NUMERICAL STUDY OF STEEL PIPES REPAIRED WITH ANGLE PLY LAMINATES

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Abstract

The aim of this work is to present some numerical results concerned with the mechanical behavior of steel pipes 6 m long (length over diameter, L/D = 12; diameter over thickness, D/t = 100), subjected to internal uniform static pressure. These pipes were endowed with a thickness discontinuity (reduction of 60% in t) at the center section (L/2), covering a length of 1% of L, to simulate a defect in the form of a ring, and repaired with unidirectional Fiber Reinforced Plastic (FRP) angle ply laminates at the damaged area. The simulations were carried out using an in-house finite element code (COMPSHELL), and the results obtained so far indicate that it is possible to restore both the stiffness and the strength of the pipes using E-glass/epoxy composites.

Key - words: Composite repairs, Steel pipes, Numerical simulation.

1. INTRODUCTION

The search for new materials to repair metallic pipes is very important, mainly when they are located in remote areas where there is no welding equipment available. With the advent of the aerospace industry there was a necessity for new materials combining high strength and stiffness with low weight. Such materials, in particular the polymeric matrix composites, also have the advantage of good corrosion resistance in the presence of water (Levy Neto, 1991). Presently, in many other industries (e.g. chemical, oil, marine, car and building) carbon and E-glass Fiber Reinforced Plastics (FRP) are now replacing metallic materials in some applications (Hull and Clyne, 1996), and, in particular situations (e.g. ducts located in remote places), being used just to repair steel pipes (Soares and Lisboa, 1999).

Another aspect which is relevant to the pipe industry is the fact that thin FRP shell structures usually tend to present linear elastic behavior up to failure (Levy Neto, 1991), even when subjected to low velocity (less than 10 m/s) impact loads (Levy Neto, 1983). So, if a catastrophic failure does not take place and only localized damage occurs, due to the normal absence of plastic deformations such structures return to their initial shapes after the loads are removed. In practical terms, this means that FRP pipes and pressure vessels, for instance, would keep their original geometry even after they were loaded slightly beyond their limiting critical loads (i.e. material failure or local buckling). However, if a major accident takes place, their capacity to absorb energy is limited. In addition, FRP pipes are much more expensive and brittle, in comparison with steel pipes, and, due to the fact that they use a thermoset polymer as matrix they can not be recycled. In this context, there are some theoretical and experimental studies concerned with the repair of FRP structures (Baker, 1990; Mistry and Levy Neto, 1992), but the problems of high costs and low toughness still remain. Another possibility, which is the focus of this study, is to use FRP laminates, in the form of localized patches, only to repair steel pipes.

An additional practical aspect, which is relevant to the repair of pipe structures, is the fact that the epoxy resin is a good adhesive and the repair process does not involve any kind of welding. In such case, if the repair needs to be carried out in the field, this is a major advantage. A general repair procedure using FRP laminates includes: (i) preparation and cleaning of the metallic surface; (ii) patch application; (iii) vacuum bag and cure of the resin; (iv) surface finishing; and (v) inspection (Baker, 1990). The main objective of this theoretical investigation was to simulate the mechanical behavior of: (i) intact steel pipes subjected to static internal pressure; (ii) steel pipes with a localized decrease in the wall thickness resulting from corrosion, erosion, penetration, or lighting strike; and (iii) steel pipes with an axisymmetric discontinuity of the thickness, as described in item (ii), and repaired with carbon/epoxy and/or E-glass/epoxy angle ply laminates. The finite element code COMPSHELL (Levy Neto, 1991) was utilized to determine the theoretical failure pressures.

2. DESCRIPTION OF THE MODELS

The main geometric characteristics of the steel pipes simulated in this study are: total length (L) equal to 6000 mm; nominal diameter (D) equal to 500 mm; and thickness (t) equal to 5 mm, as shown in Figure 1. The material normally used in such structures is a mild carbon steel presenting elasticity modulus E = 205000 GPa; Poisson ratio ν = 0.3; shear modulus G = 78846 GPa; and yield stress σ_y = 400 MPa (Jastrzebski, 1990).

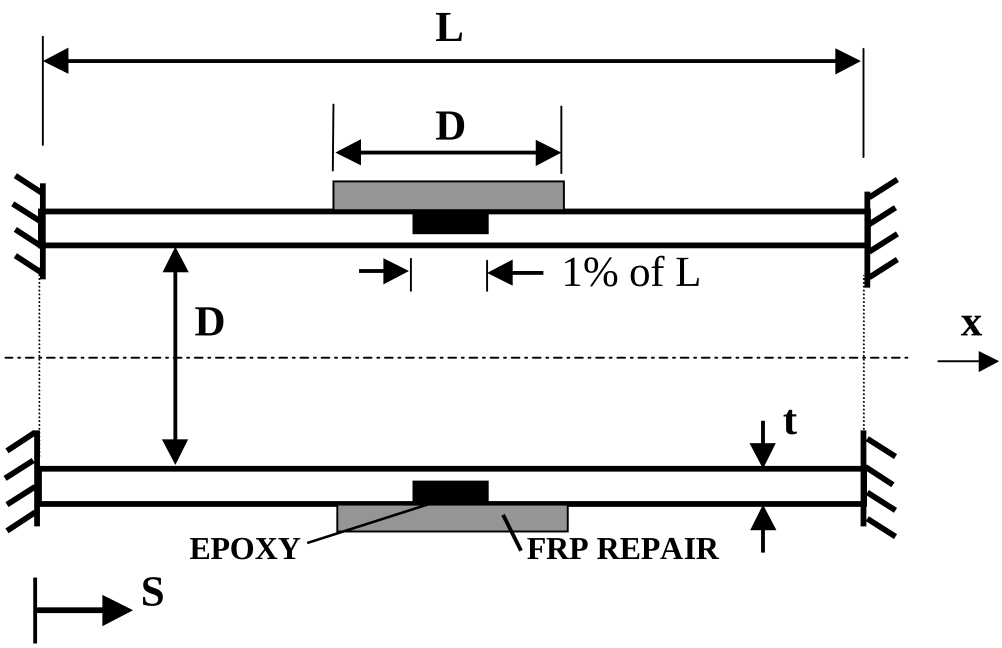

Figure 1- General view of a repaired pipe

In the numerical model, based on the finite element method, it was assumed that the pipe is a perfect cylinder (i.e. an axisymmetric shell) clamped at both ends. Steel pipes can not be manufactured longer than about 6 m (Silva Telles, 1997). So, in a pipeline, many cylindrical segments need to be connected by flanges or welded. The flanges naturally contribute with a significant increase on the bending stiffness at the ends of the pipes; and, at the welded joints, there is an overlapping of the walls of the adjacent pipes, increasing the thickness at the joint by a factor of 2, which also increases the stiffness locally. So, the assumption of the clamped ends at the model seems to be a fair one.

The coordinates which are important for the in plane stress analysis of the pipes are the longitudinal, or meridian, direction x (see Figure 1), the shell circunferential direction y, and the directions 1 and 2, as shown in Figure 2, related to the orientations of the fibers in the FRP laminate. The angle θ refers to the orientation of the fibers relatively to x.

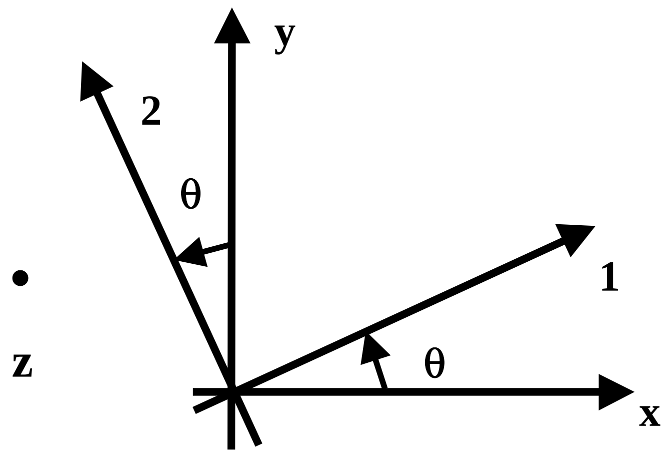

Figure 2 – Systems of Coordinates (x,y), and (1,2).

The shell element adopted in the finite element code COMPSHELL was a two-node axisymmetric ring with 4 degrees of freedom (displacements u, v, w; and the meridian rotation β) per node, and the shell equations are those based on the theory of Novozhilov for thin shells. The displacement u is longitudinal (i.e. along direction x shown in Figure 1), v corresponds to the circunferential direction y of the shell, and w, along z shown in Figure 2 is normal to the shell surface. The program is able to calculate the stress resultants and the bending moments along x and y, as well as in plane stresses and strains in the coordinate systems (x,y) and (1,2), and has 7 special failure criteria to estimate the threshold of failure of FRP laminae subjected to in plane stresses (σ_1, σ_2 , and τ_{12}), where 1 and 2 refer to the directions parallel and perpendicular to the fibers of a FRP unidirectional lamina, respectively (Levy Neto, 1991). So, σ_1 and σ_2 are normal stresses along and perpendicular to the fibers, respectively, and τ_{12} a shear stress in the plane of the lamina. The theory adopted in the present investigation is the failure criterion of Tsai-Hill (Gibson, 1994), which is based on a quadratic equation as shown below:

$$\left(\frac{\sigma_1}{X}\right)^2 - \left(\frac{\sigma_1\sigma_2}{X^2}\right) + \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \leq 1 \qquad (1)$$

where:

X : is the tensile (X_{1T}) or the compressive strength (X_{1C}) of the FRP in direction 1, depending on the sign of σ_1;

Y : is the tensile (X_{2T}) or the compressive strength (X_{2C}) of the FRP in direction 2, depending on the sign of σ_2; and

S_{12}: is the shear strength of the FRP in the plane (1, 2).

For the static failure analysis of the damaged steel pipe repaired with FRP a laminate, which is a brittle material, the criterion of Tsai-Hill is very convenient. First because it presents good correlation with experimental results when FRP laminates are tested to failure (Gibson, 1994); and second because it turns itself into the yield theory of von Mises, for ductile materials, when the values of X, Y, and S_{12} are substituted by σ_y in equation (1). So, it is able to predict the onset of yield in the steel and the threshold of failure in FRP layers.

Two kinds of unidirectional composites, E-glass/epoxy and Carbon/epoxy, were used as the FRP repair in the numerical simulations. Their mechanical properties together with those of the epoxy resin are shown in Table 1 (Soares and Lisboa, 1999). The FRP layers have two different elasticity moduli, E_1 and E_2, and Poisson ratios, ν_{12} and ν_{21}, depending if the FRP is stretched along or perpendicular to the fibers, respectively (Gibson, 1994).

Table 1 – Mechanical properties, in MPa, of the materials used in the repair

Mech. Properties	**E – glass/epoxy**	**Carbon/epoxy**	**Epoxy**
E_1	38600	138000	3100
E_2	8270	8960	3100
ν_{12}	0.28	0.31	0.39
ν_{21}	0.06	0.02	0.39
G_{12}	4140	7100	1115
$\mathbf{X}_{1T}$	1062	1447	75
X_{1C}	610	1447	120
$\mathbf{X}_{2T}$	31	52	75
$\mathbf{X}_{2C}$	118	206	120
S_{12}	72	93	90

The FRP repairs consisted of symmetric angle-ply laminates with four layers and stacking sequences: $[\theta / -\theta / -\theta / \theta]$, or $[\theta / -\theta]_s$, in which $20° \leq \theta \leq 90°$, where the subscript s means symmetric about the middle surface of the laminate.

3. MAIN RESULTS

The simulations carried out so far, in order to predict the onset of failure of the models (i.e. yield of the steel, or material failure of the FRP) subjected to uniform pressure (p), included 4 situations, as illustrated in Figure 3: (i) perfect steel pipes (i.e. t = 5 mm all over); (ii) steel pipes with a local thickness reduction at the central region, simulating a defect, or damage, in the form ring; (iii) same as situation (ii), in which the “ring” is filled with epoxy resin and the central region is repaired with one laminate having 4 plies of FRP with fiber orientations $[\theta / -\theta]_s$; and (iv) same as (iii) but repaired with two laminates of 4 plies each. The thickness reduction was 60% (3 mm), over a distance equal to 1% of L, the total thickness of each repair laminate was 5 mm (1.25 mm per ply), and the extension of the repair was equal to the diameter (D) of the pipe, as shown in Figure 3 (situations iii and iv).

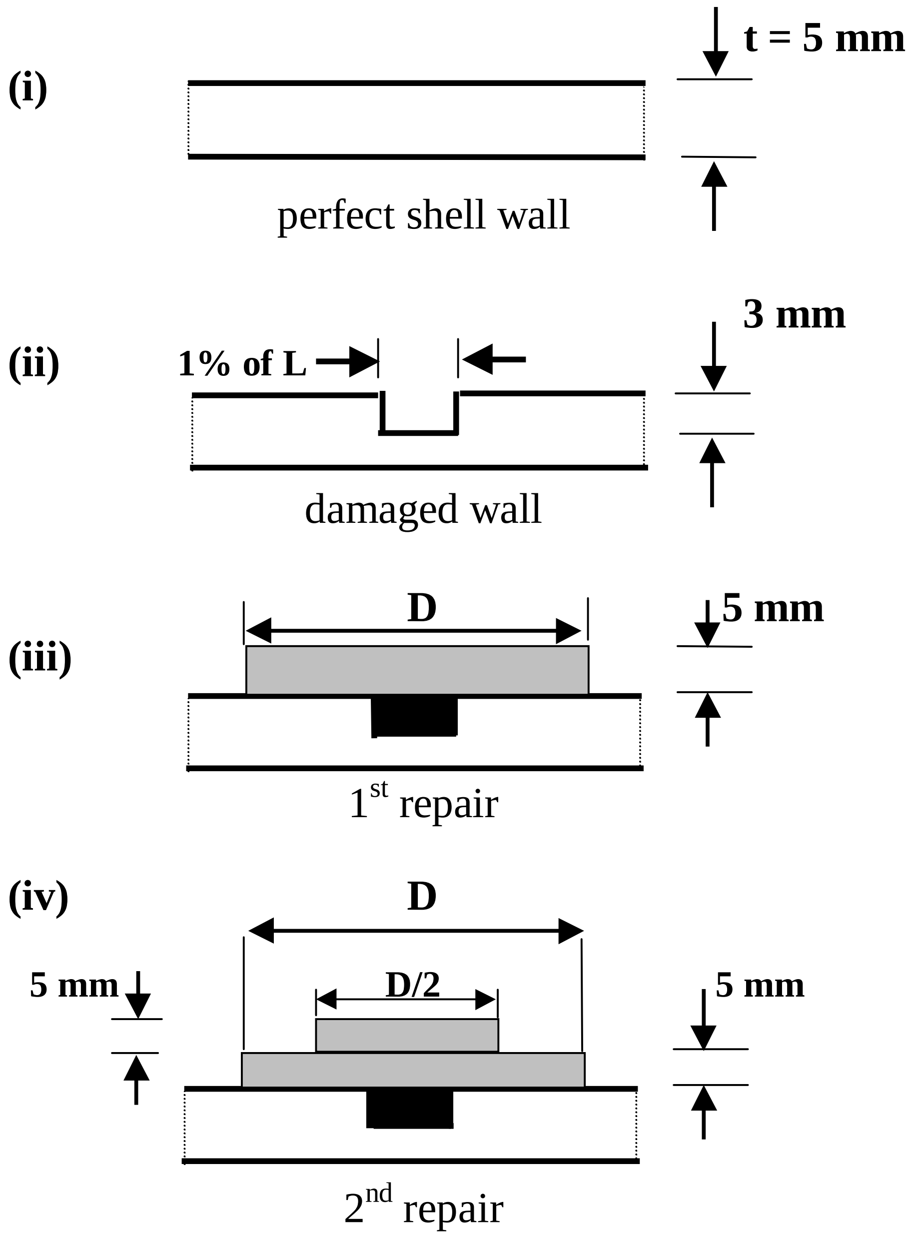

Figure 3 - Four situations for the shell wall at central region of the pipes

According to a survey carried out by Soares and Lisboa (1999) involving PETROBRAS / CENPES, in Rio de Janeiro, steel ducts with D = 500 mm and t = 5 mm should resist to at least p = 5 MPa of internal hydrostatic pressure (p). So, one of the purposes of this work was to find out if the damaged and the repaired pipes were able to resist to $p \geq 5$ MPa.

Using the program COMPSHELL, and the model with the shell wall of situation (i), corresponding to the perfect steel pipe in Figure 3, after the finite element mesh was refined the results converged to **p_{max} = 6.3 MPa**. In this simulation, p_{max} corresponds to the onset of yield, which occurred at the clamped edge (S = 0, in Figure 1). Under p = 6.3 MPa, the radius of the pipe increased uniformly all over, except at the clamped edges where w = 0, by the value $w_{max} = w_{unif}$ = 0.26 mm (radial displacement). The failure mechanism, according the distribution of stresses obtained in the simulations, was controlled by the peaks of bending moments occurring at the clamped edges (S = 0, and S = L). Away from the clamped edges the bending moments vanish. Krauss (1967) using analytical solutions based on the hypergeometric functions also obtained similar results for an equivalent problem.

The threshold of failure of the steel pipe with the "ring" defect, corresponding to situation (ii) in Figure 3, was **p_{max} = 3.8 MPa (drop of 39%)**, and the position of the onset of yield now migrated to S = L/2 (i.e. S = 3 m). Close to S = L/2 the bending moments were very high, and there was a local increase in the radial displacement w_{max} = 0.45 mm. Away from this region $w = w_{unif}$ = 0.26 mm, which is the same value as in situation (i). When the "ring" was only filled with epoxy resin, without any FRP repair, the obtained values of p_{max} , w_{max} , and w_{unif} were practically as those obtained in situation (ii).

When a repair consisting of 4 plies of E-glass/epoxy, $[90°]_4$, i.e. one laminate with 5 mm of thickness, was applied, as shown in Figure 3, situation (iii), the onset of failure remained at S = L/2 but increased to **p_{max} = 4.9 MPa,** w_{max} was reduced to 0.42 mm close to S = L/2, and $w = w_{unif}$ = 0.28 mm along the pipe. Since p_{max} was lower than 6.3 MPa, the strength of the perfect pipe, two laminates of E-glass/epoxy, of 5 mm each, were used as repair, as illustrated in Figure 3, situation (iv). This time the onset of failure shifted to the clamped edge S = 0 and the pressure increased to **p_{max} = 6.2 MPa,** w_{unif} = 0.28 mm, and w_{max} = 0.284 mm.

Using the repair configuration of situation (iv), shown in Figure 3, with two laminates of $[\theta / -\theta]_s$, and varying the orientation of the fibers from 20° to 90°, at intervals of 5°, the values of p_{max} obtained in the simulations, as shown in Table 2, remained practically unchanged. Only the location of the failure, S, changed from 0 to L/2, and back to 0.

Table 2 – Effect of the variation in the fibers orientations, θ in the results.

θ	S [mm]	Failed Ply	Z [mm]	p_{max} [MPa]
20°≤θ≤30°	0	1	-2.5	6.182
35°	3000	1	-7.5	6.155
40°	3000	1	-7.5	6.115
45°	3000	1	-7.5	6.125
50°≤θ≤55°	0	1	-2.5	6.185
60°≤θ≤70°	0	1	-2.5	6.192
75°≤θ≤90°	0	1	-2.5	6.200

The results presented in Table 2 indicate the sensitivity of p_{max} with the orientation of the fibers in the FRP repair is very reduced. In fact, for 20°≤θ≤30°, and 50°≤θ≤90° the failure occurs at the clamped edge, away from the FRP repair. For 35°≤θ≤45° the failure occurs at the repair region but the influence of θ on p_{max} was reduced. It is also important to mention that all the values of p_{max} in Table 2 are very close to the onset of yield of the perfect pipe, p_{max} = 6.3 MPa.

Finally, some simulations were also carried out using an unidirectional carbon/epoxy laminate of 2.5 mm , $[90°]_s$, according to situation (iii) shown in Figure 3, as the FPR repair. The value of p_{max} obtained was 6.3 MPa, which is the same of the perfect pipe. However, the values of w in the repair region were smaller than w_{unif} by about 82% (w_{min} = 0.21 mm), indicating that the FRP repair was so stiff that it subjected the damaged region in compression, relatively to the rest of the pipe. On the other hand, the thickness of the carbon/epoxy can laminate be reduced in order to solve this problem easily.

4. COMMENTS AND CONCLUSIONS

The results obtained in this study indicate that, using E-glass/epoxy laminates, it is possible to restore both the strength and the stiffness of steel pipes subjected to a severe thickness discontinuity (only 40% of the original thickness remained) at the middle section. After the repair with two $[\theta / -\theta]_s$ laminates of 5 mm each (situation (iv) in Figure 3) the failure pressure (p), and the maximum radial displacement (w) of the damaged pipe, were practically restored to those values presented by the perfect steel pipe.

Although different fiber orientations can be adopted for the repair, the laminate $[90°]_4$ (i.e. all fibers in the hoop direction), is the easiest to apply and figures among the most efficient, as shown in Table 2. According to the data presented in Table 2, the onset of failure always occurred at the innermost ply (layer 1), so, not visible at the external surface of the pipes.

Carbon fibers are known to be lighter, stiffer (at least 3 times), more brittle, and stronger than E-glass, but they are about 10 times more expensive (Hull and Clyne, 1996). According to the simulations carried out so far both kinds of fibers can be used for the repair of pipes. If the final cost in one of the design priorities the best choice is an E-glass fiber. But, if the repaired pipe needs to be as light as possible, then the choice must change to the carbon fibers instead.

Due to the discontinuity of thickness and stiffness close to the damaged area, the state of stresses at the repair region is very complex, and the initial results obtained so far should be confirmed by experimental data as well as by additional simulations using other finite element codes, based on different formulations. In the present study, the shape functions for u and v were linear, for β quadratic, and for w cubic. It is the intent of the authors to compare the simulations carried out so far with those based on alternative interpolation polynomials like a non Hermitian, for instance.

REFERENCES

Baker, A. A., 1990, Repair Techniques for Composite Structures, in Composite Materials in Aircraft Structures, edited by D. H. Middleton, Longman Scientific and Technical, London.

Gibson, R. F., 1994, Principles of Composite Material Mechanics, McGraw-Hill, New York.

Hull, D. and Clyne, T. W., 1996, An Introduction to Composite Materials, Cambridge University Press, Cambridge.

Jastrzebski, Z. D., 1987, The Nature and Properties of Engineering Materials, John Wiley & Sons, New York.

Krauss, H., 1967, Thin Elastic Shells, John Wiley & Sons, New York.

Levy Neto, F., 1983, Estudo da Falha ao Impacto de uma Estrutura de Material Conjugado Usada em Aeronaves, Tese de Mestrado, ITA, São José dos Campos (in Portuguese).

Levy Neto, F., 1991, The Behaviour of Externally Pressurised Composite Domes, Ph.D. Dissertation Thesis, University of Liverpool, U.K..

Mistry, J. and Levy Neto, F., 1992, The Behaviour of Repaired Composite Domes Subjected to External Pressure, Composites, vol. 23, number 4, July, pp. 271 – 277.

Silva Telles, P. C., 1997, Tubulações Industriais: Materiais, Projeto e Montagem, Editora LTC, Rio de Janeiro (in Portuguese).

Soares, V. B. e Lisboa, W. R., 1999, Simulação Numérica Simplificada do Reparo Estrutural em Dutos Utilizando-se Materiais Compósitos Tipo Fibra / resina, Projeto Final de Graduação, UnB, Dept. de Engenharia Mecânica, Brasília (in Portuguese).