INTERNALLY PRESSURIZED ALUMINIUM PIPES STRENGTHENED WITH A COMPOSITE REPAIR

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Abstract. *The main purpose of this work is to study the elastic behaviour of 6065-T5 aluminium pipes, closed at both ends with circular steel plates, which are subjected to internal pressure. The specimens, with total length L = 1000 mm and nominal diameter D = 80 mm, are divided into three groups: (i) perfect tubes (i.e. with constant nominal thickness, t); (ii) tubes machined at the central region, endowed with a circunferential groove with 100 mm of extension and depth equal to 0.25 **.** t; and (iii) machined tubes in which the external groove is repaired with a circunferential composite patch, consisting of an epoxy resin reinforced with high strength carbon 8-satin woven fabric (AG370-8H /AS4 from Hexel®). The composite repairs, also with total thickness of about 0.25 **.** t, were cured with and without vacuum bag, in order to vary the volume fraction of fibers (v_f) in them. In addition to the experiments, the elastic behavior of the specimens was simulated using the finite element programs ANSYS and COMPSHELL. It was found that the best results were obtained when the composite patch was cured in the vacuum bag, due to the fact that the elasticity modulus of the patch, in this casa, was closer to the Young´s modulus of aluminium, relativelly to a patch cured without vacuum bag.*

Keywords*: mechanical behavior, repaired pipes, stress analysis*

1. Introduction

With the advent of pipelines as means of long distance transportation of oil and gas, in which the pipe wall is normally prone to suffer superficial damage caused by a range of environmental as well as load factors, that accelerate corrosion, engineers started to be faced with the task of rehabilitating metallic cylindrical shells subjected to internal pressure. The costs involved in repair operations are significant, particularly when the rehabilitation involves welding as well as the replacement of pipe sections. In addition, when conventional methods such as welding are employed, the flow of fluids inside the pipeline needs to be interrupted, increasing the economic losses. The search for polymer matrix composite materials to repair metallic pipes is very important nowadays, mainly when they are located in remote areas, where there is no welding equipment available. Carbon fiber/epoxy composites have been establishing a strong position as an effective mean for the rapid repair and rehabilitation of metallic pipes in the last years (Toutanji and Dempsey. 2001). Such materials are inherently light, stiff, strong and present good corrosion resistance in the presence of water (Prince, 2002). In view of such attractive characteristics, in many industries, Carbon Fiber Reinforced Plastics (CFRP) are now replacing metallic materials in many structural applications (Matthews and Rawlings, 1994), and, in particular situations (e.g. ducts located in remote places), being used with the specific purpose to repair metallic pipes (Levy Neto, Soares and Lisboa**,** 2000**;** Maia, 2003). The main objective of this work is to present some experimental and numerical results concerned with the elastic behavior of perfect and repaired aluminum pipes subjected to internal uniform static pressure (p). The numerical results are obtained using the finite element codes ANSYS and COMPSHELL.

2. Experimental procedure

The pipes investigated in this study were divided in three groups: (i) as bought 6065-T5 perfect aluminum tubes (i.e. with constant nominal thickness, t) of total length L = 1000mm and nominal diameter D = 80 mm; (ii) tubes which were machined at the central region (from 450 to 550 mm) with a circumferential groove of depth corresponding to 25% of the original thickness t (i.e. 0.25**.**t); and (iii) machined tubes in which the central groove was repaired with a stripe of high strength carbon fabric (AG370-8H /AS4 from Hexel®) epoxy matrix composite. The specimens of group (ii) were endowed with a thickness discontinuity, on purpose, to simulate a defect (e. g. uniform external corrosion) in the form of a shallow groove, and the repair restored the original thickness t.

For the manufacture of the specimens tested in this study, four meters of an extruded aluminum tube (6063-T5, aged Al-Si-Mg alloy), with additional geometric features consisting of: external diameter, D_{ext}, = 80.35 mm; internal diameter, d_{int}, = 76.15 mm; and nominal thickness t = 2.1 mm, was bought, cut into four cylinders of length L=1000 mm and machined to the final dimensions. More details can be found in Maia (2003).

The tube 1, included in the group of perfect specimens (i), was tested with constant thickness along all the length (i.e. the original wall thickness t remained). The wall of the tubes 2 to 4, on the other hand, was trimmed along an extension of 100 mm in the central region, with a depth of 0.5 mm, as showed in Fig. 1. The tube 2 was included in the group of machined specimens (ii) and tested with a circumferential groove of depth corresponding to about 25% of the original thickness. The extension of the groove was 100 mm. In the initial phase of the tests, tubes 1 to 4 were subjected to internal pressure ($p \leq 0.5$ MPa) and the stresses in the cylinder wall were much lower than the elastic limit of the material. After the preliminary pressurization tests, the tubes 3 and 4 were repaired with one layer of 100 mm wide stripes of high strength carbon fabric (AG370-8H /AS4 from Hexel®) impregnated with a cold cure epoxy resin, which thickness of about 0.5 mm corresponded, approximately, to the depth of the groove, as shown in Fig. 2. After the repair the tubes 3 and 4 were tested again.

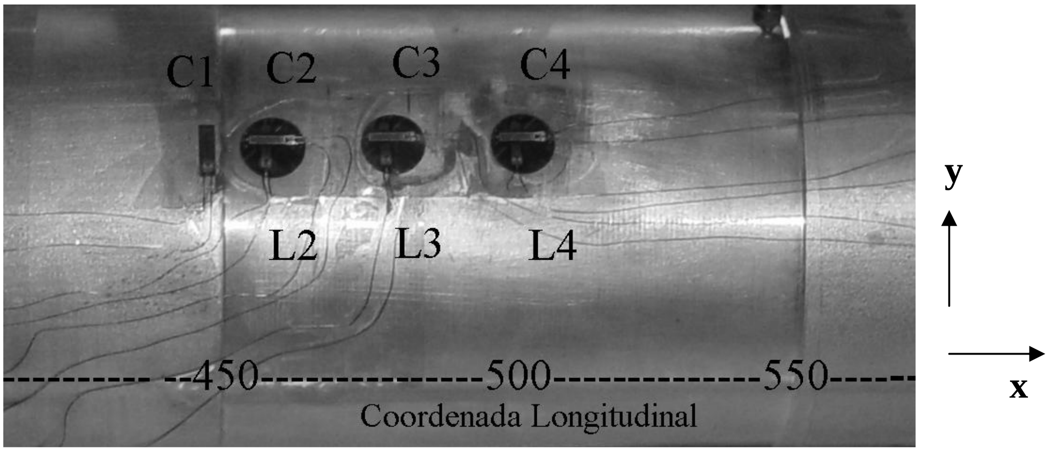

Figure 1 - Detail of the central region of a machined specimen

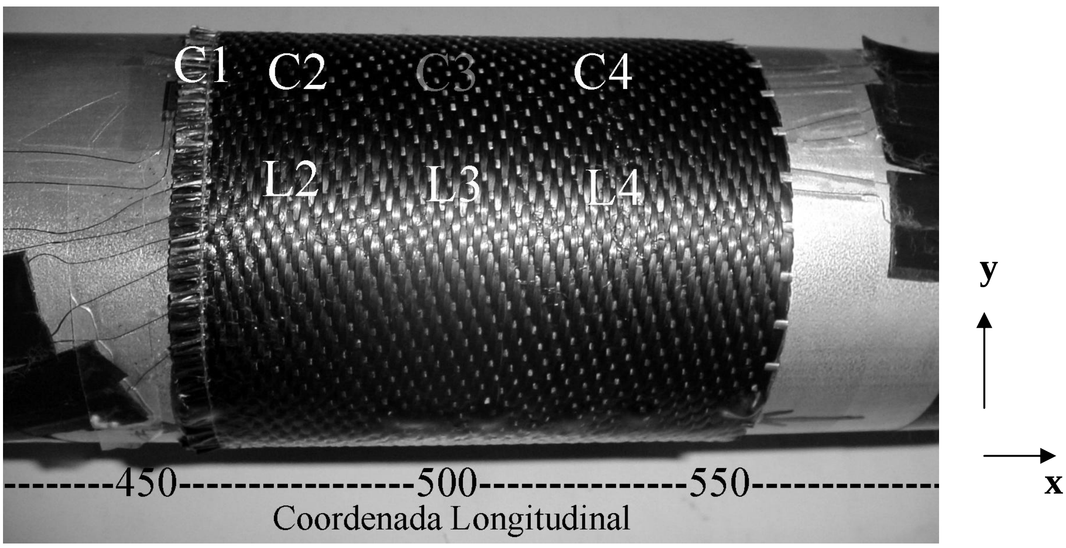

Figure 2 - Diagram of shear modulus versus frequency at 303 K

The repair of the tubes 3 and 4 was based on strict guidelines, which include some details that can be found in the literature (Baker, 1990; Mistry and Levy Neto, 1992; and Maia, 2003). The basic steps concerned with the repair process adopted in this study were:

1. Weight the machined tubes to be repaired, with precision of 0.01 grams;
2. Cut and weight the 100 mm wide carbon fabric stripes to be used in the repair;
3. Weight the total amount of adhesive and catalyzer of the cure epoxy resin;
4. Manual impregnation of the woven fabrics with the catalyzed resin;
5. Application of a single layer of carbon/epoxy repair to the tube;
6. Application of the release film and the bleeder to the repaired region (only for tube 4);
7. Application of a vacuum bag for 12 hours, during the cure at room temperature (only for tube 4);
8. Weight of the repaired tube as soon as the repair operation is completed; and
9. Calculate the content of resin in the composite repair from the data obtained in steps 1, 2 and 8.

2.1. Elasctic and physical properties of the composite repairs

In order to evaluate the influence of the vacuum bag on the volume fraction of the fibers (v_f , equal to the volume of the fibers over the total volume of the composite), the tube 3 was repaired without vacuum and the tube 4 was cured inside a vacuum bag. Using the weight of the fibers, as well as the weight of the tubes, before and after the repair, it was possible to obtain the weight of the resin in the composite repair. In addition, with the densities of the epoxy resin (1.17 g/cm^3) and the carbon fibers (1.78 g/cm^3), it was possible to calculate the volume fractions of the fibers (v_f) and the matrix of resin (v_m), as shown in Table 1. More details concerned with these calculations, using the basic equations of micromechanics (Matthews and Rawlings, 1994) and neglecting the volume fraction of the voids, can be found in Maia (2003).

Table 1 – Volume fractions of fibers and matrix in the composite repairs for tubes 3 and 4.

Tube	**Mass of fiber [g]**	**Mass of matrix [g]**	**Volume of fiber [cm^3]**	**Volume of matrix [cm^3]**	**Volume fraction of fibers %**	**Volume fraction of matrix %**
3	13.1	23.0	7.3	19.7	27	73
4	11.1	7.30	6.2	6.2	50	50

The elastic properties of the composite repairs can be estimated from the properties of the fibers and the matrix, as well as the respective volume fractions (v_f and v_m), using the rule of mixtures technique (Gibson, 1994; Hull and Clyne, 1996). Additional information concerned with this procedure, which, in the case of the present study, took into account the fact that the carbon fibers used were in the form of balanced woven fabrics, can be found in Maia (2003). For this kind of composite, the elasticity modulus along the warp (1) and fill (2) directions of the fabric, as well as the respective Poisson's ratios, can be assumed to be the same (i.e. $E_1 = E_2$, $\nu_{12} = \nu_{21}$). Such properties and the shear modulus, G_{12} , of the composite repair used on the tubes tested in this study, are presented in Table 2. It is clear from the properties of Table 2 that the composite repair cured with vacuum (with higher v_f , used in tube 4) is stiffer than the composites cured without vacuum, used in tube 4, by an average factor of about 2.

Table 2 – Elastic properties of the composite repairs

Tube	$E_1 = E_2$ [MPa]	$\nu_{12} = \nu_{21}$	G_{12} [MPa]
3	36605	0.19	1864
4	65180	0.05	4663

2.2. Instrumentation of the test specimens

All the specimens tested in this investigation were instrumented in the region where $450 \leq x \leq 550$ mm, approximately, with 120Ω strain gages (in the form of single and rectangular rosettes), with gage factors equal to 2.10, and orientated along the longitudinal (x) and the circumferential (y) directions of the cylinders. These coordinates are shown in Fig. 1. The specimens were closed and clamped with flat metallic circular ends glued with epoxy resin at both extremities and then subjected to static internal pressure using an air compressor. The signals from the strain gages and the pressure transducers were sent to a 16 channels data acquisition system (Micro Measurement System Model 6200), integrated with a microcomputer. The applied pressures (p), which varied from 0 to 0.5 MPa, at increments of 0.1 MPa, and the corresponded strains, were stored during the tests. The behavior of all the tubes in the range of the applied pressures was linear elastic (i.e. reversible). The instrumentation used in the perfect specimen (tubes 1) was simplified, relatively to the remaining tubes, and included only one circumferential strain gage (C, in direction y) and one longitudinal (L, in direction x) strain gage. For the machined and repaired specimens (tubes 2 to 4) the instrumentation was more complex and included one strain gage and three additional rosettes (0° / 90°), as shown in Figs. 1 and 2.

3. Main Results

For each experiment, the average meridian (ε_x) and circumferential (ε_y) strains (ε_{exp}), for p = 0.5 MPa, is presented in Table 3. In addition to the strain measurements, calculations based on numerical simulations, using the finite element programs ANSYS and COMPSHELL were carried out (Maia, 2003). These results, divided by experimental strains (ε_{exp}), are also presented in Table 3. As indicated in the second column, the strains were evaluated, experimentally and numerically, along the longitudinal, x, and the circumferential, y, directions. The tubes 3 and 4 were tested twice (before and after the repair) and the results of Table 3 refer to those obtained after the repair.

Table 3 – Experimental and numerical results of the strains, for p = 0.5 MPa.

Tube	**Direction analyzed**	**Experimental average strain ε_{exp} (10^{-6})**	**ANSYS simulation over ε_{exp}**	**COMPSHELL simulation over ε_{exp}**
1	**y**	140	1.043	1.014
1	**x**	23	0.913	0.957
2	**y**	150	0.947	0.920
2	**x**	25	1.120	1.120
3	**y**	155	1.052	1.019
3	**x**	34	1.059	1.088
4	**y**	111	1.018	0.982
4	**x**	27	1.074	1.037

As far as the numerical analyses are concerned, the program COMPSHELL (Levy Neto, 1991) is an "in house" finite element code based on axisymmetric two nodes elements in which the shell wall can be made of orthotropic layers, and each node has four degrees of freedom, three displacements and one meridian rotation. The program ANSYS is a commercial software which includes a complete library of elements. In the numerical analysis for the simulation of the mechanical behavior of the tubes using the program ANSYS the elements SOLID95 and SHELL91 where used (Maia, 2003). A plot of the radial displacement w for the machined tube 2, when p = 0.5 MPa, obtained using the program COMPSHELL, as shown in Fig. 3.

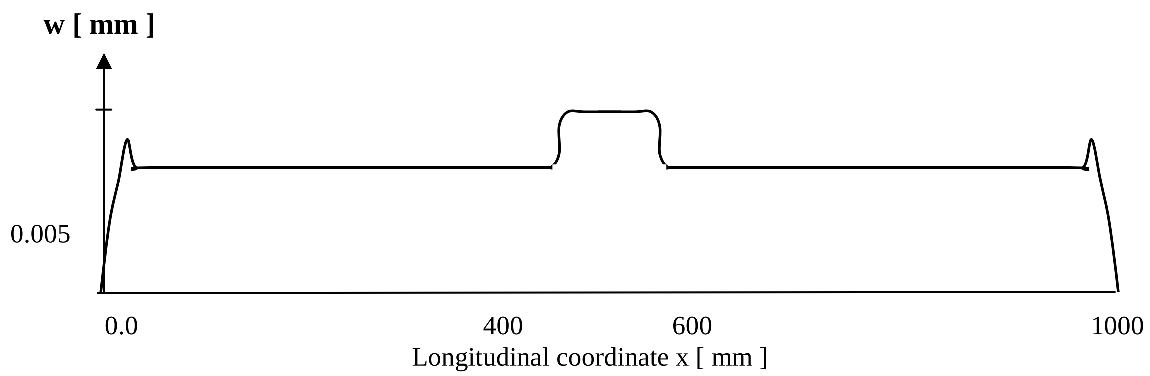

Figure 3 - Radial displacement w = w(x) for the machined tube 2, when p = 0.5 MPa

It is clear analyzing the plot of w(x) versus x, presented in Fig. 3, that in the thinner machined zone (i.e. $450 \le x \le 550$ mm) the tube was bulged out due to the local larger radial displacement w. In an equivalent plot for the **perfect** tube 1, for instance, the distribution of w for $50 \le x \le 950$ mm, approximately, was a smooth and constant horizontal line. For the tube 3, repaired with the carbon/epoxy stripes with $v_f < 0.30$, the bulge in the region in which $450 \le x \le 550$ mm was reduced (to ~ 60% of t, but not eliminated). Finally, for tube 4, in which the composite repair had $v_f \cong 0.50$, the bulge was practically eliminated.

Additional experimental results for the circumferential strains, in which the applied internal pressures (p) in tubes 1 to 4 were: 0.1; 0.2; 0.3 and 0.4 MPa, respectively, are presented in Table 4. From these results, one can say that the variation of the experimental circumferential strain, (ε_y), with the applied pressure (p), is roughly linear.

Table 4 – Experimental results for the circumferential strains, for p = 0.5 MPa.

	Experimental circumferential strain, ε_y (10^{-6}),			
P [MPa]	**Tube 1**	**Tube 2**	**Tube 3**	**Tube 4**
0.1	26	28	37	23
0.2	57	59	70	44
0.3	82	91	99	68
0.4	113	117	124	90

4. Discussion of the Results

The comparison of the experimental and numerical results presented in Table 3 indicates that the correlation between them was very good, in most cases. In particular, the correlations involving the experimental and numerical results were always better than 91%. One of the reasons for this good correlation, on the main, is the fact that, typically, the composite materials exhibit a linear elastic mechanical behavior almost up to their fracture stresses, so that the relationship between stresses and strains does not change significantly.

Another important aspect was the fact the elastic behavior of the tube 2 (machined) was totally restored (i.e. the bulge was practically eliminated) with the composite repair applied in tube 4 (cured with vacuum). In fact, the elasticity modulus (E_{Al}) of aluminum 6063-T5 used in the manufacturing of the tubes 1 to 4 is about **70 GPa**, while the composite repair of tube 4, which had $v_f \cong 0.50$, has $E \cong$ **65 GPa**, as shown in Table 2. So, the aluminum removed in the machining operation was replaced by a patch material that had almost the same elasticity modulus (E). That did not occur for the tube 3, cured without vacuum, since the respective value of E ($\cong$ 37 GPa, presented in Table 2) was significantly lower than 70 GPa. In a simulation carried out using the program ANSYS, hypothetically, 1mm of the cylinder wall of an aluminum tube with t = 2 mm (initially) was machined, for $450 \leq x \leq 550$ mm. Three different repairs, with the same geometry as the illustration of Figure 2, were simulated. In the first (see segmented line of ε_Y versus x, in Figure 4) the elasticity modulus of the repair (R) was such that $E_{R1} = E_{Al} / 2$ (i.e. $E_{R1} =$ 35 GPa); in the second (see solid line in Figure 3) $E_{R2} = E_{Al}$; and in the third $E_{R3} = 2 . E_{Al}$ (see dotted line in Figure 3). Figure 3 shows that the perturbation of ε_Y is lowest when $E_{R2} = E_{Al}$.

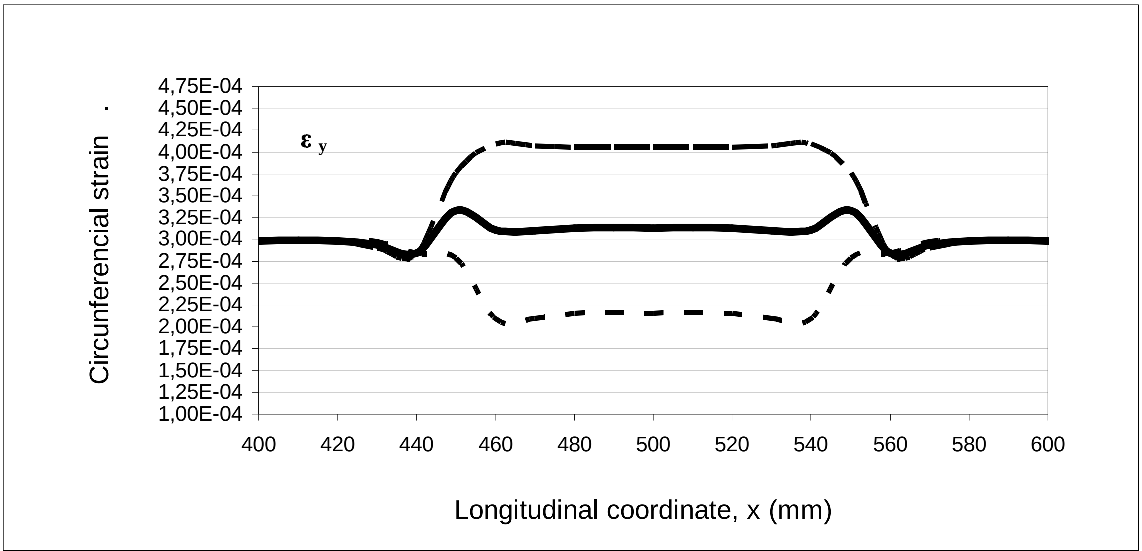

Figure 4 - Numerical results for the circumferential strains, ε_y , for p = 1 MPa.

When $\mathbf{E_{R1} = E_{Al} / 2}$, the tube is bulged out in the repaired region, as suggested by Fig.4, because the stiffness of the repair is not high enough to restore the rigidity of the perfect tube. On the other hand, when $\mathbf{E_{R3} = 2 . E_{Al}}$ the repair is excessively stiff and the tube is gripped so tight that a local inward circumferential strain takes place. The local perturbation is minimum, according to Fig. 4, when the stiffness of the repair is such that $\mathbf{E_{R2} = E_{Al}}$.

5. Conclusions

An important conclusion of this investigation is the clear indication that, for the damaged aluminum tubes tested in this study, the composite patch cured inside the vacuum bag (Tube 4) was far more effective than the repair cured without vacuum (Tube 3), and practically restored to original stiffness of the perfect pipe. In fact, the volume fraction of fibers, $\mathbf{v_f}$ = 50%, obtained using the vacuum bag during the consolidation of the repair, produced a composite endowed with an elasticity modulus ($\mathbf{E_1 = E_2}$ = 65180 MPa) which is very close relatively to the elasticity modulus of the aluminium alloy of the repaired pipe (E = 70000MPa).

6. Acknowledgements

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