STRESSES IN COMPOSITE MATERIALS USED IN PIPELINE REPAIRS

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Abstract. *Maintenance of oil and gas pipelines presenting corrosion damage can be done following conventional routes as cutting and substitution of the damage parts or double sleeve welded method. Recently, the use of composite materials for repair of damaged pipelines is increasing due to the advantages presented by this process like the ease application and the possibility of performing the repair without interrupting the use of the line. A requisite for the composite materials is that they have adequate mechanical properties to guaranty the integrity of the repaired pipe during its operation. As the pipe operates under hydrostatic pressure, it is important to make a stress analysis in order to know the stresses transferred to the composite material repair. In the present work, a microstructural and mechanical characterization of two composite materials used in pipe repair is made. One of the composites is made of continuous fiber glass and the other of a fiber glass fabric, both with polymeric matrix. The first was pulltruded and the second was processed by hand lay up. The microstructural characterization was done through optical microscopy and the mechanical properties were evaluated by tensile tests. From the mechanical properties of the composite materials and models available in the literature, the stresses acting in the composite repairs due to the hydrostatic pressure were evaluated. The main objective of the paper is to correlate the microstructural and mechanical characteristics of the composite materials with the circunferencial stresses acting in the pipes repaired using the studied composite materials*

Keywords*. Pipeline Repair, Composite Materials, Pipeline Failure, Stresses in Composite Materials*

1. Introduction.

In steel pipelines for oil and gas transportation internal and external damage can be caused by corrosion. Mechanical damage can also occur in the pipes due to impact loading during their operation. As a consequence of the different source of damage the defective pipe walls normally present a reduction of thickness with the resulting risk of leakage with production, economic and sometimes human life losses and environment damage.

In steel oil and gas pipelines internal corrosion is caused by the presence of humidity and water mixed with acids originated from dissolved gases, mainly CO_2 and H_2S (Palmer-Jones and Paisley, 2000). Through the internal inspection of the pipes using appropriated apparatus denominated “pigs” it is possible to detect and quantify internal defects. It is possible then to decide about their risk and necessity of repairs.

In the case of pipe repair using composite materials , these materials are normally made using fiber glass in a polymeric matrix. Repair of external defects with composite materials are already considered permanent whereas the repairs of internal defects are only considered temporary (Palmer-Jones and Paisley, 2000).

There is a sequence of operations which must be followed in the application of the composite repair like: careful preparation of the pipe surface, application of a primer layer, application of a layer of resin with the same composition of the matrix of the composite material, application of the necessary layers of the composite and application of an extra layer of material to protect the composite against the environment and ultra-violet rays. The composite material to be applied in the repair can have several configurations depending on the type of fibers arrays and matrix type.

In the present work the mechanical and microstructural characteristics of two composite materials that can be used for repairing steel pipelines for oil transportation are presented. The mechanical characteristics presented are the fracture stress and deformation obtained through tensile tests. The microstructural characteristics were obtained using optical microscopy. A pipe of diameter of 500 mm and wall thickness of 15 mm was considered. Surface defects with different lengths and deepness were arbitrated and the pipe failure stress was calculated. After, the composite layer thickness was estimated in order to guaranty the integrity of the pipe in the presence of the defect.

2. Circunferencial Failure Stresses of the Pipe.

2.1. Pipe Without Defects.

To determine the circunferencial failure stress in the pipe caused to the internal pressure, the following equation is used (Gere and Timoshenko, 1997):

$$\sigma_f = \frac{P_{\text{int}}.r}{t} \tag{1}$$

where:
σ_f = failure stress of the pipe;
P_{int} = internal pressure;
r = internal radius of the pipe;
t = thickness of the pipe.

2.2. Pipe With Defects.

The pipe strength, following the pipe safety criteria of ASME B31G (ASME, 1991) is giving by:

$$\sigma_p = \sigma_f \frac{1 - A/A_0}{1 - A/(A/A_0 M)} \tag{2}$$

where:
σ_p = circunferencial failure stress of the pipe;
σ_f = flow stress of the steel;
A = defect area on a plane longitudinal to the defect length;
A_0= area of the original longitudinal section of the pipe.

The flow stress has a value between the minimum and maximum recommended value of the yield stress of the pipe steel. The B31G standard recommends a value 10% higher than the minimum yield value of the material. A value 68.98 MPa higher than the minimum yielded limit is recommended (Coulson and Worthington, 1990).

$$\sigma_f = \sigma_{y\min} + 68.95 \quad \text{(MPa)} \tag{3}$$

The expression $\frac{1 - A/A_0}{1 - A/(A/A_0 M)} = k$ represents a factor of pressure magnification in the region of the defect.

For a rectangular or approximately rectangular defect equation (2) can be re-written as:

$$\sigma_p = \sigma_y \frac{1 - d/t}{1 - d/(tM)} \tag{4}$$

where d is the defect deepness, σ_y is the yield stress and M is the Folias Factor, given by:

$$M = \left(1 + 0{,}6275\frac{L^2}{Dt} - 0{,}003375\frac{L^4}{D^2t^2}\right)^{1/2} \qquad \text{for} \qquad L^2/Dt \le 50 \tag{5}$$

$$M = 0{,}032\left(\frac{L^2}{Dt}\right) + 3{,}3 \qquad \text{for} \qquad L^2/Dt > 50 \tag{6}$$

where:
L = corroded region length;
D = pipe diameter;
t = pipe thickness.

3. Thickness of the Composite Repair on a Pipe with a Surface Defect.

The mechanical strength of the pipe with the repair is given by:

$$P_{\text{int}} r = \sigma_{pipe} t_{pipe} + \sigma_{repair} t_{repair} \quad (7)$$

where:

P_{int} = internal pressure of the pipe;

σ_{pipe} = circunferencial stress in the pipe;

σ_{repair} = circunferencial stress in the composite repair;

t_{pipe} = pipe thickness;

t_{repair} = composite repair thickness.

Figure 1 shows a schematic draw of a repaired region of a pipe. The internal pressure and stresses P_{int}, σ_{pipe} and σ_{repair} are shown in the figure (Armor Plate, 1998).

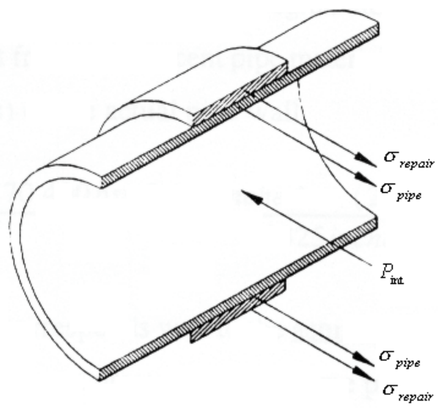


Figure 1- Schematic draw showing the stress in the pipe thickness and composite material layer in a repaired pipe section (Armor Plate, 1998).

From equation (7) it is possible to calculate the thickness of the composite layer on a pipe with a uniform thickness reduction:

$$t_{repair} = \frac{P_{\text{int}} r - \sigma_{pipe} t_{pipe}}{\sigma_{repair}} \quad (8)$$

Assuming that the pipe had suffered a process of localized thickness reduction due to corrosion, the pressure associated to this defect is given by (Armor Plate, 1998):

$$P_{wdefect} = \text{k}\ P_{ndefect} \quad (9)$$

where:

$P_{wdefect}$ = pressure in the pipe with defect;

$P_{ndefect}$ = pressure in the pipe without defect;

k = stress magnification factor due to the corroded region, as described before.

Considering a rectangular defect and combining equations (1), (4), (5) and (9), the thickness of the composite material necessary in order that the pipe can resist the presence of the defect is given by equation:

$$t_w = \frac{D_p}{(2.\sigma_w)} \frac{1}{\frac{1}{X} - \frac{1}{2.\sigma_w}} \quad (10)$$

where:
X = difference between the pressure of the pipe without and with defect ($X = P_{wdefect} - P_{ndefect}$).

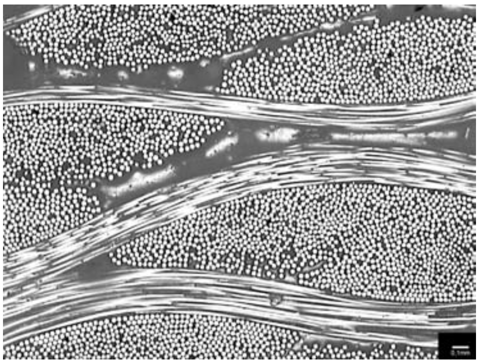
4. Composite Materials.

Table 1 shows the microstructural characteristics of the materials studied, showing the fibers volume percent, arrangement of the fibers and manufacturing process.

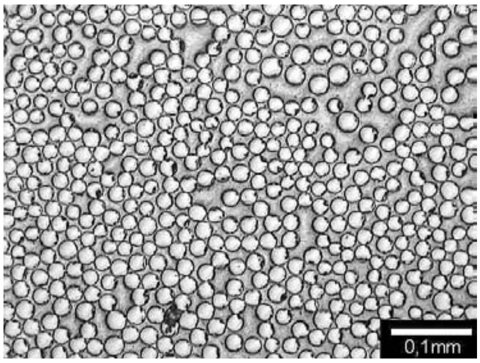
Table 1- Characteristics of the Composites Material.

Composite Material	Fiber Volume Percent (%)	Fiber Arrangement	Manufacturing Process
MC3	48,36	Fabric	Hand-lay-up
MC4	43,53	Unidirectional	Pulltrusion

Micrographs of transverse sections of composites MC3 and MC4 are shown in figure 2.



(a) Composite MC3.



(b) Composite MC4.

Figure 2- Micrographs of transverse sections of composites MC3 and MC4.

Figure 2.a shows the typical microstructure of a composite with fabric fibers (MC3) whereas figure 2.b shows the transverse section of the unidirectional glass fibers of composite MC4.

5. Tensile Mechanical Properties of the Composite Materials.

The tensile tests were done following the standard ASTM D3039 (ASTM, 1995). The results of the tests are shown in Table 2, average of 5 specimens.

Table 2- Tensile Properties of the Composite Materials.

Composite Material	Fracture Stress (MPa)	Fracture Strain (%)
MC3	310,60 ± 26,25	1,01 ± 0,33
MC4	379,58 ± 8,99	0,25 ± 0,03

Composite materials made of continuous and aligned fibers presented better tensile properties along the fibers direction when compared to composites made of fiber fabrics. Composite material MC4 presented a failure stress 18% higher than that of material MC3. The elongation of MC4 is 25% lower than MC3.

6. Influence of the Defects on the Pipe Strength.

The presence of surface defects increases the risk of failure of the pipe. From the equations presented before it is possible to calculate the circunferencial stress on the pipe. The tensile properties of steel API X60 of the pipe are presented in Table 3 (Silva, 2002):

Table 3- Tensile Properties of Steel API X60 of the Study (Silva, 2002).

Tensile Properties of the Steel		
Yield Strength (MPa)	Ultimate Tensile Stress(MPa)	Elongation (%)
482,87 ± 8,54	597,57 ± 2,42	29,53 ± 1,85

The pressure used in pipe design for steels grade X60 is 17.00 MPa. During the qualification test, these pipes are subjected to pressures as high as 90% of the design pressure (15.30 MPa), unloaded and then load to 138% of the design pressure (23.00 MPa). This pressure is then maintained for a period of 4 hours, following standard ASME B31G.

For the pressure levels of 17.00 MPa, 15.30 MPa and 23.60 MPa it is possible to calculate the resulting circunferencial stresses. The calculated circunferencial stresses are presented in Table 4.

From the equations presented before it is possible to calculate the stresses acting in the pipe due the presence of defects. For a pipe of steel grade X60 with thickness t=15.0 mm and rectangular defects of deepness ranging form 2.5 to 80% of the thickness of the pipe (d= 0.375, 0.75, 1.5, 2.25, 3, 3.75, 4.5, 5.25, 6, 6.75, 7.5, 8.25, 9, 9.75, 10.5 and 12 mm) and lengths ranging from 2.5 to 60% (L= 2.5, 5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280 and 300 mm) of the internal diameter of the pipe (D= 500mm) it is possible to calculate $L^2 / Dt \leq 50$. Using equations 5 and 6 it is possible to calculate the circunferencial stresses for the failure of the pipe for the different lengths and deepness of the defects and the mechanical properties of the pipe steel.

Table 4- Circunferencial Stresses Resulting from the Pressure Levels of 17.00 MPa, 15.30 MPa and 23.60 MPa.

Hydrostatic Pressure (MPa)	Circunferencial Stress (MPa)
17,00	289,12
15,30	229,59
23,60	401,36

Figure 3 shows the circunferencial failure stresses for defects with rectangular geometry. The defect lengths are L= 2.5, 20, 50, 120, 200 e 300 mm and deepness of 0.75, 3, 5.25, 8.25 e 12 mm. The pipe pressure was 17.0 MPa and the flow stress of the steel was 482.87 MPa.

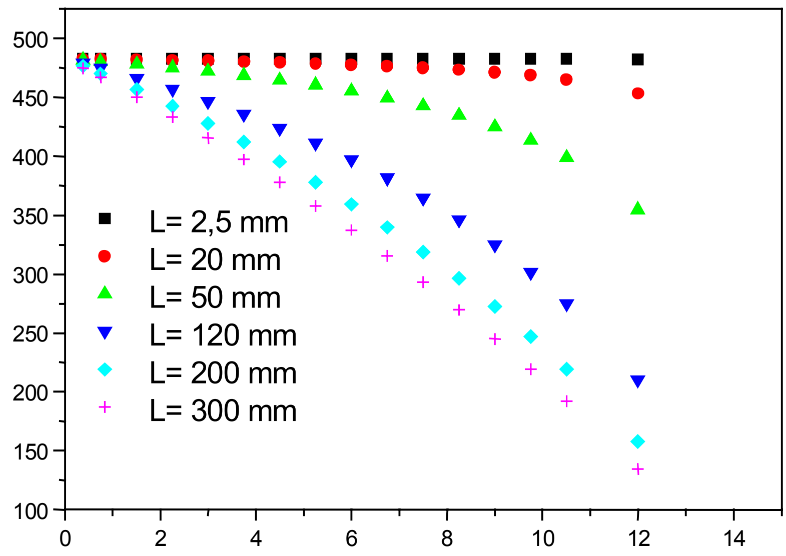


Figure 3- Circunferencial stresses for the failure of the pipe due to the rectangular defects.

From the obtained results shown in figure 3 it is possible to see that defects 2.0 mm deep have a small influence on the failure stress of the pipe for all defect lengths. Defects of length till 20.0 mm and deepness till 8.00 mm also do not reduce the failure stress markedly. For defects larger than 50.00 mm the influence on the pipe failure stress is large for almost all defect deepness.

7. Thickness of the Composite Material Layer for the Repair of Pipes with Surface Defects.

The thickness of the composite layer for the two composite materials studied (MC3 and MC4) as function of defect dimensions was obtained using equations 4, 9 and 10. In the calculations, the design pressure of 17.00 MPa, the flow stress of 482.87 MPa, ultimate tensile stress of 310.60 MPa for composite material MC3 and 379.58 MPa for composite material MC4, pipe steel grade X60, pipe thickness of 15.00 mm and internal diameter of the pipe D= 500.00 mm were used. The rectangular defect dimensions used in the circunferencial stress calculations were also used.

Figure 4 and 5 show the calculated composite layer thickness to avoid failure of the pipe, for composites MC3 and MC4 with different defect lengths and deepness.

The results presented in Table 2 show that composite MC3 has ultimate stress lower than composite MC4. Equation 10 shows an inverse relationship between the strength of composite and composite layer thickness. This is confirmed by the graphs of figure 4 and 5, where the layer thickness are larger for composite material MC3.

Defects of thickness smaller than 6.0 mm and lengths smaller than 20.0 mm do not need the composite repair.

Attention must be called that in the calculations the composite materials were considered free from internal defects like porosities, delamination, etc. In order to increase the reliability of the repair, safety factors should be used taking into consideration the possibility of occurrence of defects and other problems in the composite layer.

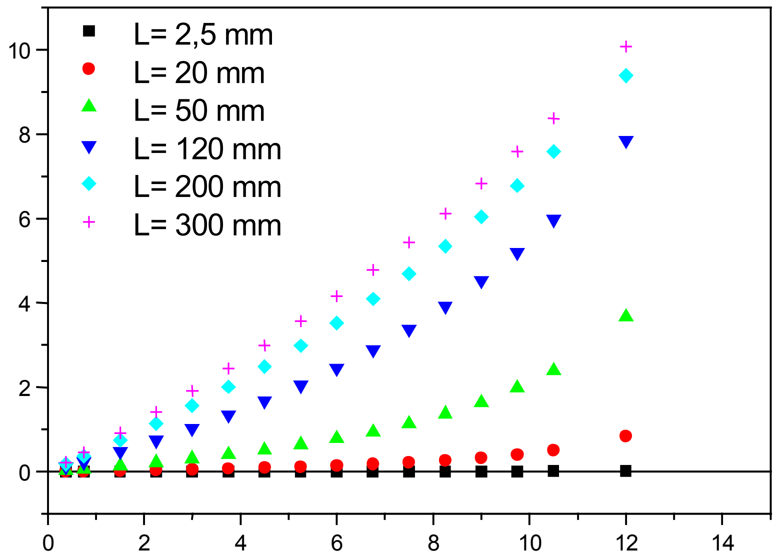


Figure 4- Composite layer thickness to avoid failure of the pipe with different defect lengths and deepness for composite MC3.

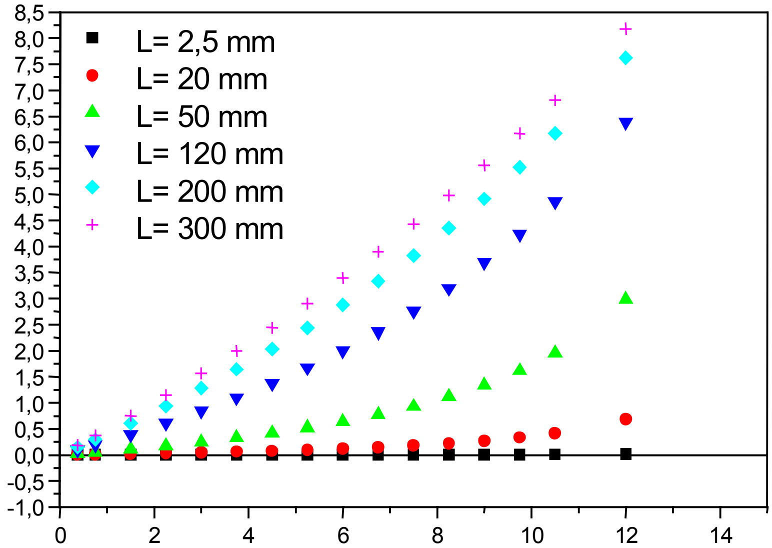


Figure 5- Composite layer thickness to avoid failure of the pipe with different defect lengths and deepness for composite MC4.

From the methodology adopted, the values of layer thickness were calculated using only the ultimate stress limits of the composite materials. However, the strain levels supported by the composite materials are also important, considering that these levels of strain can supply enough energy to induce failure of the composite material.

8. Conclusions.

In the present work, the use of composite materials in the repair of steel pipelines used in oil transportation was presented.

The tensile properties and microstructures of two types of composite materials of different configurations that can be used for this application are presented.

Composite material MC4 made of continuous and aligned fibers presented higher fracture strength than material MC3 made of fiber fabric. As a result, the thickness of the composite layer repair to maintain the integrity of the pipe is lower using material MC4.

The results obtained in present work show that the thickness of the layer of composite material necessary to repair steel pipelines with surface defects depends on the composite material strength such that the lower the strength of the composite the larger the necessary layer thickness.

Pipes with small defects did not show a substantial decrease of failure stress suggesting that in these cases the repair might not be necessary.

Defects with larger lengths and deepness demand larger composite material layer thickness to prevent failure.

9. Acknowledgments.

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