VISCOELASTIC BEHAVIOR OF INTERNALLY PRESSURIZED PVC PIPES WITH AND WITHOUT COMPOSITE REPAIRS

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Abstract. *The fluid transportation in industrial plants is made, essentially, by metallic or polymeric pipes which are prone to suffer from mechanical, physical and/or chemical damages, thus needing repairs that do not interrupt the industrial processes. The conventional repairs, in use, present limitations that can be surpassed by the use of composite repairs. The main objective of this work is to study the phenomenon of viscoelasticity in new PVC pipes, as well as in damaged and repaired ones. And, in addition, analyze the recovery of the mechanical integrity of the repaired specimens. In this context, it presents theoretical and experimental studies of the mechanical behavior of polymeric pipes repaired with composite material, submitted internal pressures. Thin pipes of PVC rigid walls with diameter (D) over thickness (h) ratio above twenty, $D/h \geq 20$, were analyzed. The experimental results showed that the PVC pipes present viscoelastic behavior at room temperature, about 25 °C. However, it is possible to restore the original stiffness of damaged PVC pipes and also to eliminate the viscoelasticity through the use of composite repairs, in which the matrix is a cold cure epoxy resin and the reinforcement E-glass woven fabrics or cotton cloth.*

Keywords*: Polymeric pipes of thin wall, Viscoelasticity, Composite repair.*

1. INTRODUCTION

The complex infrastructure of the industrialized countries depends on systems of pipes and ducts for the fluid transport. The North American infrastructure system can be cited, referring to the fluid transport for systems of piping and ducts, where there is statistical data of damages (SES, 2002) that shows the faced difficulties to solve problems of damages using the technology of conventional repair of this system. The conventional repairs are classified in four basic types that are presented as: iron braces; gloves; flanges and connectors. In these cases, the interruption of the flow of products is necessary, causing economic losses.

The polymeric pipes found in industrial plants carry fluids of important use as diesel, salty water, air, fluids using generalized chemical products; and hydrocarbons. The technology of composite repair in industrial installations and the civil construction presents advantages for situations of damage in polymeric and metallic pipes, where the process of fluid transport cannot stop. It has three main scenes of damages in systems of metallic pipes and ducts, considered in literature (AEA, 2001): (i) loss of metal in the external wall; (ii) loss of metal in the internal wall; and (iii) component of the piping with leakage. This work serves as analysis of real situations for loss of external material, not occurring leakage. The pressures and ranges of permissible temperatures for polymeric pipes, in accordance with international norms, are up to 5 MPa and from – 20 ºC to + 60 ºC, respectively.

In this scenario, the objectives of this work are: (a) to compare the results of the analytical solution of the Burger's two-dimensional viscoelastic model, with the experimental ones, for rigid PVC perfect pipes of thin wall; (b) to analyze the effect of the machining on the PVC pipes; (c) to carry out composite repairs in PVC machined pipes; and (d) to analyze the phenomenon of the viscoelasticity in the PVC pipes repaired with composite layers, with epoxy matrix reinforced with E-glass fibers.

In the conclusion it will be shown, in percentage terms, the recovery of the mechanical integrity of repaired rigid PVC pipes, and the elimination of the viscoelasticity in the machined region submitted to constant ambient temperature.

2. BURGER MODEL FOR PVC VISCOELASTIC PIPES

Many successful models in the study of the plastic materials reinforced or not, were based in associations of springs and shock absorbers, which, respectively, represent the intermediate state between elastic and viscous behavior of those materials (Christensen, 1971). The viscoelasticity of plastic components, submitted to mechanical loadings, presents two kinds of deformation, one which is independent of the time, and another one, viscous, which depends on the fluency of the material along the time. In this study, the loading occurs due to the internal pressurization of the pipe. One of the main objectives of this work is to compare the analytical results obtained from a theoretical model of viscoelasticity, with those measured using rigid PVC pipes, tested in the range of constant room temperature T = 25 ºC ± 0,5 ºC. The glass transition temperature of PVC is T_g = 80 °C (Crawford, 1998). In this investigation, it will be possible to find out if the viscous term of the phenomenon of viscoelasticity is reduced, or not, as suggested by Crawford (1998). Additionally, for segments of PVC pipes, repaired with woven fabric of E-glass fiber in matrix of epoxy resin, tested in this work, the viscous effect should be constrained, as a consequence of the fact of the fibers of E-glass present linear elastic behavior in temperatures near to 25 ºC and even higher (Gandur, 2001). So, it is expected that the composite repair will inhibit the viscoelasticity of the PVC.

In this section, the Burger model (or "model of four parameters") will be presented. In such model, the phenomenon of the viscoelasticity can be observed by means of the graphic of the deformation in function of the time (Gandur, 2001a). The first models created with simple association of a spring to a shock absorber were: (i) in series – Maxwell model and (ii) in parallel – Voigt model. The models of viscoelasticity, in general, can be associated to tests of retardation and relaxation. The choice of the Burger model, constituted of the assembly of the elements in series of Maxwell and Voigt models associated – called Kelvin model, took into account, that each one of these, alone, fail in the rigorous description that occurs with the dependent deformation of the time, being the first one in the test of relaxation, and the second, in the retardation.

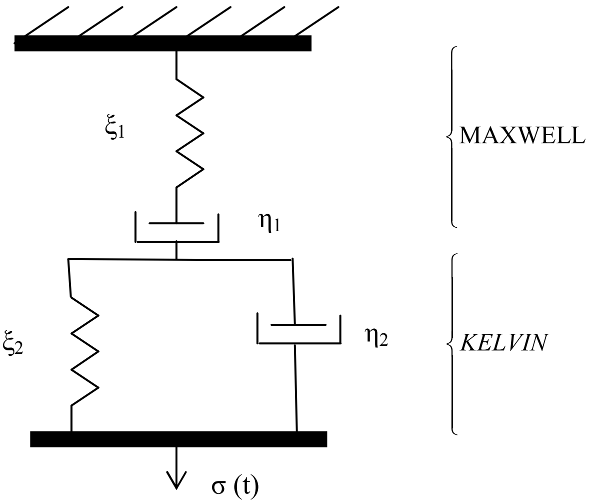


Figure 1. Burger model representation (Gandur, 2001)

In Figure 1, it is shown the dependent unidirectional tension of the time, σ(t), the constants of the springs ξ_1 and ξ_2, analogous to Young's modules, the constant of the shock absorbers η_1 and η_2, to viscosities, representing each state of transition, from glass to the rubber one. In terms of mathematical modeling, the retardation test corresponds to keep the internal pressure constant in the pipe. Therefore, the tensions in the longitudinal direction and the circumferential one remain unchanged. The relaxation test, carried through after the stage of retardation, associates with the relief of the pressure, when the tax of variation of the deformation in function of the time already is practically null. The general equation of the unidirectional deformation of the model of Burger is given, in accordance with Crawford (1998), by Equation (1):

$$\varepsilon(t) = \frac{\sigma(t)}{\xi_1} + \frac{\sigma(t)}{\eta_1} t + \frac{\sigma(t)}{\xi_2}\left[1 - e^{-\frac{\xi_2}{\eta_2}t}\right] \tag{1}$$

The constants $\xi_1 = \sigma_0 / \varepsilon_1$ and $\eta_1 = \sigma_0 / \varepsilon_1$ are determined from the deformation's graphic in function of the time in the test of retardation in the most stable stretch of the curve, where the deformation grows linearly with the time. And still, the constant $\xi_2 = \sigma_0 / \varepsilon_2$ and η_2 they also can be determined in the stretch of the curve that the deformation grows quickly in the beginning of the test, and, being η_2 given by the Equation (2):

$$\eta_2 = \frac{\xi_2 t}{\ln\left[\dfrac{1}{1 + \dfrac{\xi_2}{\xi_1} + \dfrac{\xi_2}{\eta_1} t - \dfrac{\xi_2}{\sigma_0}\varepsilon(t)}\right]} \tag{2}$$

3. EXPERIMENTAL PROCEDURES

The general plan of the experimental procedures, shown in the Figure 2, present all of the important components of the experimental set up. The gage shown in the illustration, in order to give more details of the instrumentation, is composed by two strain gages, rosette type, in the center of the pipe, located opposite side each other. The pressure system was installed to pipe specimens with the connections of the hose to the hydraulic pump.

3.1. The determination of the mean radius and the thickness

The rigid PVC pipes that exist in the market present mechanical and physical variable properties (Albuquerque, 1990; Matweb, 2005) which includes, among them, density, Young's modulus, tensile strength and absorption of water.

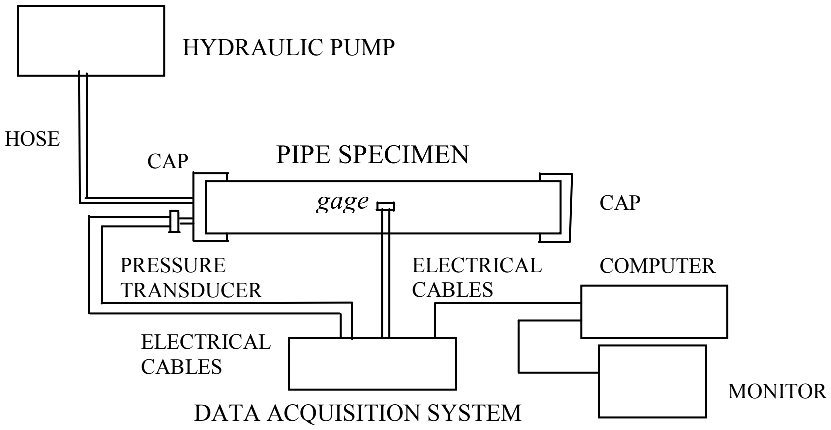


Figure 2. The test set up of the instrumented pipe specimen

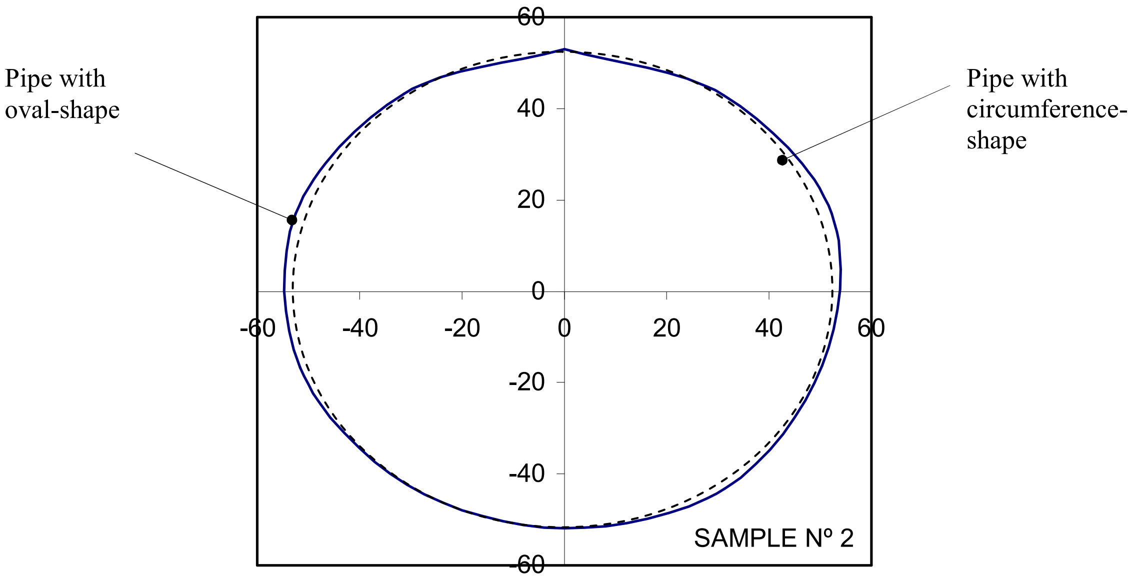


Figure 3. Oval-shape representation of the rigid PVC perfect pipe specimen in the central region

The method of measure the radius variation of the pipe (Piratelli Filho, 1976) permits to quantify for the PVC pipes, how much it deviates from a perfect circumference, as shown in Figure 3. In addition, measurements of the thickness and other geometrical parameters were carried out for the calculation of mean radius of the five PVC pipe specimens with nominal diameter 100 mm. The mean and standard deviation values of the radius are 51,93 mm and 1,00 mm and the thickness 1,85 mm and 0,05 mm, respectively, of pipe's specimens, identified with numbers from 1 to 5, carried out to the mean temperature of 21 ºC.

It is important to obtain the mean values of radius and thickness of the specimens, regarding the variation of the radius along one of the circumferencial lines, because they define how much severe is the oval-shape of the pipe in the central region. The nominal thickness PVC pipes is 1,80 mm, exemplified in the Figure 3, that was carried out in the program Excel 2003, to determine up to which point can be machined the pipe specimen.

3.2. The pipe sample configurations

The figures 4 and 5 illustrate the configurations of specimens clamped in the left extremity, and, in the right, supported with axial displacement freedom: perfect pipe (PP) and repaired pipe (RP).

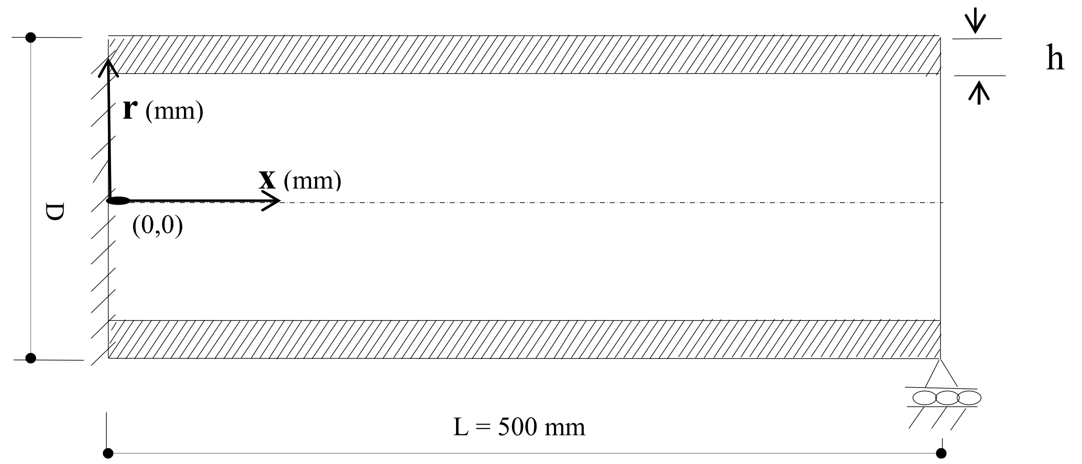


Figure 4. Perfect pipe specimen (PP) representation with caps at the ends

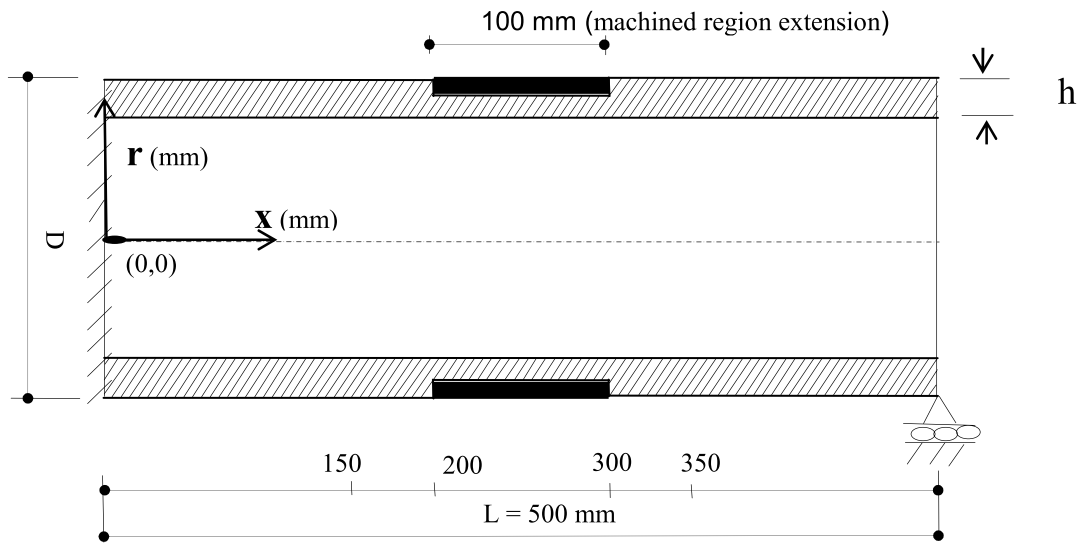


Figure 5. Repaired pipe specimen (RP) representation with caps at the ends

3.3. Procedure of gluing the caps, machining the pipes and repairing it with composite material

Two kinds of caps were used to close the extremities of the specimens: one of aluminum at the clamped end (with screwed openings for fixation of the pressure transducer and the hydraulic pump) and to another one of rigid PVC at support with axial displacement freedom. The manufacturation of the aluminum cap was carried out with a piece of extruded aluminum, measuring 250 mm of length and 127 mm of diameter. Six caps were manufactured, with diameter of 120 mm, circular grooves of depth of 20 mm and width of 6 mm, that permitted them to be set on PVC pipes of diameters 80 mm and 100 mm. In the cleaning of the grooves, a wet cotton with grease cleanerwas used, initially. After that, acetone followed with sulphuric acid, that presented 12% of concentration in weight, was also used (Pardini, 2005). In the sequence, the grooves of the aluminum caps were filled with epoxy adhesive, for insulation and clamping of the caps.

The fixation of the caps at the pipes end was carried out with adhesive (epoxy resin), that is a mixture of proportion, per weigth, of 100 g Araldite LY 1316 BR for 13 g of Catalyzer HY 1208, of cold cure of 24 hours, temperatures between 20 ºC and 25 ºC, that also was the operation range temperature, whose this adhesive physical and mechanics properties are found in the manual fabricant Huntsman (2005).

The clamping of the cap was carried out with stretch extension k_{real} = 15 mm, that is much greater than the theoretical value of $k_{theoretical}$ = 1,09 mm to pipe with R = 50 mm, h = 1,8 mm, and the shear tension of the adhesive is 22,5 N/mm^2, according to the manual of the Huntsman (2005) and internal pressure of p = 2 N/mm^2, therefor the factor of security (F) of the specimens is F = 15 / 1,09 = 13,76 (Faluhelyi, 2006).

From the rigid PVC pipe properties and the definition about the deviation of circumference-shaped of the transversal section of pipe specimens, it's chosen the process of reduction of 50% of the wall thickness. The specimens 1 to 3, with initial nominal the thickness of 1,8 mm, were machined along in the central region with $h_{machined}$ = 0,9 mm. The machining process of the pipe wall, was carried out in a lathe, and consumed only 7 minutes. The thermal deformations during the machining were negligible because the operation was careful and carried out at constant room temperature (25 °C).

The composite repair chosen in the machined specimens was the Epoxy/E-glass (balanced woven fabric) with a layer of thickness 0,25 mm, witch can eliminate the effect of viscoelasticity in the repaired region of the rigid PVC pipe specimens.

After the E-glass woven impregnation with epoxy, the repair was applied straightly over the central machined region the pipe. The vacuum bag process in the experimental procedure was not carried out, to keep the mechanical properties lower as possible, reducing to the maximum the strangulation in the region of the composite repair.

The application of the composite repair follows a procedure such that to be able to measure, at the end of the task, the masses and volumes of fiber E-glass and resin contained in the composite. The procedure with description summarized is: measurement of the weight of the pipe; cutting and measurement of the weight E-glass woven fabric; measurement of the components of the resin, adhesive and catalyst; mixture of the components of the resin; impregnation of the resin; application of the repair in the machined region of the specimen; and now measurement of the weight of the pipe, with the repair incorporated.

3.4. Tests on the pipe specimens

The tests with the PVC pipes were carried out in two configurations: (i) in perfect pipes (PP) and machined ones (MP) and (ii) repaired pipes (RP). Initially, they were pressurized and measure the deformations, circunferencial and longitudinal, respectively, of all of the specimens, during a break of time, that for the specimen number 1 was of five hours, submitting to the constant pressure for the attempt, with the values of 0,3 MPa and 0,6 MPa. In the third test, of the specimen identified like number 1, it was realized the continuous pressure increasing up to the instant of the break. For the specimens from number 2 to 4, the procedure was similar to that the specimen number 1, maintaining constant the pressure during 15 minutes, and, to the end of each test, the pressures were released, with records in the data acquisition system. The same way was done for the test in the instant of the failure of the specimen number 3.

In the second phase, the machined pipe (MP) number 5 repaired with stuff composite of a layer of E-glass (balanced woven fabric), of thickness 0,25 mm, in the central region, being the resin cured, without vacuum, at the room temperature, between 25 ºC and 29 ºC. The specimen pipe repaired nº 5 was pressurized up to 0,3 MPa, after then increasing of 0,1 MPa to 1,2 MPa, in constant intermittent intervals of pressure during 10 minutes, and finally with increments of 0,1 MPa to the instant of failure.

4. RESULTS AND DISCUSSION

The specimen number 1 (PP) presented during the tests of five hours (300 min) a strain of 4,4% of viscoelastic deformation (blue line), that is visualized at the Figure 6 by the graphic of circumferential deformation *versus* time subjected to pressure of 0,6 MPa.

The figures 7 and 8 show the circumferential deformation *versus* time curves, experimental and analytical by the Burger model, of perfect pipes (PP) and machined (MP), respectively. The retardation test, with constant pressure of

0,6 MPa, was carried out with 15 minutes of duration, and after this follow the relaxation test of more 15 minutes, that is done releasing the hydrostatic pressure. It observed that in the specimen number 1 the circumferential deformation reaches more than 90% of his stabilized value, after 10 minutes. It observed that in the specimen number 1 the circumferential deformation reaches more of 90% of his value stabilized, after 10 minutes.

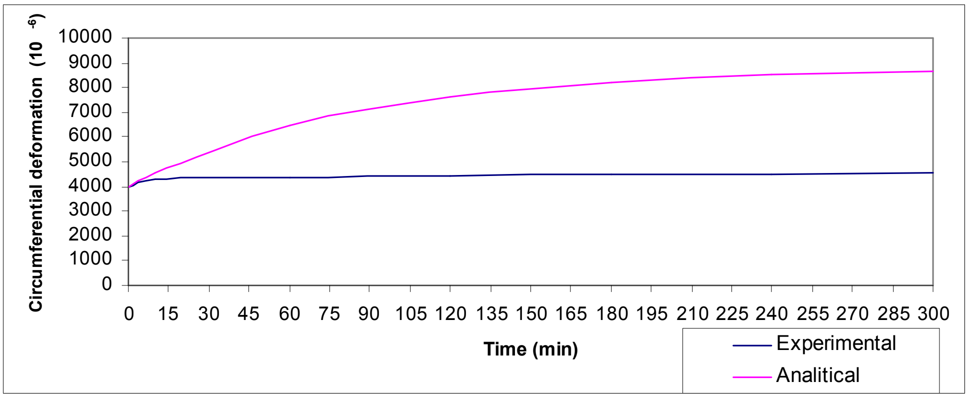
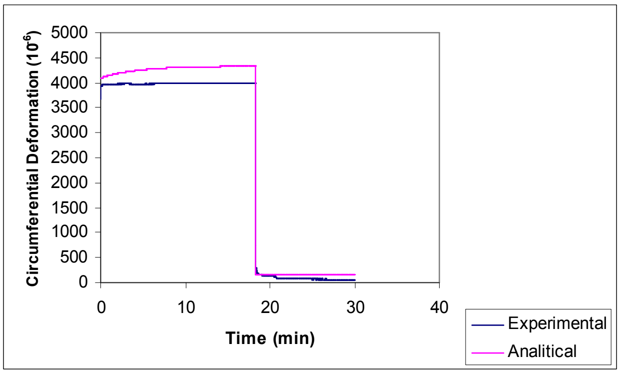


Figure 6. Comparative curves of circumferential deformation *versus* time between experimental and Burger model of the specimen number 1 (PP) for p = 0,60 MPa



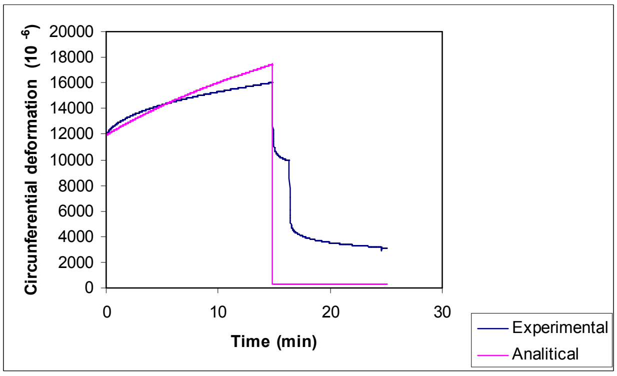


Figure 7. Number 2 specimen (PP) for p = 0,60 MPa

Figure 8. Number 4 specimen (MP) for p = 0,60 MPa

The specimen number 5 (RP), repaired with E-glass/Epoxy, presented the graphic of the circumferential tension *versus* circumferential deformation, shown in the Figure 9, obeying the Hooke's law, with increments of hydrostatic pressure of 0,1 MPa, from 0,2 MPa to 0,6 MPa; at intervals of 10 minutes, therefore, the phenomenon of the viscoelasticity was negligible in the region of the E-glass/Epoxy repair composite. However, this observation is valid only in the repaired region, in which the strains gages were applied. In the rest of the pipe, where there is only PVC without any repair, they were no strain measurements.

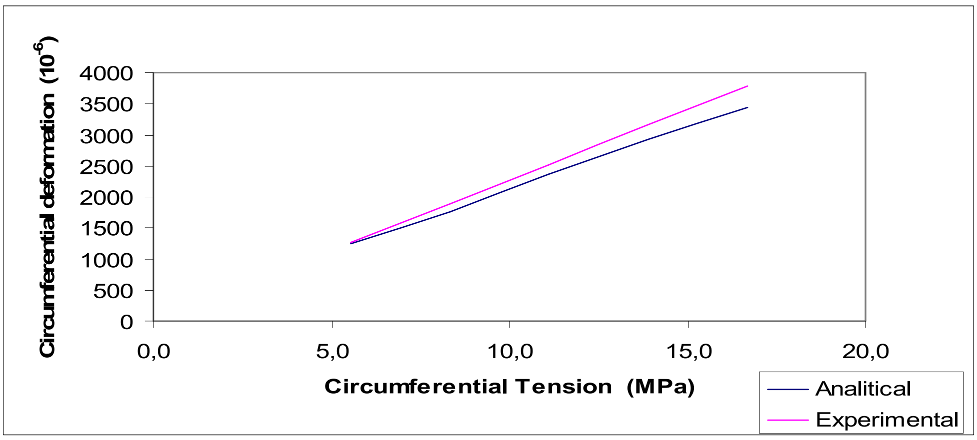


Figure 9. Comparative curves of circumferential deformation *versus* circumferential tension between Burger model and experimental of the specimen number 5 (RP) for p = 0,60 MPa

5. CONCLUSIONS

The rigid PVC perfect pipes (PP) and machined ones (MP) presented viscoelasticity. The experimental results of the circumferential deformations presented reasonable correlation with the Burger model, with maximum error between -35,81% and +7,90%. The experimental circumferential deformations presented a better correlation with the numerical simulations than the longitudinal deformations.

The experimental curves of circumferential deformation *versus* circumferential tension of the repaired pipe with E-glass woven fabric epoxy impregnated with epoxy resin, at the repaired stretch, presented linear with a maximum discrepancy value of 9,57% between the results of the numerical simulation program COMPSHELL (Faluhelyi, 2006) and the experimental for pressures up to 0,6 MPa. And, in the continuation of the tests, the linear tendency of this curve was observed through the values of deformations being maintained constant. For each pressure applied, during 10 minutes, increased progressively in increments of 0,1 MPa, until achieve 1,1 MPa. After verification that the repaired rigid PVC pipe, reinforced with fiber of E-glass, obeyed to the Hooke’s law, there is strong indication that the viscoelastic behavior can be negleted at the repaired stretch.

6. ACKNOWLEGMENTS

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