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EXPERIMENTAL AND NUMERICAL STUDY OF THE PERFORMANCE OF EXISTING PRESTRESSED CYLINDRICAL CONCRETE PIPES STRENGTHENED WITH REINFORCED CONCRETE OR CARBON-REINFORCED FIBER POLYMER JACKETS

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Abstract

Prestressed cylindrical concrete pipes (PCCPs) are widely used as precast moduli of water supply systems worldwide. This study experimentally investigates the bearing capacity of 5 PCCPs under internal hydraulic pressure loads to check the capability of specific retrofitting/strengthening schemes to upgrade this bearing capacity. Provided that the prestressing wires are fully active according to design specifications, the original specimen performed satisfactorily for the set internal hydraulic pressure limit of 8.5 bar. Specimens retrofitted with either internal or external CFRP or RC jacketing performed satisfactorily for internal hydraulic pressure levels well above this 8.5 bar limit. A critical factor is, as expected, the loss of prestress. The measured response of the pipes was used to validate a numerical approach aimed at numerically simulating the behavior of the original and retrofitted PCCP pipes. The numerical predictions are in good agreement with the corresponding experimental measurements.

Keywords: prestressed concrete cylindrical pipes, experimental investigation, numerical simulation, reinforced concrete jackets, carbon fiber reinforced polymers

1 INTRODUCTION

This manuscript focuses on the behavior of prestressed concrete cylinder pipes (PCCP) under hydraulic internal pressure. An existing major pipeline generated this research [1,2]. In a Greek city, a PCCP pipeline breakage caused a serious interruption of the normal supply of water for more than 10 days in 2018. To this end, regular inspection and maintenance of the water pipe network are of great importance. The applied prestressing through the steel wires is the most significant parameter of the structural performance of a PCCP [3-5]. The loss of the prestress is the most common cause for the deterioration of the bearing capacity [6-8]. Herein, specimens representing the modulus of the pipe in situ, which was almost identical to the modulus that makes up the actual pipeline that is in operation are studied experimentally and numerically as well. The experimental procedure involves the testing of five specimens with

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external diameter 2.10m, internal diameter 1.80m and length 1.00m, including one specimen with the prestressing wires removed, one as built and 3 strengthened specimens with different retrofitting schemes. In particular, the strengthening schemes involve applying internal CFRP jacket, external CFRP jacket and external R/C jacket.

2 METHODOLOGY

Laboratory tests were carried out by subjecting a number of specimens under internal hydraulic pressure. Following numerical models of this experimental procedure were developed in an effort to numerically simulate the measured behavior of the tested specimens. Figure 1 depicts a typical cross-section of the original pipe with a fully active prestressed reinforcement with a total thickness equal to 156 mm. From the internal face to the outside layer of the concrete core, where the prestressing wires are placed, the concrete thickness is equal to 141.5 mm (including the steel membrane). Within this concrete thickness, a thin steel cylindrical membrane is placed at a distance equal to 90 mm from the internal face of the pipe. The thickness of this membrane is equal to 1.5 mm, as measured in the laboratory. Samples of the concrete core were taken of the tested PCCPs, with dimensions 100 x 100 x 100 mm3. The average compressive strength was found equal 61.11MPa. Steel coupons of this membrane were tested in axial tension as well. The ultimate tensile stress was equal to 385.3 MPa, and the yield stress was equal to 296.7 MPa. At the outer face of the concrete core, 4 mm diameter wires were wrapped radially and stressed. Coupons were sampled from these prestressing wires, which resulted in an average ultimate tensile stress equal to 1756 MPa and an assumed yield stress equal to 1400 MPa.

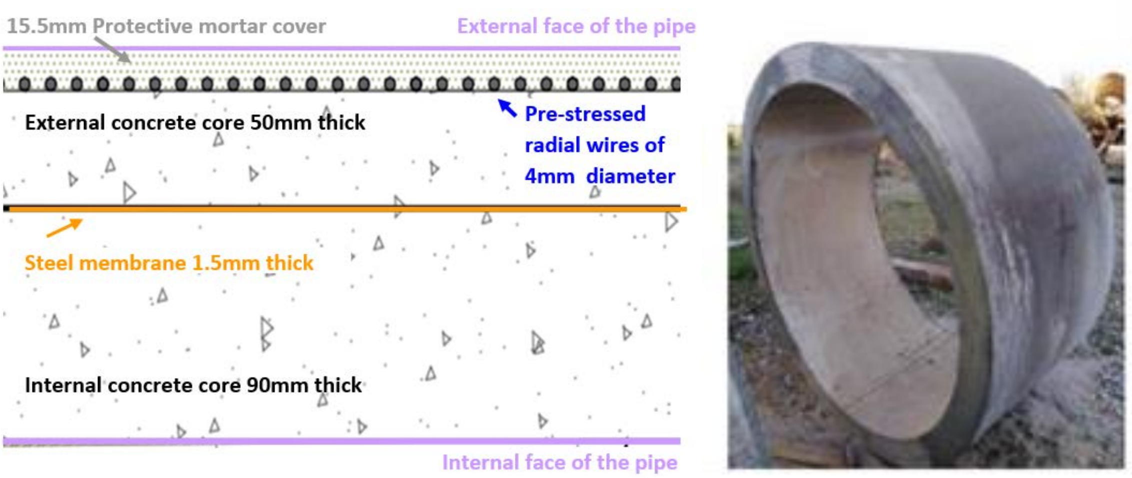


Figure 1: Cross-section of the original PCCP with fully active prestressing wires (left) and the original pipe with fully active prestressing wires (right)

The current study utilized internal hydraulic pressure equal to 8.5 bar, representing pressure levels due to hydraulic gradient and water surge conditions. To achieve this objective, a strong internal tubular cylinder was constructed with a low-shrinkage concrete mix, with a compressive strength of 25 MPa, and light longitudinal and radial reinforcement. The external diameter of this cylinder was approximately 1680 mm, its length was the same as that of the specimens (1000 mm), and its average thickness was equal to 260 mm; it was designed to act as a loading reaction cylinder. Each pipe specimen was placed with its longitudinal axis vertical, placing this reaction cylinder inside its internal diameter, thus forming a system of twin tubular concentric vertical cylinders with a gap of 60 mm (Figure 13a–c). Two identical thick steel circular plates (25 mm thick flanges) formed the top and bottom sealing covers of the whole system (Figure 2). These plates were stiffened with twelve (12) radial stiffeners, which were provided with the appropriate anchoring seats so that each could host two steel rods of 20 mm diameter (24 rods in total). Prior to applying the internal hydraulic pressure, all these steel rods were lightly prestressed consecutively in a step-by-step controlled manner so that these covers would provide the necessary sealing of this loading system. The same loading arrangement was used for all tested specimens to compare their measured behaviour under identical boundary conditions. A very flexible but strong plastic membrane was placed within the internal gap to augment the sealing conditions and to ensure that the whole experimental process was free from any accidental fluid leakage, especially when the internal hydraulic pressure attained relatively high amplitudes.

Pressure sensors were provided to measure the applied pressure at both the top and bottom piping near the corresponding valves and to record it with an automatic data acquisition system. Each part of this test rig was designed through a detailed numerical simulation [9]. Displacement transducers were placed at mid-length outside of each tested specimen at specific diametrically opposite locations (namely East, West, North and South) for two diameters perpendicular to each other in order to monitor the variation in the pipe's horizontal radial expansion. At the same locations, strain gauges were attached in order to monitor the variation in the radial strain of certain parts of each specimen at these locations. In the present study, for a specimen without prestressed bars (Spec. 10), these strain gauges were attached to the steel membrane. For specimens in which the fully active prestressing wires were accessible (Spec. 7 (original pipe) and Spec. 5 (internal CFRP jacket)), these strain gauges were attached to the prestressing wires. For specimens with external jackets, the strain gauges were placed on either the surface of the FRP jacket (Spec. 3) or the radial reinforcing bars of the external RC jacket.

Figure 2: A cross-section of the loading arrangement of the pipe showing the 260 mm thick reaction cylinder in the interior (pink colour) with internal and external radial of 580 mm and 840 mm, respectively. The pipe specimens at the exterior (grey colour) with a thickness ranging from 100 mm to 200 mm. The gap in between (white colour) is filled with water under pressure.

Figure 3: Experimental set-up for testing the PCCP pipe specimens under an internal hydraulic pressure loading arrangement.

3 EXPERIMENTAL RESULTS

The measured internal pressure behaviour of each of the five (5) tested specimens is presented in the following way. The variation in the average expansion of the pipe radius, measured at four locations, is plotted against the variation in the internal hydraulic pressure amplitude. As can be seen in Figure 4, for the specimen without prestress (spec. 10) the slope of the curve corresponding to the variation in the radius expansion against the internal pressure changes when the internal pressure reaches 2.8 bar. When the internal pressure increases further, the expansion of the radius increases at a higher rate than before. This must be attributed to the cracking of the concrete, which means that for internal pressure values higher than 2.8 bar, the internal pressure is resisted solely by the steel membrane. For internal pressure values higher than 5.0 bar and up to 5.2 bar, the radial expansion continued to increase at an even higher rate than before. Considerable permanent deformation and strain levels remain at unloading.

Spec. 7 refers to the specimen with fully active prestressing wires. Its response is almost linear with no remaining strains at unloading, confirming that the prestressing wires perform within their elastic range up to the applied internal maximum pressure of approximately 8.5 bar. Due to safety precautions, no attempt was made to increase the internal pressure beyond this set limit value. At the same figure, the recorded behavior of Spec. 5, retrofitted with radial 3 layers CFRP jacket to its internal pipe surface, shows that up to pressure amplitude 10.0 bar prestressing wires deform within elastic range, whereas beyond internal pressure 8.0 bar micro-cracking of internal concrete volume occurs. The response of Spec.3, which is retrofitted externally with 3 CFRP layers, plotted, at figure 4, is almost linear up to an amplitude of 10.0 bar. Beyond this internal pressure amplitude till the pressure amplitude of approximately 12.0 bar, there is remaining permanent expansion of the radius of the pipe, which is again attributed to the micro-cracking of the internal concrete volume. Finally, the externally strengthened with R/C jacket specimen (spec. 1) is depicted in figure 4 as well. An initial change in slope can be seen for an internal pressure amplitude above approximately 6.0 bar. The radial expansion versus the internal pressure variation changes its slope even further for an internal pressure amplitude higher than 11.0 bar. For pressure values larger than 11.0 bar up to almost 23 bar, the slope of the curve remains almost constant. After unloading, there is considerable remaining permanent radial expansion.

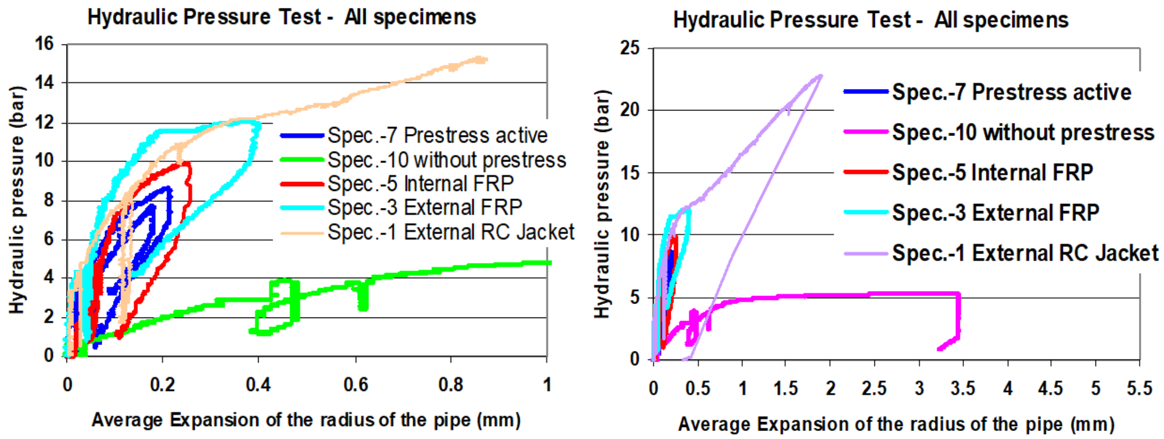


Figure 4: Radial expansion versus internal hydraulic pressure response for all tested specimens.

4 NUMERICAL PREDICTIONS

A series of 3D numerical simulations were next performed using solid elements for the concrete volume (either for the original cylinder or the RC jacket), shell elements for the steel membrane and the CFRP jackets (internally or externally), and truss elements for the pre-stressing wires and reinforcing rebars of the RC jacket (figure 5). Each of these elements were provided with nonlinear constitutive laws, which followed the measured behavior for the steel membrane, for the prestressing wires for the pipe-concrete and for the CFRP layers, respectively [1]. Five different numerical models were developed, in correspondence with the tested specimens, as depicted in figure 6. A step-by-step nonlinear analysis was utilized first by applying the prestress force. The prestressing force was applied as an initial loading condition, defining the desired prestress level for each of the fifty-two (52) prestressing wires within the 1 m length of the tested samples, numerically simulated as truss elements. The actual prestress level of each specimen was not exactly known during testing. A prestress level equal to 1300 MPa was adopted for all specimens as an initial prestress level. Due to the deformability of the concrete volume at the end of the first loading condition, the resulting balanced prestress level for the numerical model was equal to 1270 MPa, also approximating in this way the loss of prestress due to creep. Following, the hydraulic internal pressure was applied at the second loading condition, starting from the state of deformation, stress, and strain domain at the end of the first loading condition. This pressure was uniformly distributed in an axisymmetric way all around the internal face of the numerical model. The hydraulic internal pressure was applied in successive numerous steps of the nonlinear analysis process of continuously increasing amplitude, thus simulating exactly the hydraulic internal pressure which was gradually applied during testing. The adopted boundary conditions prevented the pipe from moving as a rigid body. This was done by constraining the horizontal displacement in a direction parallel to the axis of the cylinder for all the nodes located at the cross section of the vertical plane of symmetry for the pipe as well as the vertical displacement, the horizontal displacement normal to the axis of the cylinder, and the rotation around the same axis at the central point of the whole structure. The boundaries of the two cross sections at the end of the vertical pipe as well as all the cylindrical surfaces of the internal and external pipe were left free from any displacement constraints. The numerical results obtained are presented by plotting the variation of the applied internal hydraulic pressure versus the variation of the resulting radial expansion in comparison with the corresponding experimental measurements.

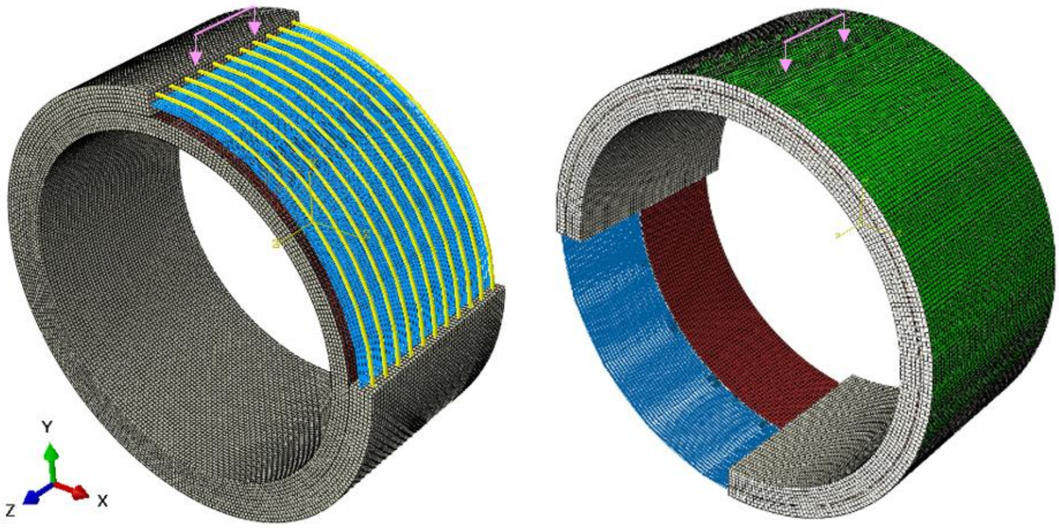
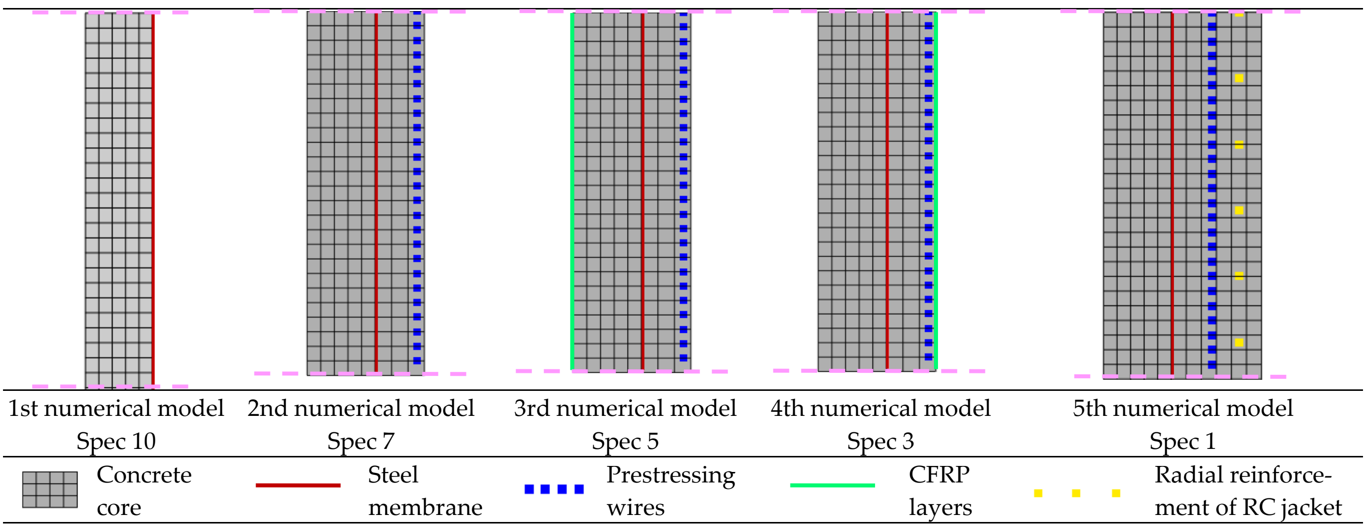


Figure 5: 3D view of the model (left) with the RC jacket (right) with the external CFRP jacket



The concrete core is depicted in gray, the steel cylinder in red, the prestressing wires in blue, the CFRP jacket in green and the reinforcing bars of the RC jacket in yellow.

Figure 6: Typical cross-sections of developed numerical models.

In Figure 7 (left) the numerically predicted radial expansion versus internal pressure response is compared with the one measured during testing. In Figure 7 (right), the numerically predicted zones of plastic strain with relatively large values are shown when the internal pressure amplitude is equal to 2.45 bar, indicating in this way the initiation of concrete cracking. This was also identified from the measured response (see a change of slope of the plotted curves in Figure 4) but at somewhat higher internal pressure value (approximately 3.0 bar). For pressure values higher than the concrete cracking pressure, the nullification of the concrete volume contribution to resisting the internal pressure occurs, thus having only the steel membrane to resist the internal pressure. From Figure 7 it can be seen that the widespread yield of the steel membrane occurred for 5.0 bar internal pressure during testing whereas this was predicted to occur for 5.9 bar.

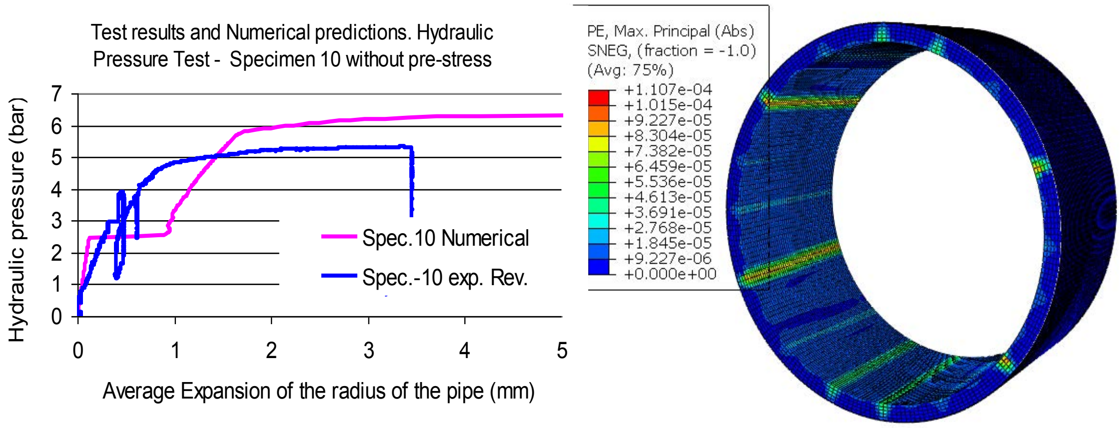


Figure 7: Internal hydraulic pressure versus radial expansion response. Measured and numerically predicted (b) The numerical simulation of the zones with concentrated large concrete plastic strains.

Following, the numerical predictions of the model with all prestressing wires is presented. As described, the numerical analysis commenced by first applying to all the prestressing wires a prestress force corresponding to a radial axial stress equal to 1300 MPa. As already discussed, the actual level of prestress for the tested specimens is not known. To study the effect of a prestress level variation an additional numerical analysis was performed for this specimen by introducing a small increase to the prestress level thus applying a prestress level equal to 1400 MPa, instead of 1300 MPa. The resulting variation of the internal hydraulic pressure versus the radial expansion of these two models together with the experimental results is plotted in Figure 8 (left). As can be seen, the resulting differences are relatively small. Therefore, all subsequent numerical simulations were performed and the corresponding results were derived for prestress level equal to 1300 MPa. At the same figure (8 right) the predicted mode of failure is shown as concentrated plastic stains of the concrete core.

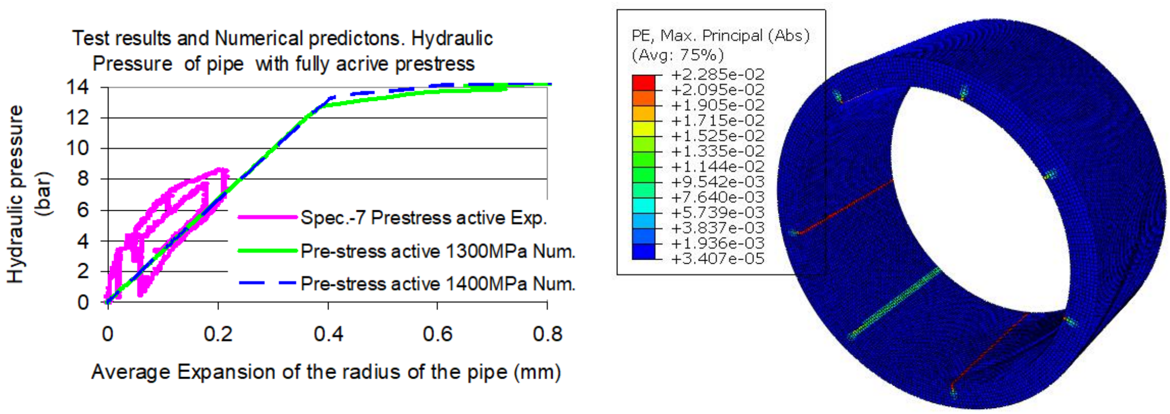


Figure 8: Measured and numerically predicted response for specimen 7: internal hydraulic pressure versus radial expansion response (left), the predicted plastic strains for the concrete volume for internal hydraulic pressure of 14.6 bar (right).

The same procedure was followed in the 3rd model, which was formed by adding in the previous numerical simulation an internal layer of shell finite elements corresponding to the internal CFRP jacket of spec. 5. The numerical simulation was extended to pressure levels higher than the pressure levels applied during testing. Figure 8 (left) shows the variation of the inter-

nal hydraulic pressure versus the radial expansion of the model strengthened with internal CFRP jacket together with the corresponding experimental results. Again, the predicted radial displacement versus internal pressure response compares in a reasonable way with the corresponding measured response up to the pressure level of 10.0 bar. Beyond this pressure level no measurements are available. For internal pressure amplitude equal to 18.5 bar, the steel membrane and the prestressing wires are beyond yield. However, the CFRP jacket is still below its tensile strength. From these predictions it can be concluded that the internal CFRP jacket can be quite successful in increasing the hydraulic internal pressure capacity for this pipe.
The same procedure described before was repeated by adding in the numerical simulation of an external layer of shell finite elements corresponding to the external FRP jacket of specimen 3. As it was found with the internal CFRP jacket, again both the steel membrane and the prestressing wires are beyond yield. However, the CFRP jacket is still below its tensile strength. From these predictions it can be concluded that the external CFRP jacket can be quite successful in increasing the hydraulic internal pressure capacity for this pipe (figure 9 right).

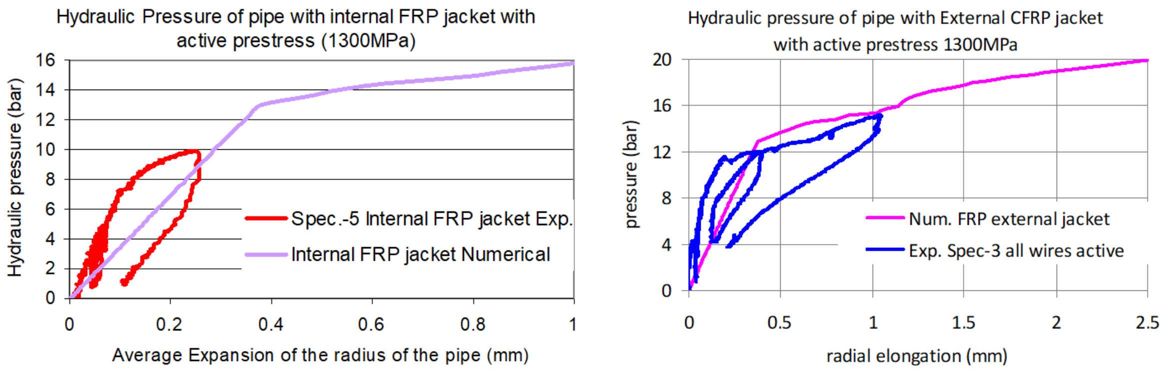


Figure 9 Internal hydraulic pressure versus radial expansion response of measured and numerically predicted response for PCCP strengthened with CFRP jacket internally (left and externally (right)

Next, the response of the R/C jacket strengthened PCCP model is presented. This time the numerical simulation includes external layers of solid finite elements together with line truss elements corresponding to the external RC jacket of specimen-1. The response in terms of applied hydraulic pressure versus the radial expansion is depicted in figure 10 (left). Again, the predicted radial displacement versus internal pressure response compares reasonably well with the corresponding measured response up to the pressure level of 22.5bar, which is a maximum pressure level reached both during testing as well as in the numerical simulation.

The numerical predictions of the internal pressure versus the radial expansion response for all studied specimens is shown in Figure 10 (right). As can be seen, in contrast to the response of the original pipe with no jacket, the presence of all the jacketing schemes restrains the development of radial expansion to relatively low levels even for high internal pressure values. As was discussed, the presence of jacketing does not allow the yielding of either the steel membrane and / or the pre-stressing wires to develop but for internal pressure values considerably higher than without the presence of such jacketing. In all cases, such yielding is predicted to develop for internal pressure values well above 14bar. This pressure level is 60% higher than the maximum operating internal pressure specified for such pipes. This represents a satisfactory safety precaution on condition that the pre-stressing wires are fully active, as was assumed up to now in this numerical investigation.

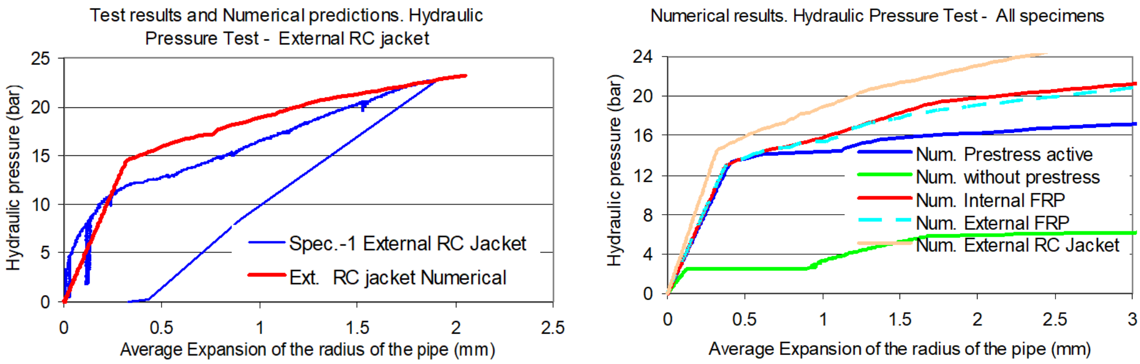


Figure 10: Measured and numerically predicted response for specimen(left) and numerical predictions of the internal pressure versus radial expansion response for all specimens (right)

5 CONCLUSIONS

The main conclusions of the present investigation can be summarized as follows:

- Provided that the prestressing wires are fully active according to design specifications, the original specimen performed satisfactorily for the set internal hydraulic pressure limit of 8.5 bar.
- Specimens retrofitted with jacketing performed satisfactorily for internal hydraulic pressure levels well above this 8.5 bar limit. All used retrofitting schemes were shown to be satisfactory in upgrading the hydraulic internal bearing capacity.
- The assumed nonlinear mechanisms of the concrete volume and steel membrane were verified by comparing numerical predictions with measurements in terms of strain response of the steel membrane, when available, damage patterns of the concrete volume and the overall internal pressure versus radial expansion response.
- The numerical predictions of the contribution in the bearing capacity of the fully active prestress as well as the three specific jacketing schemes were also verified from comparisons with the corresponding measured pressure versus radial expansion response.
- From these comparisons it can be concluded that the used numerical simulation methodology results in acceptable predictions of the internal pressure–radial expansion response for such pipes in their original construction.
- Similarly, from these comparisons it can be concluded that the used numerical simulation methodology also results in acceptable predictions of the internal pressure versus radial expansion response for such pipes when retrofitted with the studied jacketing schemes employing either CFRP or RC concrete jackets.
- From all the above, it can be concluded that the employed numerical simulation methodology can be a valid tool for predicting the bearing capacity of this type of water pipes, either in their original form or retrofitted with the specific studied schemes provided that the employed assumptions are realistic. Apart from the material properties a very important assumption is the level of the existing prestressing. The way prestressing defects are recorded in-situ is of great importance. The level of confidence of such numerical predictions is directly linked with the validity of all these important assumptions.

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