

MECHANICAL BEHAVIOR OF STEEL PIPES REPAIRED WITH A HYBRID LAMINATE

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Abstract. *Any kind of tube is prone to suffer from superficial wearing due to corrosion. In this context, techniques that allow a pipe repair to be fast and reliable are of fundamental importance. In order to obtain information about repair of technological importance to industrial sectors, this investigation includes numerical as well as experimental analysis of low carbon steel pipes, closed with flat ends at both extremities and subjected to hydrostatic internal pressure. It will be shown that the hybrid repairs allow a better control of the strangulation of the pipes and can be more efficient, relative to those that use only carbon fibers, when the cost of the raw materials is considered. They can incorporate the advantage of distinct materials, as well as minimize their individual disadvantages, improving the properties of the laminate and avoiding a galvanic corrosion of the steel pipe caused by the contact of a carbon fiber (i. e. cathode) with the metal (anode).*

Keywords*: steel pipes, corrosion, composite repair, hybrid laminates*

1. INTRODUCTION

Worldwide, steel pipes present fundamental importance in many industrial sectors. However, any kind of tube is prone to suffer from superficial wearing due to corrosion. In this context, techniques that allow a pipe repair to be fast and reliable are of fundamental importance to increase their useful life, avoid accidents, minimize environmental damages and allow the maintenance of their efficiency after the repair. Composite material patches are receiving great attention in the international market due to its high efficiency, low weight and accessible cost. Specially, repairs with polymeric matrix reinforced with hybrid laminates (i. e. including layers of carbon and E-glass fibers) are possible solutions and will be analyzed in this work.

During the investigation, three kinds of steel tubes, SAE 1010, will be analyzed: (i) intact (as bought); (ii) machined in the central region; and (iii) repaired with composites of epoxy resin reinforced with hybrid laminates. The last specimen was machined in the central region, to simulate a defect (i.e. thickness loss) and repaired with epoxy resin reinforced with woven fabrics of hybrid laminates. These tubes will be analyzed in elastic and burst domains.

The main objective of this work is to present some experimental and numerical results concerned with the elastic and burst behavior of hybrid laminate repair, comparing these results with the 100% carbon/epoxy repair. The numerical results are obtained using the finite element code COMPSHELL.

2. EXPERIMENTAL PROCEDURE

2.1. Material selection for the repairs

Considering the engineering materials most common in pipes repair, composite materials can present better ultimate tensile strength and lower weights, having a better relation between modulus of elasticity/weight (Levy Neto, 2006).

There are three kinds of fiber that can be used in repair: glass, carbon and kevlar fibers. Nowadays, most repairs are made by polymeric matrix reinforced with glass/epoxy laminates, mainly because it lower costs if compared with the others fibers. However, it has lower stiffness, so a glass/epoxy repair needs a larger thickness to restore the mechanical properties of a problematic pipe, if compared with the other kind of repair. Consequently, it increases the material quantity and the difficulties to use this repair in the steel pipes.

About carbon fibers, there are some kinds of this fiber that are stiffer and stronger than steel (Levy Neto, 2006). However, due to their fragility and high costs, they are used very often with others fibers in the same laminate, like glass/epoxy and Kevlar/epoxy (Levy Neto, 2006). As Kevlar fiber doesn't present any better results than the other fibers, according other investigations (Thomazi, 2006), besides having high costs, one of the best solutions using composites repairs is represented by polymeric matrix reinforced with hybrid (including layers of carbon and glass fibers) laminates. This repair offers efficiency, good mechanical properties and lower costs.

This kind of laminate has others advantages, like avoiding corrosion between the steel pipe and the carbon fiber, by using at least one layer of glass woven between these materials (Coutinho, 1992), and avoiding pipe strangulation due the repair, by reducing stiffness when some carbon fibers are substituted by glass fibers. All these advantages increase the repair's efficiency. After that, according PETROBRAS analysis, the use of glass fiber increases the life of the pipe and reduces the maintenance costs (Rust Engenharia, 2006).

Finally, this hybrid repair allows to a fine adjustment of the results (better thickness and length of repair), because it uses two different materials and presents more combinations and options for the design of the repair.

2.2. Geometry of the Specimens

The three kinds of steel tubes analyzed in this investigation and theirs geometric details are shown in Fig. 1, 2 and 3.

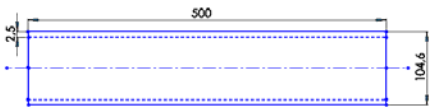

Figure 1. Perfect Pipe

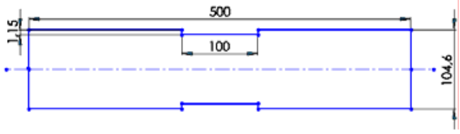

Figure 2. Machined Pipe

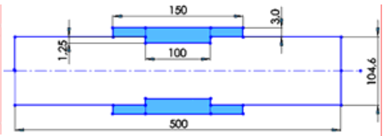

Figure 3. Repaired Pipe

The main specimens are **Tube 1** (for perfect and repaired cases) and **Tube 2** (for machined pipe in the central region), presented in Fig. 4. Both tubes are clamped in the left extremity and closed flat ends, having 10 equidistant and settled screws in the flanges, which are fixed with TIG welding.

Figure 4. Tube 1 (right) and Tube 2 (left)

Table 1: Geometry of Pipe

Geometry of Pipe	Perfect	Repaired	Machined
l_{RH} (mm)	---	100	100
R (mm)	52.30	52.30	52.30
$R_{x = 250\ mm}$ (mm)	52.30	52.30	51.05
t_T (mm)	2.50	2.50	2.40
$t_{x = 250\ mm}$ (mm)	2.50	1.25	1.15
t_L (mm)	---	1.25	1.25

where:
l_{RH} $\longrightarrow$ *length of roughed-hew region*
R $\longrightarrow$ *outer radius*
$R_{x = 250\ mm}$ $\longrightarrow$ *radius of roughed-hew region*
t_T $\longrightarrow$ *tube thickness*
$t_{x = 250\ mm}$ $\longrightarrow$ *thickness of roughed-hew region*
t_L $\longrightarrow$ *thickness loss*

2.3. Equipments and Test Rigs

The equipment for data acquisition is *Lynx ADS 2000*, with 16 channels, connected on a microcomputer that carries through the tasks of compensation of temperature, bridge balancing and reading the measures of axial and circumferential strains, with precision of 0.1×10^{-6} (Faluhelyi, 2006). The hydraulic pump is *Enerpac of* ½ HP and capacity of 70 MPa (700 bar). The pressure transducer, with band of operation between 0 and 40 MPa, measures the pressure during the tests and receives an excitement from to 24 Volts. The bench of tests is composed of a metallic steel 1020 box, with thickness of 3 mm, 1200 mm of length, 300 mm of width and 400 mm of height, with two supports, fixed in the base of the box, to hold the pipes in place.

3. NUMERICAL ANALYSIS

3.1. Description of the Program Compshell and Simulation Metodology

The COMPSHELL program, for thin axissymetric shells of revolution, is based on the Classical Laminate Theory (CLT) and includes the membrane stresses as well as the bending moments on the shell wall. Its only element is a layered ring with two nodes. Geometrically, the thin shells are 2-D (Maia, 2003).

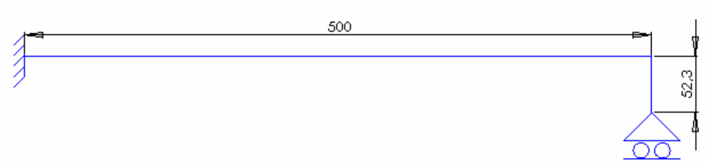

Figure 5. Schematic representation of the numerical simulation of a perfect pipe

According to this theory, for (R/t) > 10, the shell wall can be considered thin. In this work, (R/t) = 20.92, for tube 1, and 21.79, for tube 2. So the analyzed pipes are thin wall ones. More details about COMPSHELL are found in Alencar (2006). In Figure 5 a schematic representation of a perfect pipe, with length of 500 mm and R = 52.3 mm, is shown.

3.2. Elastic and physical properties of the composite repairs and specimens

The elastic and physical properties of the materials used in this investigation are shown in Table 2.

Table 2: Properties of the materials used in this work (Datoo, 1989).

Mechanical Properties	Carbon/*Epoxy **[1]	Glass/*Epoxy **[2]	Steel SAE 1010 **[3]
E_1 (GPa)	70	25	200
E_2 (GPa)	70	25	200
G_{12} (GPa)	5	4	80
υ_{12}	0.10	0.20	0.29
X_{1T} (MPa) ***	600	440	300
X_{1C} (MPa) ***	570	425	300
X_{2T} (MPa) ***	600	440	300
X_{2C} (MPa) ***	570	425	300
S_{12} (MPa) ***	90	40	150
ρ (kg/m^3)	1600	1900	7870

E_1 → *modulus of elasticity in direction 1*
E_2 → *modulus of elasticity in direction 2*
G_{12} → *shear modulus of elasticity*
υ_{12} → *Poisson ratios*
X_{1T} → *tensile strength in direction 1*
X_{2T} → *tensile strength in direction 2*
X_{1C} → *strength in compression in direction 1*
X_{2C} → *strength in compression in direction 2*
S_{12} → *shear strength*
ρ → *density*

OBS:
* The epoxy matrix used is Araldite and its catalyser is HY 1208.
[1] This is an Epoxy Matrix reinforced with carbon fiber ***High Strength* woven, witch is balanced, has a volumetric fraction v_f = 50% and has 0.50 mm of thickness.
**[2] This is an Epoxy Matrix reinforced with glass-E fiber woven, witch is balanced, has a volumetric fraction v_f = 50% and has 0.25 mm of thickness.
**[3] *The steel pipes have sewing and are hot rolled.*
**** The mechanical properties refer to an ambient temperature about 25ºC.*
***** The steel strengths can be ultimate tensile strength (S_u = 323.73 MPa) or yield strength in tension (S_y = 179.523 MPa).*

3.3. Mathematical Modeling of the Laminated Shell Walls

Considering CLT, the Eq. 1 refers to a laminate stress resultants (Levy Neto, 2006):

$$\begin{Bmatrix} Nx \\ Ny \\ Nxy \end{Bmatrix} = \sum_{k=1}^{n} \left[\bar{Q}\right]_k \left[(z_k - z_{k-1}) \begin{Bmatrix} \varepsilon_{xo} \\ \varepsilon_{yo} \\ \gamma_{xo,yo} \end{Bmatrix} \right] + \sum_{k=1}^{n} \frac{1}{2} \left[\bar{Q}\right]_k \left[(z_k^{\,2} - z_{k-1}^{\,2}) \begin{Bmatrix} \kappa_{xo} \\ \kappa_{yo} \\ \kappa_{xyo} \end{Bmatrix} \right], \qquad (1)$$

In addition, the Eq. 2 refers to a laminate moment resultants (Levy Neto, 2006):

$$\begin{Bmatrix} Mx \\ My \\ Mxy \end{Bmatrix} = \sum_{k=1}^{n} \frac{1}{2} \left[\bar{Q}\right]_k \left[(z_k^{\,2} - z_{k-1}^{\,2}) \begin{Bmatrix} \varepsilon_{xo} \\ \varepsilon_{yo} \\ \gamma_{xo,yo} \end{Bmatrix} \right] + \sum_{k=1}^{n} \frac{1}{3} \left[\bar{Q}\right]_k \left[(z_k^{\,3} - z_{k-1}^{\,3}) \begin{Bmatrix} \kappa_{xo} \\ \kappa_{yo} \\ \kappa_{xyo} \end{Bmatrix} \right], \qquad (2)$$

In summary, Eq. 3 gives the relation between the applied loads with the strains and curvatures:

$$\begin{Bmatrix} Nx \\ Ny \\ Nxy \\ Mx \\ My \\ Mxy \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{x_o} \\ \varepsilon_{y_o} \\ \gamma_{xy_o} \\ \kappa_{x_o} \\ \kappa_{y_o} \\ \kappa_{xy_o} \end{Bmatrix}, \qquad (3)$$

3.4. Ideal repair methodology for steel pipes

Currently, most of the methodologies used for applying repair in damaged pipes demands a reduction in the internal fluid flow pressure or even its total interruption. In both cases, the work time is reduced and the productivity of the production is harmed. The procedure considered in this proyect for tubes composite repair, already used in many companies, does not need to interrupt no habitual procedure of work and it is made quickly and in a simple, efficient and low cost way. The repair is made in a cold way, provides an additional security to the operator and uses a resistant material to the corrosion, little toxic products during the application and is practically harmless to the environment.

4. MAIN RESULTS AND DISCUSSION

4.1. Numerical Results and Analysis

To verify the advantages of hybrid laminate over a carbon/epoxy one, it's quite important to compare some mechanical results and behavior of both. For the analysis, the geometric parameters given in Table 3 are relevant.

Table 3: Geometric parameters of both repairs.

PARAMETERS	CARBON/EPOXY	HYBRID
l_R (mm)	150	150
t_{NRH} (mm)	3.0	0.5 (glass/epoxy) e 2.5 (carbon/epoxy)
t_{RRH} (mm)	4.25 (carbon/epoxy)	0.5 (glass/epoxy) e 3.75 (carbon/epoxy)

Where:
$l_R \longrightarrow$ *repair length.*
$t_{NRH} \longrightarrow$ *thickness in the region not roughed-hew.*
$t_{RRH} \longrightarrow$ *thickness repair in the roughed-hew region.*

4.1.1. Analysis Based on the Failure Pressure

The numerical results based on failure pressure P_y due to the yield of the steel pipe can be seen in Tab. 4. On the other hand, the numerical results based on the burst pressure P_u due to the ultimate strength of the pipe can be seen in Tab. 5. In both tables are comparisons about the failure pressures (P_y or P_u) and longitudinal coordinate (x_y *or* x_u) where the tube fails, between two kinds of repair, to the four most common failure criteria of composite materials.

Table 4: Yield Behavior.

Failure criteria	Parameter	Carbon/Epoxy	Hybrid
Tsai-Hill	*Xy* (mm)	325.0	175.0
	Py (bar)	90.15	88.74
Maximum Stress	*Xy* (mm)	165.5	167.9
	Py (bar)	82.12	81.82
Hoffman	*Xy* (mm)	325.0	175.0
	Py (bar)	90.15	88.74
Owen	*Xy* (mm)	175.0	325.0
	Py (bar)	64.07	63.04

Table 5: Ultimate Behavior.

Failure criteria	Parameter	Carbon/Epoxy	Hybrid
Tsai-Hill	*Xu* (mm)	175.0	175.0
	Pu (bar)	162.7	160.1
Maximum Stress	*Xu* (mm)	334.5	167.9
	Pu (bar)	148.3	147.7
Hoffman	*Xu* (mm)	175.0	175.0
	Pu (bar)	162.7	160.1
Owen	*Xu* (mm)	175.0	175.0
	Pu (bar)	115.6	113.7

It is clear that, in all failure criteria analyzed, the ultimate (Pu) and yield (Py) pressures of carbon/epoxy is greater than the hybrid laminate's pressures. However, the difference is almost insignificant (1.6 % in both pressures).

4.1.2. Analysis based on the radial and axial displacements

In Fig. 6 and 7, can be seen that the carbon/epoxy behavior is almost the same of that presented by the hybrid, considering radial and axial displacement.

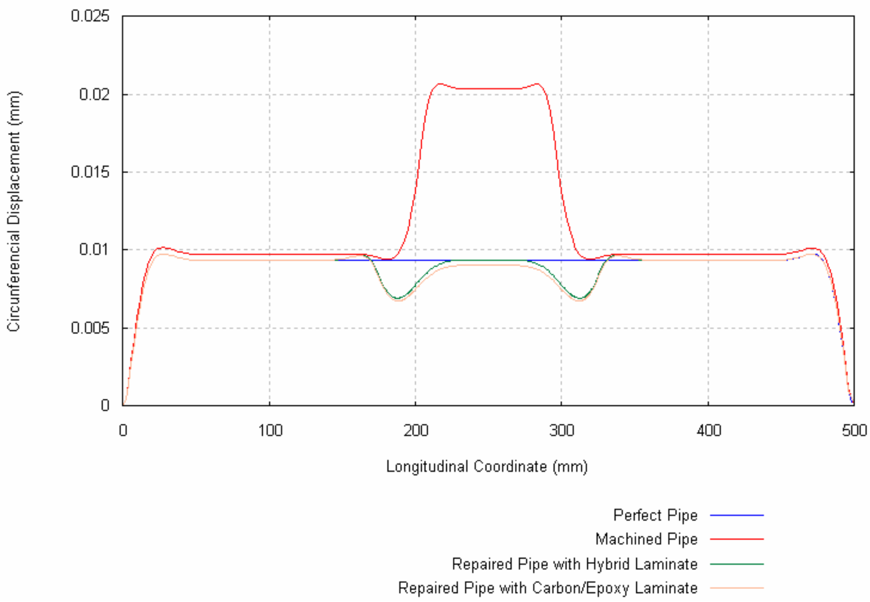

Figure 6. Radial displacement w = w(x), when P = 2MPa

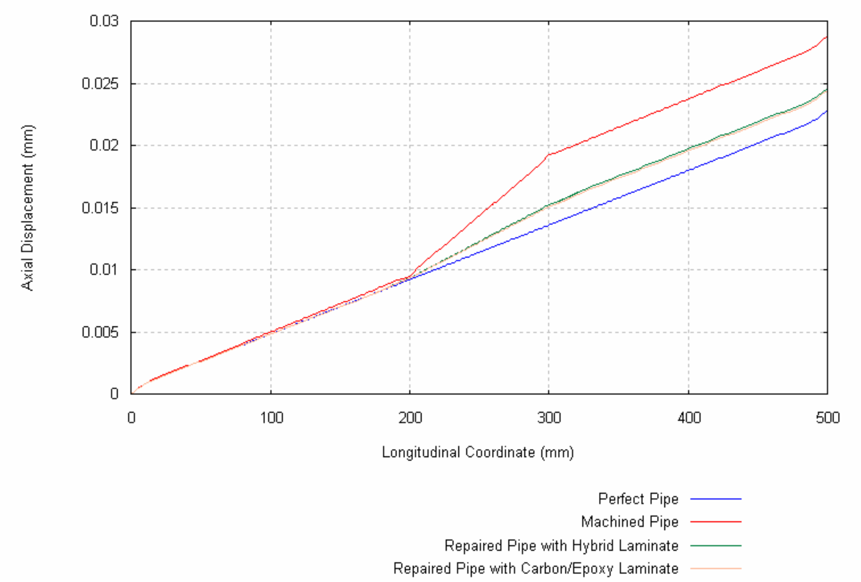

Figure 7. Axial displacement u = u(x), when P = 2MPa

It is clear that the displacements presented by the repaired tubes are close to those of the perfect and are much lower than those of the machined tube. This is desirable and justifies the efficiency and use of composite repair. In Fig. 6 is clear that in the repair extremities were strangulated (due to the high stiffness of the cover lids) and in the thinner machined zone the tube was bulged out (due to a lack of stiffness). These effects in each case are symmetric in relation to the center of the pipe. In Fig. 7 it can be seen that before the machined zone (x = 200 mm), all tubes have the same axial displacement. After that point, the displacement of repair tube is bigger than the perfect tube because of the small reduction of the stiffness of the repaired pipe, in relation to the perfect pipe. As expected, due to stress concentration, the regions of the extremities of the machined zone presented discontinuities in the axial displacements of the repaired and machined pipes. In this context, measuring the radial and axial strains in all tubes, it may be verified that the hybrid repair tube has larger radial strain, if compared with carbon/epoxy repair tube and lower axial strain (Table 6).

Table 6: Pipes radial and axial strains.

	Perfect	Machined	Carbon/Epoxy	Hybrid
ε_w ($\mu Strain$)	1604.6	1565.7	1510.286	1549.9
ε_u ($\mu Strain$)	409	204.6	410.2	407.2

4.1.3. Analysis based on the resultants of axial and circumferential stress

With Fig. 8 and 9, it can be perceived that the behavior of the pipes repaired with composite material is similar, being also next to the one to the perfect pipe. One perceives, still, that it has significant variations of stresses in the extremities of the machined zone and repair zone, due to stress concentration caused by geometrical discontinuities.

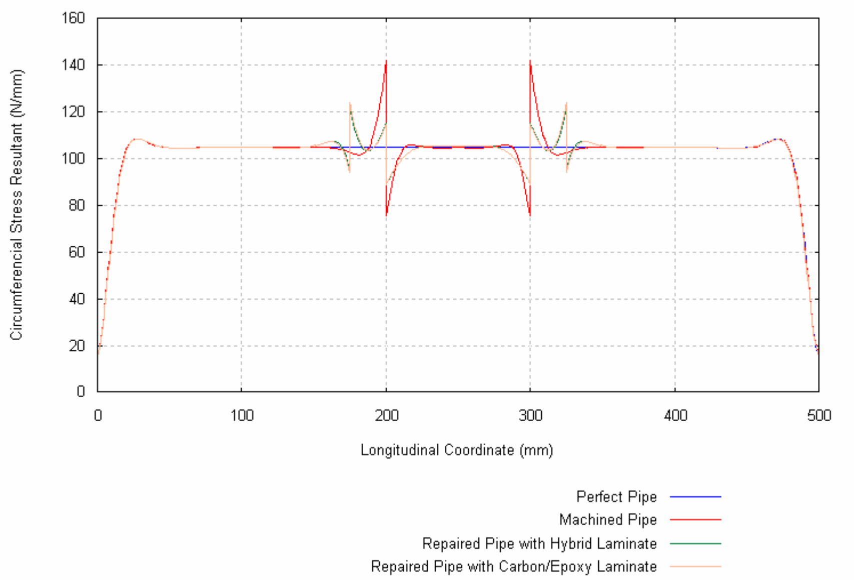

Figure 8. Circumferential stress resultants Nc (N/mm), when P = 2MPa

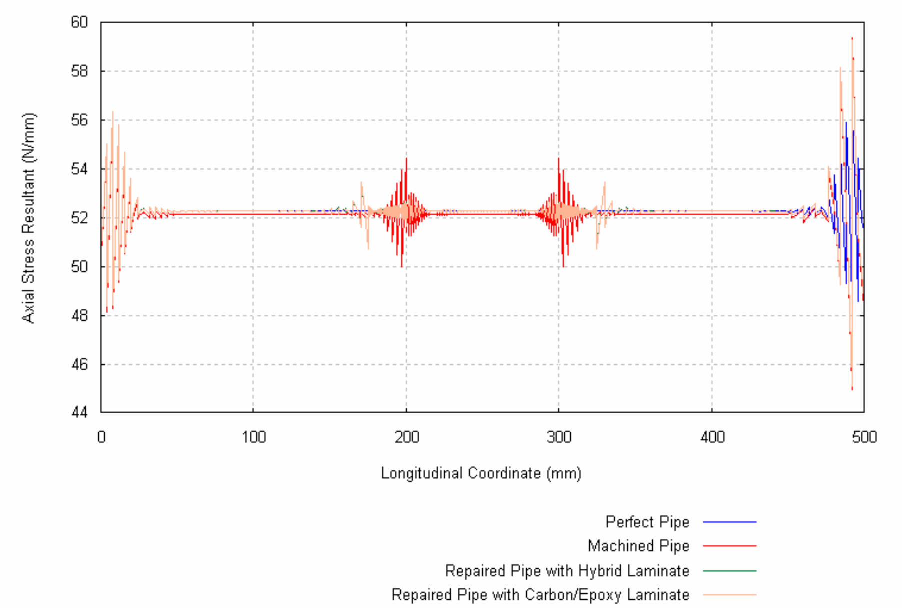

Figure 9. Axial stress resultants Na (N/mm), when P = 2MPa

Moreover, it proves the membrane theory, where the circumferential stresses are the double of the axial ones.

4.1.4. Analysis based on the resultants of axial and circumferential moment

With Fig. 10 and 11, it is perceived that axial and circumferential moments in the extremities of the machined zone for the machined pipe always is positive and less intense, if compared with the moment of the extremities of the machined zone of the repaired pipe, which always is negative.

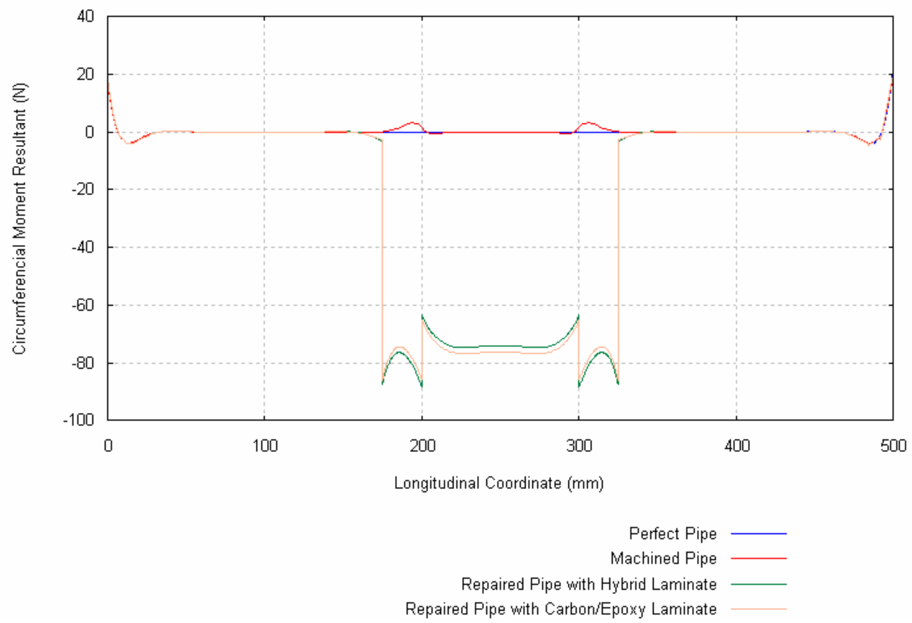

Figure 10. Circumferential moment resultants Mc (N), when P = 2MPa

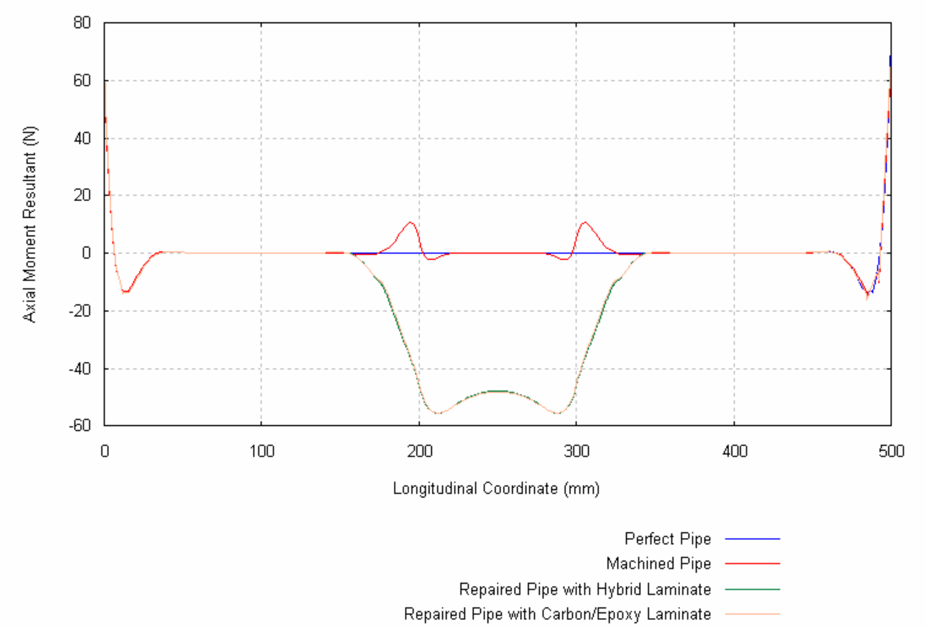

Figure 11. Axial moment resultants Ma (N), when P = 2MPa

Moreover, one perceives that in the extremities of the repair (region not roughed-hew) also it has an increase in the magnitude of the resultants of axial and circumferential moment. However, this value is always smaller than the value of the moment in the extremity of the machined zone. So the extremities of machined zone are more harmful than the repair extremities.

4.1.5. Analysis based on the weight of the repaired pipes

Observing Table 7, one perceives that the carbon/epoxy repair is lighter than the hybrid, whose dimensions are the same ones. This occurs because the density of glass/epoxy is greater than carbon/epoxy. However this difference is of 4%, only. So the hybrid repair continues being an advantageous repair, mainly considering the costs, since glass staple fibers have lower costs if compared with carbon staple fibers (around eight times less).

Table 7: Analysis of the volumes [mm3] and masses [g] of the analyzed repairs.

<table>
<tr><th>Repair</th><th colspan="2">Material Repair</th><th colspan="2">$\rho(g/mm^3)$</th><th colspan="2">t_{RH} (mm)</th><th colspan="2">t_{RNRH} (mm)</th><th>l_R (mm)</th><th colspan="2">V_R (mm^3)</th><th colspan="2">M_R (g)</th></tr>
<tr><td>Carbon/epoxy</td><td colspan="2">carbon/epoxy</td><td colspan="2">0.0016</td><td colspan="2">1.25</td><td colspan="2">3</td><td>150</td><td colspan="2">201454.63</td><td colspan="2">322.33</td></tr>
<tr><td rowspan="2">Hybrid</td><td rowspan="2">carbon/epoxy</td><td rowspan="2">glass/epoxy</td><td rowspan="2">0.0016</td><td rowspan="2">0.0019</td><td rowspan="2">0.75</td><td rowspan="2">0.5</td><td rowspan="2">2.5</td><td rowspan="2">0.5</td><td rowspan="2">150</td><td rowspan="2">160496.11</td><td rowspan="2">40958.51</td><td>256.79</td><td>77,82</td></tr>
<tr><td colspan="2">334.61</td></tr>
</table>

4.2. Experimental Results and Analysis

4.2.1. Elastic Behavior

In the elastic regimen, the perfect, machined and repaired pipes (Fig. 12, respectively) had arrived approximately until P = 25 bar and had not suffered plastic deformation or physical modifications in the composite repair.

Figure 12. Pipes on the Test Bench, for elastic behavior

4.2.2. Burst Behavior

The machined pipe (Fig. 13) and the repaired pipe (Fig. 14), tested to failure, confirmed that the repair is efficient. The Table 8 summarizes the main numerical resulted referring to the ultimate pressures of perfect pipes, machined and repaired, for posterior comparison with the experimental results.

Figure 13. Machined pipe after burst

Table 8: Critical pressures of perfect, machined and repaired pipes.

Tube	Perfect	Machined	Hybrid Repaired
Py (bar)	99.15	44.60	88.74
Xy (mm)	80.0	286.7	175.0
Pu (bar)	178.9	81.13	160.1
Xu (mm)	81.31	286.7	175.0

Figure 14. Repaired pipe after burst

Nowadays, the onset of the rupture of the fibers can be detected by acoustic emission and/or microscopy (Hull, 1988). In the present study, from the pressure of 92 bar (9.4 MPa), cracking sounds, indicating that the fibers were breaking started to be heard. At final failure, the right side of the pipe (which is not clamped) was the region where most of the swallowing took place, as shown in Fig. 14.

The failure of the repair was longitudinal and along all its extension (Fig. 17). This failure occurred at about 90º (measured along the circumferential direction) from the welded line of the sewed pipe. Along the welded line the steel pipe is locally stiffer. So, the region more swallowed, which applied more pressure on the repair, was far from the welded line.

Experimentally, the burst of the repaired tube took place at the pressure of 157 bar (16.0 MPa). According to COMPSHELL predictions, the failure should occur at 160 bar (16.3 MPa), which is a difference of only 2% between the experimental and numerical results. After the failure of the repair, the pipe behaved like a machined pipe and failed with about 126 bar, which is nearly the burst pressure of the machined pipe, tested previously. The pressure dropped from 157 to 114 bar, because the repaired region swallowed intensively after the failure of the repair layer. The failure of the steel wall was detected, at 126 bar, due to the different noise emitted by the steel (relatively to the noise emitted from the composite repair layers).

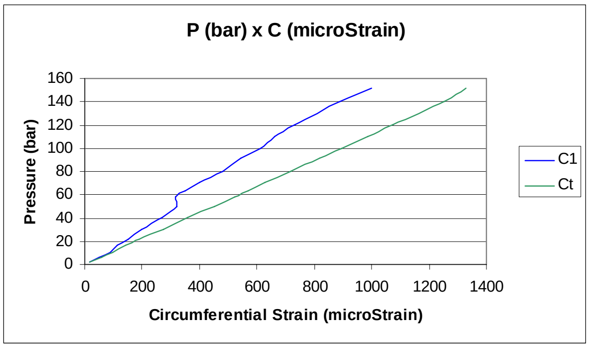

Figure 15. Plot of internal pressure (bar) x Circunferencial strain (µStrain) for the repaired pipe up to failure

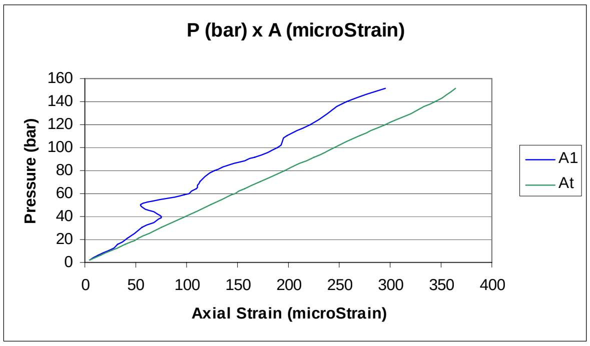

Figure 16. Plot of internal pressure (bar) x Axial strain (µStrain)) for the repaired pipe up to failure

In the composite layers, the elastic properties are constant and the stress x strain diagram is linear up to the failure (Amijuma e Adachi, 1979). As observed at Figures 15 and 16, both experimental curves (C1 and A1) are practically linear, as well as the theoretical curve Ct. In this experiment, the difference between the theoretical and the experimental strain curves was about 2.05 %.

It is important to notice that experimental failure pressure of the repaired pipe (157 bar) is very close to the theoretical burst pressure of the perfect pipe (178.9 bar) and that the difference is only 12 %. In addition, the experimental burst pressure of the machined pipe, 125 bar (12.7 MPa), is significantly lower than the burst pressure of the perfect pipe, with a difference of 30%. This justifies the use of composite repairs in damaged pipes and confirms their efficiency.

Figure 17. Fracture and delamination of the repair, as well as strangulation of the steel wall and less deformation at the sewed region of the pipe (i.e. the welded meridian)

It was observed experimentally that, in fact, the repaired pipe withstand greater pressures than the machined pipe and the relative difference is about 20%.

Figure 18. Details of the rupture zones for the machined and repaired pipes

6. MAIN CONCLUSIONS

An important conclusion of this investigation is the clear indication that, in most situations, the hybrid repair is a better solution than the 100% carbon/epoxy repair, and one of the best solutions for repairing tubes. It is a refined solution which incorporates less strangulation, lower costs with raw materials as well as less chances of corrosion in the steel wall, if compared with the 100% carbon/epoxy repair. In addition, it presents low strains and weight.

The numerical and experimental results were close to each other and, in the elastic domain, the program COMPSHELL analyzed the three cases efficiently. The correlations for all the steel pipes investigated, as far as the experimental and numerical strains are concerned, were better than 91 %. Close to the burst pressures, on the other hand, the correlations were not that good, but still satisfactory. The main cause for this is the fact that the program COMPSHELL does not include plasticity.

Finally, this study demonstrates that hybrid composite repairs can be designed to be very efficient and confirms why the composite are used worldwide for pipe repair.

7. ACKNOWLEDGEMENTS

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