.

The materials properties as compressive strength, tensile strength, young modulus and yielding stress adopted in numerical model were the same values determined in the experimental program. Table 2 summarizes the mechanical properties adopted in numerical model.

4. Numerical results

The validation of the numerical models was done based on the loading versus displacement behavior. The displacements were measured in the crown, the invert and the springlines. The displacement in the crown and in the invert had inverse direction, so the values were subtracted to represent the distance from each other. The loading used in the analysis was the total load applied by the hidraulic actuator divided by the extension of the pipes. In the case of SPP the length was 1.2 m and the OJP was 1.5 m.

The measurements of the springline displacement (horizontal displacement) were done in three points, in both sides of the pipe. For the OJP, the horizontal displacements along the length of the pipe were the same, and for the SSP, the displacements had a slight dispersion due to the presence of the pocket, which made the region more rigid. In the comparisons for validating of the numerical models, for the OJP just, one measurement was considered. Fig. 8 illustrates the sections where the horizontal displacements were measured; the numbering of the sections in the figure is the same in the indication of the curves in Fig. 9.

The correlation between numerical and experimental results was satisfactory. The displacements in the crown were more similar to the experimental measurements than the displacements in the springlines. The difference between the experimental and numerical results is due to geometric nonlinearity, especially in horizontal displacements (springlines). Flexible structures such as pipes, these effects should be considered to obtain a real assessment of the structural behavior.

Another important point to be discussed refers to the vertical displacements in the crown of the SPP. The correlation between the numerical and experimental results for these cases showed similarities. This fact is due to the presence of the pocket, which increases the rigidity of the tube and hence reduces the influence of geometric nonlinearity.

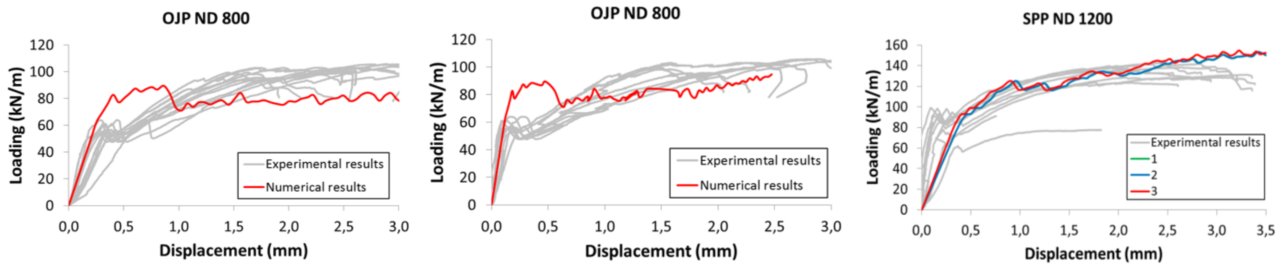
To illustrate the panorama of vertical displacements in concrete pipes, the Fig. 10 is displayed. In this figure, the load level that leads to displacement field represented is the maximum loading. Based on the results obtained in the numerical simulation, it can be observed that when under compression, the bottom of the tubes does an upward movement, both the SPP as OJP. In the region of the pockets, this upward displacement was reduced due to the increased stiffness. In the experimental results of Silva (2011) this behavior was also observed, validating once again the 3D computer model.

Comparing the maximum vertical displacements in the crown and in the invert, it was evident that the ND 1200 pipes presented lower displacement in the invert than the ND 800 pipes, due to the thickness of the walls being higher. This behavior was not observed in the crown because the displacements were similar for both diameters and types of pipes. The upward displacement of the invert was approximately 10% of the vertical displacement of the crown.

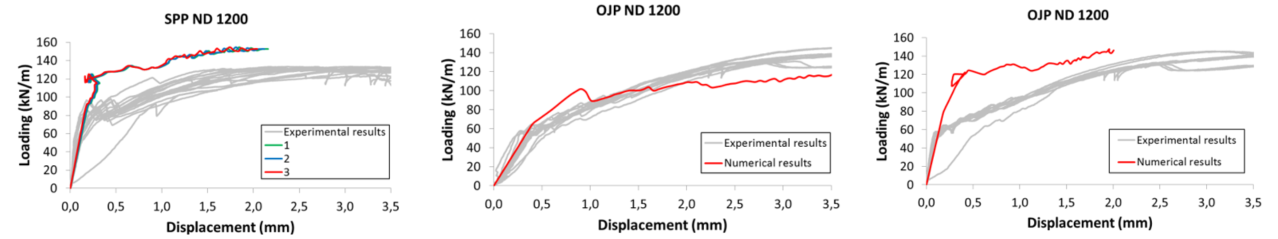
As reported earlier, the appearance of cracks inside the invert is very common. These cracks contribute to the deterioration of the reinforced concrete element because it provides the infiltration of fluids that flow through the pipe. Upon contact of the fluid with the reinforcement, the steel bars suffer corrosion and the pipe loses bearing capacity.

According to the numerical results, the cracking began at the same time inside the crown and the invert for all types of pipes. For the concrete pipes with the presence of the pocket (SPP), the cracking has initiated in this region. As expected, the cracks in springline concentrated on the outside. Considering the loading applied to the 800 mm concrete pipes, the presence of the pocket increased the loading from 62 kN/m to 75 kN/m; for 1200 mm concrete pipes, the loading was increased from 68 kN/m to 76 kN/m.

The cracking pattern obtained in numerical simulation was similar to the experimental results. As can be seen in Fig. 11, which presents the overview of cracking for the last load stage applied in the numerical models, there was the opening of a larger number of cracks in the crown and in the invert; in the springlines the cracks were also observed but in less intensity. The same situation was noted in Fig.



(a) Displacement in the crown SPP ND 1200 (b) Displacement in the springline SPP ND 1200 (c) Displacement in the crown OJP ND 800



(d) Displacement in the springline OJP ND 800 (e) Displacement in the crown OJP ND 1200 (f) Displacement in the springline PJP ND 1200

Fig. 9 Loading versus displacement curves in the crown and in the springline

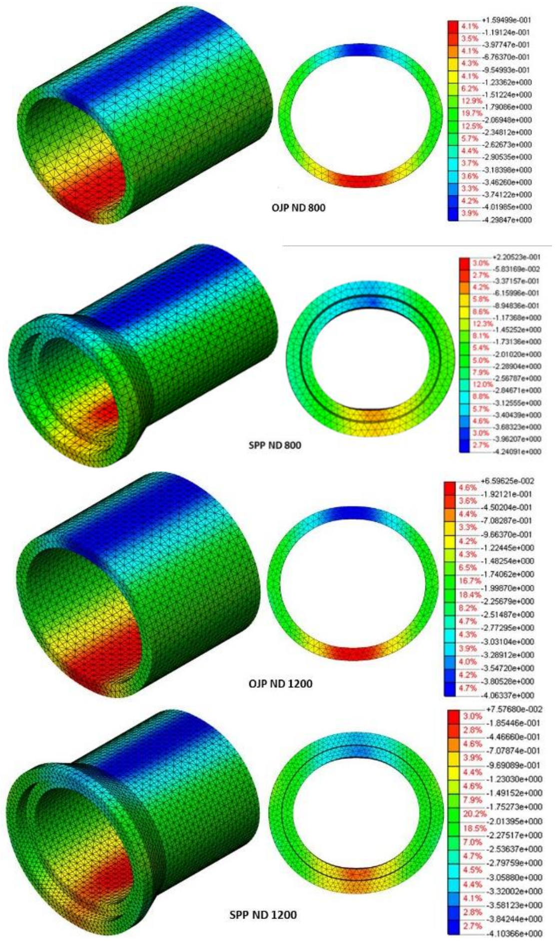
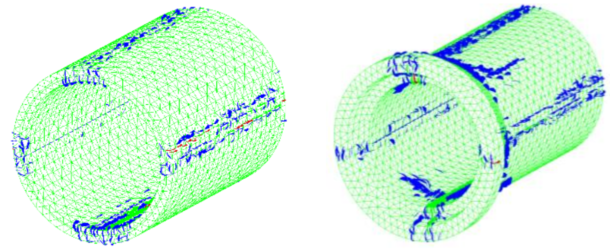
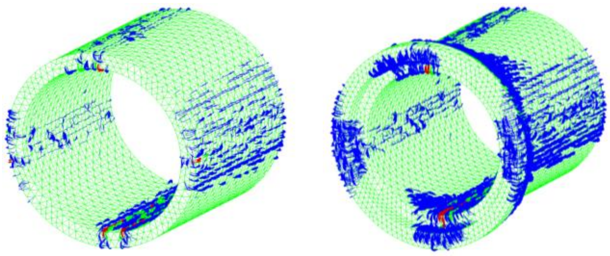


Fig. 10 Overview of the vertical displacement (Unit: mm)



(a) OJP ND 800 (b) SSP ND 800



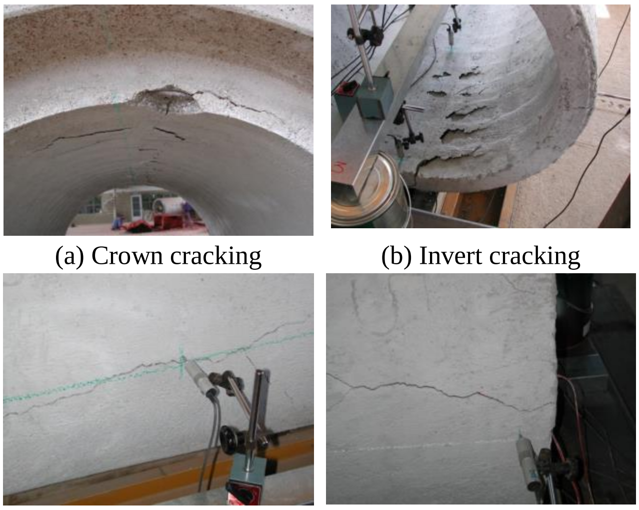
(c) OJP ND 1200 (d) SSP ND 1200

Fig. 11 Overview of cracking

12, where the tests cracking pattern are shown, the crack with higher thickness opened in the invert.

The results presented in Fig. 13 shows the strain of the inner and outer reinforcements of the pipes. Based on this information, it was possible to conclude that the reinforcement strain on the crown and on the invert were greater than the reinforcement strain on the springlines, this behavior was also highlighted by Silva (2011). It is important to emphasize that the inner reinforcement begins to deform first than the outer reinforcement in the region of the pocket.

The tensile stresses in the concrete were not measured in the experimental tests. The representations of tensions in the numerical models of the concrete pipes showed that the tensile strength is the most important mechanical property. The maximum compression strength presented by the pipes was 16.05 MPa for the SPP ND 1200, which is only 34% of its strength. The compressed regions of the pipes were the points where the load was applied and the support area, which comprise the external part of the crown and invert,



(a) Crown cracking (b) Invert cracking

(c) Springline cracking (d) Springline cracking

Fig. 12 Overview of cracking

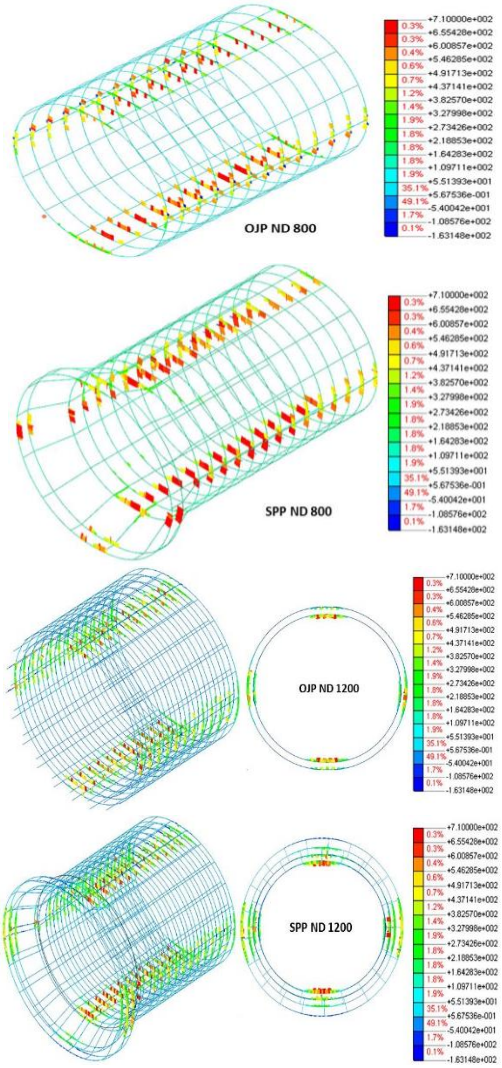


Fig. 13 Reinforcement stress (Unit: MPa)

respectively. Related to the tensile regions, the area with higher tensile stress was inside the crown and the invert and outside the spinglines, as shown in Fig. 14.

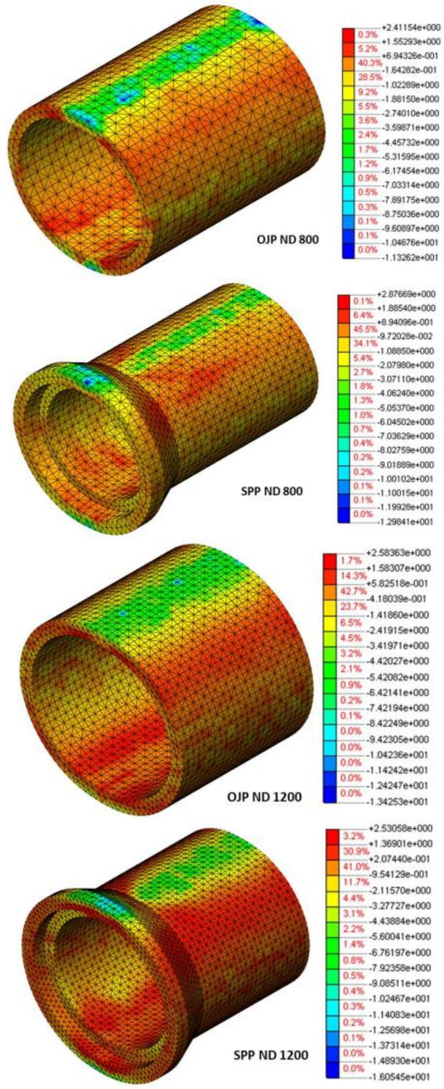


Fig. 14 Concrete stress for the ultimate stage of loading (Unit: MPa)

5. Conclusions

The numerical investigation at the reinforced concrete pipes presented in this paper provides important information on their behavior. The results of the standard tests applied on concrete pipes and the numerical analysis leads us to the following conclusions:

• The 3D numerical models were appropriated to simulate the behavior of SPP due to the presence of the pocket, which changes the stresses, strains and displacements along the length until the tip.

• The correlation between numerical and experimental results was satisfactory to validate the computation model. The difference between the curves loading versus displacement for experimental and numerical results is due to the geometric nonlinearity, especially in horizontal displacements (springlines). In flexible structures such as pipes, these effects are more significant and have an influence on global behavior.

• The cracking pattern presented by the numerical simulation was similar to the experimental results. The opening of a larger number of cracks in the crown and in the invert was observed as well as in the springlines the cracks open in less intensity.

• The reinforcement strain on the crown and on the invert was greater than the reinforcement strain on the springlines. It is important to emphasize that the inner reinforcement begins to deform first than the outer reinforcement in the region of the pocket. According to the simulation, the failure of the pipes occurs when the reinforcement reached the yield stress.

• Taking the numerical results about concrete strain into account, it was possible to conclude that the main property of this material for the concrete pipes is the tensile strength. The maximum compression stress presented by the pipes was 16.05 MPa for the SPP ND 1200, which is only 34% of its strength.

• The main conclusion of this paper is that the numerical models represented the behavior of the pipes and can be used in future studies in parametric analysis.

Acknowledgments

The authors would like to thank the financial support from CNPq (National Council for Scientific and Technological Development) and CAPES (Coordination for the Improvement of Higher Education Personnel), the Company FERMIX Indústria e Comércio Ltda for donating the concrete pipes and support in conducting the tests and the Computer Lab of the Department of Structural Engineering of the School of Engineering of São Carlos-SP by the software.

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