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STRESS MODELING OF DEFECTED PIPELINES STRENGTHENED WITH FRP COMPOSITES

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Abstract

Fiber reinforced polymer composites (FRPC) have been recognized as an effective means for repair and rehabilitation of civil infrastructure. However, the use of FRP in the repair and rehabilitation of pipelines is a relatively new concept that has the potential to improve the way we repair pipelines. The purpose of this paper is to discuss the benefits of using FRPC and to provide stress formulas on the interaction between the different stresses exerted on steel pipeline and the effects of FRPC sheets on the circumferential stresses of damaged pipe walls. The effects of three different FRPC sheets: Glass FRP (GFRP), Aramid FRP (AFRP) and Carbon FRP (CFRP) on the performance of pipe walls are compared analytically. Results show that carbon fiber composites perform better than glass or aramid in improving the ultimate internal pressure capacity of pipes, and therefore, significantly enhance the strength, durability, and corrosive properties.

KEYWORD

FRP, steel pipeline, internal pressure, external pressure, corrosion, composite repair, stress expression

INTRODUCTION AND BACKGROUND

Engineers are faced with the ongoing task of rehabilitating pipelines due to damage caused by different environmental and load factors. The major causes of pipeline damage and failure around the world are external interference and corrosion. The defects in the original material or in the manufacturing and installation process such as cracks during loading, shipping, unloading, or storage causes damage to pipes as well. The current conventional rehabilitation methods for repairing pipelines are shortcrete, polymer concrete, the trenchless method, and manhole rehabilitation. Using advanced composite materials for repair can be a cost effective method of improving safety without excavation of overlaying soil and /or replacement of pipe sections while keeping maintenance cost down. The key benefits of using advanced composite materials for steel pipeline repair are: chemical bond to steel provides leak sealing capability with chemical and environmental resistance, no interruption to plant operation during repair, install at full line pressure, site access and preparation issues minimized, lightweight repair kits are easy to transport and handle, materials formed to shape on site with no pre-fabrication, flexible materials conform to difficult shapes, no hot work required. After repair, pipe diameter is not excessively decreased, the flow capacity, therefore, would not reduce much either.

Theoretical Model

Pressurized underground pipelines must resist both internal and external pressures. To determine the effect of FRP repairs on a pipe wall, stress expressions have to be developed and applied to undamaged pipe, damaged pipeline, and FRP reinforced damaged pipes. This will in turn produce an overall expression for the maximum circumferential tensile stress at a critical section that contains different loading such as soil, traffic, and internal pressure. Pipelines that withstand loads such as traffic loads are subjected to externally applied stresses that are not uniform on any specific cross section nor are they uniform along the length of the pipe. In this theoretical model, the support and loading variations along a run of pipe will be assumed to be indistinguishable at a specific cross section where the longitudinal load variation will be ignored. It will also be assumed that the pipeline will remain at a constant and uniform temperature with its cross section in a state of plain strain (i.e. longitudinal movements or deformations being ignored) (Toutanji and Dempsey 2000).

Except for the internal and external pressures, pipelines are also subjected internal and external corrosion. Corrosion is a common form of degradation in pipelines that reduces both the static and cyclic strength of a pipeline. With either a uniform or localized nature, corrosion affects the pipeline wall thickness. Finally, with the combination of ageing coating, aggressive environment, rapid corrosion growth may lead to a corrosion failure. This failure is not simply a ‘corrosion’ failure, but a ‘corrosion control system’ failure (Cosham, Hopkins and Macdonald 2006). According to previous research, one difficult aspect of repair of pipe walls is the problem of uncertainty in predicting the location rate of corrosion (Ahammed and Melchers 1994). This problem should be of consideration for both proper design practices and for making decisions about pipeline maintenance and repair strategies.

WALL STRESSES IN UNDERGROUND PRESSURIZED UNDAMAGED PIPES

The effects of stresses exerted by external load and by internal fluid pressure on underground-pressurized pipelines should be considered. Internal pressure produces uniform circumferential tension stress across the wall if the wall thickness is comparatively small and the density of the fluid carried in the pipeline is small relative to the fluid pressure. External loads produce bending stresses both in the longitudinal and circumferential directions. This circumferential stress is the main focus since the pipe is assumed uniformly loaded and supported along its length. If the pipe wall stresses remain within the elastic range of the material, the circumferential bending stresses in the pipe wall due to the external loads are assumed to be algebraically additive to the tensile circumferential stress produced by the internal pressure.

The circumferential stress due to internal pressure can be estimated using the following expression (Stephenson 1976)

$$\sigma_f = \frac{pr}{t} \tag{1}$$

Where it is assumed that $t << r$ and where $\sigma_f =$ hoop stress due to internal fluid pressure; $p =$internal fluid pressure; $r =$ radius of pipe; and t = thickness of pipe wall.

The bending stress in the circumferential direction produced in the pipe wall by the external soil loading can be estimated using Eq. 2 (Spangler and Handy 1982).

$$\sigma_s = \frac{6k_m C_d \gamma B_d^2 Etr}{Et^3 + 24k_d pr^3} \tag{2}$$

Where $\sigma_s =$ bending stress due to soil load (MPa); $C_d =$ calculation coefficient for earth load; $\gamma =$ unit weight of soil backfill (N/mm^3); $B_d =$ width of ditch at the level of top of pipe (m); $E =$ modulus of elasticity of pipe (MPa); $K_m =$ bending moment coefficient dependent on the distribution of vertical load and reaction (MPa); and $K_d =$ deflection coefficient dependent on the distribution of vertical load and reaction.

When an external traffic load such as roadway, railway, or airplane traffic exist, the resulting circumferential bending stresses produced in the pipe wall may be estimate as follows:

$$\sigma_t = \frac{1}{A}\frac{6k_m I_c C_t FEtr}{Et^3 + 24k_d \mathrm{Pr}^3} \tag{3}$$

Where $\sigma_t =$ bending stress due to traffic load (MPa); $I_c =$ impact factor; $C_t =$ surface impact load coefficient; $F =$ wheel load on surface (N); and $A =$ effective length of pipe on which load is computed (m).

The maximum circumferential tensile stress σ_m at the critical sections can be expressed by the following, if the pipe wall remains in the elastic range under load

$$\sigma_m = \sigma_f + \sigma_s + \sigma_t \tag{4}$$

$$\sigma_m = \frac{pr}{t} + \frac{6k_m C_d \gamma B_d^2 Etr}{Et^3 + 24k_d pr^3} + \frac{1}{A}\frac{6k_m I_c C_t FEtr}{Et^3 + 24k_d \mathrm{Pr}^3} \tag{5}$$

WALL STRESSES IN UNDERGROUND PRESSURIZED DAMAGED PIPES

Internal and external corrosion are together one of the major causes of pipeline damages and failures. Corrosion is an electrochemical process. It is time dependent mechanism and depends on the local environment within or adjacent to the pipeline. The interaction between the internal fluid properties and pipe material may cause potential and /or chemical changes as the fluid flows through the pipeline which causes the internal corrosion. Evidence shows that internally uniform corrosion is less likely to occur, where localized corrosion (pitting) and general corrosion on the surrounding exterior surface is more likely (Cosham, Hopkins and Macdonald 2006). External corrosion is dependent on the localized condition, including the soil type, rate of oxygen depletion and replenishment, soil water or moisture and its movement, and presence and effectiveness of any corrosion protection measures.

The loss of pipeline thickness due to corrosion may be relatively uniform in extent or localized, but does not occur at a constant rate over the design life of the pipe. Protective properties of the corrosion product improve after the initial corrosive period. This initial period of wall thickness corrosion is due to the corrosion products that are formed on the pipe surface being porous and their protective properties being poor. The corrosion rates after this initial period gradually decreases and in some cases stabilizes.

Corrosion in a pipeline may be difficult to characterize. Typically, it will have an irregular depth profile and extend in irregular pattern in both longitudinal and circumferential directions. It may occur as a single defect or as a cluster of adjacent defects separated by full thickness material. In this theoretical model, the single corrosive defect is assumed to be the major corrosive defect and no general corrosion being observed.

Since corrosion is a time dependent mechanism, developing expressions with a function of time is a general corrosive case, whether this means weight loss, deepest pit or localized depth, or average pit or localized depth, can be modeled empirically by a power law (Kucera and Mattsson 1987).

$$d = kT^n \tag{6}$$

This law should be understood as an engineering viewpoint rather than a scientific viewpoint where $d =$ maximum defect depth; $k =$ a multiplying constant; $T =$ time at exposures; and $n =$ an exponential constant. For soil conditions, corrosion of steel, k ranges from 0.1 to 0.5 and n may wary from 0.4 to 1.2 (Kucera and Mattsson 1987).

Applying this power law to the previous circumferential stress, Eqs 1-3, the circumferential stress equation due to internal pressure then becomes the following expression when applied to a damaged pipe

$$\sigma_f = \frac{pr}{t-d} \tag{7}$$

The bending stress in the circumferential direction produced in the pipe wall by the external soil loading is then expressed by

$$\sigma_s = \frac{6k_m C_d \gamma B_d^2 E(t-d)r}{E(t-d)^3 + 24k_d pr^3} \tag{8}$$

Therefore, the circumferential bending stress produced in the pipe wall with an external traffic load is expressed by

$$\sigma_t = \frac{1}{A}\frac{6k_m I_c C_t F E(t-d)r}{E(t-d)^3 + 24k_d \mathrm{Pr}^3} \tag{9}$$

$$\sigma_m = \sigma_f + \sigma_s + \sigma_t = \frac{pr}{t-d} + \frac{6k_m C_d \gamma B_d^2 E(t-d)r}{E(t-d)^3 + 24k_d pr^3} + \frac{1}{A}\frac{6k_m I_c C_t F E(t-d)r}{E(t-d)^3 + 24k_d \mathrm{Pr}^3} \tag{10}$$

WALL STRESSES IN UNDERGROUND PRESSURIZED FRP REINFORCED DAMAGED STEEL PIPES

Applying the properties, and theory behind the wall stresses in underground pressurized damaged pipes, expressions are developed to include the addition of fiber reinforced polymer composites (FRP) for repair and rehabilitation of pipelines. Using FRP to repair and rehabilitate damaged pipe causes t (thickness of pipe) to change. The following expression takes into consideration FRP addition and is substituted for t as t_t (Toutanji 1999).

$$t_t = (t-d)[1+\frac{E_{FRP}t_{FRP}}{E(t-d)}] \tag{11}$$

Thus, with the consideration of FRP addition to the pipe wall thickness, the following expressions are developed for the circumferential stress due to internal pressure and the bending stress in the circumferential direction produced in the pipe wall by the external soil loading

$$\sigma_f = \frac{pr}{t_t} \tag{12}$$

$$\sigma_s = \frac{6k_m C_d \gamma B_d^2 E_s t_t r}{E_s(t_t)^3 + 24k_d pr^3} \tag{13}$$

The circumferential bending stress produced in the pipe wall with an external traffic load with the addition to the FRP sheets

$$\sigma_t = \frac{1}{A}\frac{6k_m I_c C_t F E_s t_t r}{E_s(t_t)^3 + 24k_d \,\mathrm{Pr}^3} \tag{14}$$

$$\sigma_m = \sigma_f + \sigma_s + \sigma_t = \frac{pr}{t_t} + \frac{6k_m C_d \gamma B_d^2 E_s t_t r}{E_s(t_t)^3 + 24k_d pr^3} + \frac{1}{A}\frac{6k_m I_c C_t F E_s t_t r}{E_s(t_t)^3 + 24k_d \,\mathrm{Pr}^3} \tag{15}$$

APPLICATION AND ANALYSIS: EXAMPLE

The purpose of this example application is to illustrate that the basis of this model is realistic and solid. To generate the circumferential stress analytical curves, it is necessary to know the internal fluid pressure, the pipe radius, the various constants, the elastic modulus, and the thickness of fiber sheets. This and other necessary data to use in conjunction to the developed model are provided in Tables 1 and 2.

Table 1. Mechanical properties and constraints of a given length of pipe

Symbol	Description	Value
r	Pipe radius, (mm)	325
t	Pipe wall thickness, (mm)	7.5
K_m	Bending moment coefficient	0.235
C_d	Calculation coefficient for earth load	1.32
γ	Unit Weight of soil, (N/mm^2)	18.85 x 10^{-6}
B_d	Width of ditch at the level of top of pipe, (mm)	762
E	Module elasticity of pipe, (N/mm^2)	207,000
k_d	Deflection coefficient	0.108
I_c	Impact factor	1.5
C_t	Surface load coefficient	0.12
F	Wheel load on surface, (N)	267,000
d	Maximum defect depth, (mm)	2.75
A	Effective length of pipe, (mm)	914

Table 1 shows the constraints and mechanical properties of a given length of pipe to develop plotted curves stresses due to soil, traffic, and internal pressure. Table 2 shows the mechanical properties of FRP sheets.

Table 2. Mechanical properties of FRP sheets

Specimens	Thickness t (mm)	Tensile Strength (MPa)	60% Hoop Strength (MPa)	Modulus of Elasticity (GPa)
Glass	0.118	1,790	1074	80
Aramid	0.138	2,480	1488	131
Carbon	0.165	3430	2058	230

The analytical results obtained from the model are shown in Figures 2-5. Figure 2 shows the comparison of circumferential stresses due to soil load, traffic load, and internal pressure in an undamaged pipe. Figure 3 shows the same comparisons but in a damaged pipe. As expected, a pipe without defects withstands higher stresses due to soil and traffic loads and lower stresses due to internal pressure than a pipe with defects. For example, in the pipe without defect, the circumferential stress due to internal pressure is 173.3 MPa with an internal pressure of 4 MPa, whereas in the damaged pipe, the circumferential stresses are 273.7 MPa. The circumferential stress due to traffic in the pipe without defects at an internal pressure of 4 MPa is 84.4 MPa, whereas in the damaged pipe the stress is 62.7 MPa.

What and how much benefit do FRP composite sheets provide in a pipeline circumferential stresses? And if they do provide benefit, what type of FRP sheet (CFRP, AFRP, and GFRP) has a greater ultimate internal pressure when reinforced material ruptures or does not provide reinforcement very well. Previous research shows that FRP reinforcement does not work well after hoop stresses is greater to 60% of material tensile stress. Therefore, in this paper, the internal pressure-circumferential stress curves end when the total circumferential stresses reach 60% of tensile strength for different hoop material. Figure 4 shows, as an example, the circumferential stresses of the CFRP repaired damaged pipeline due to the soil and traffic loads as well as to internal pressure. The curve shows an increase in stresses due to soil and traffic loads and a decrease in the stress due to internal pressure when compared to Figure 3.

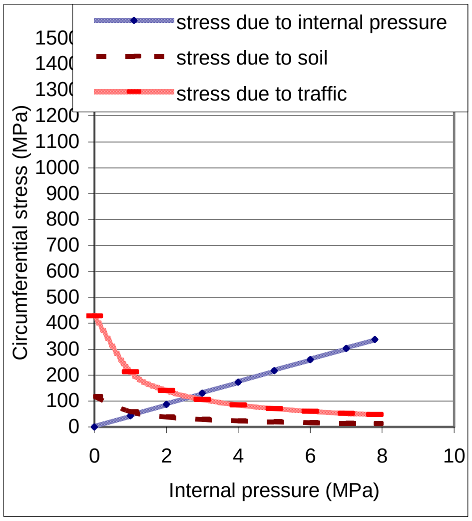


Figure 2. Circumferential stresses due to soil load, traffic load, and internal pressure in pipeline without defects

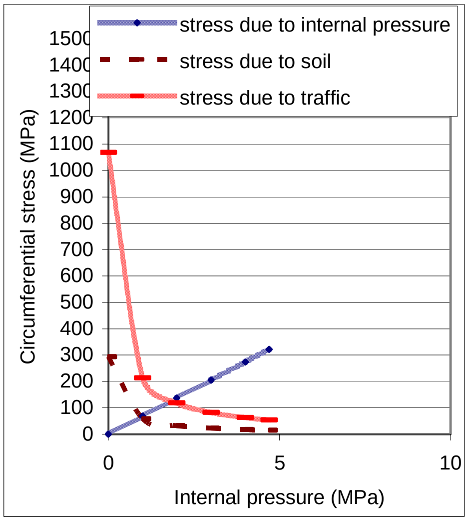
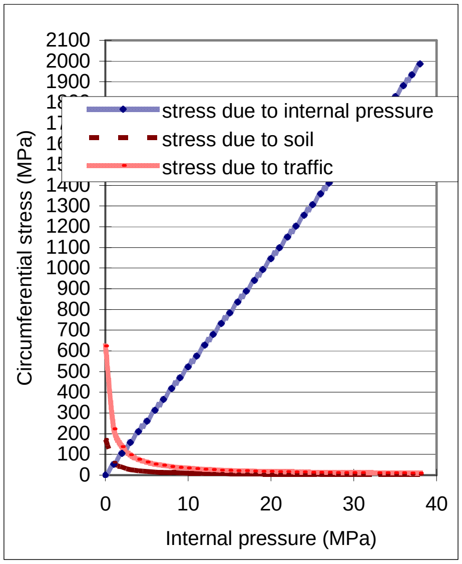


Figure 3. Circumferential stresses due to soil load, traffic load, and internal pressure in pipeline with defects



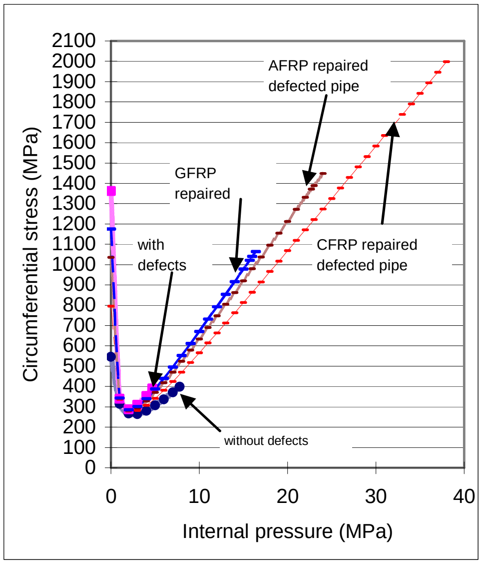


Figure 4. Circumferential stresses due to soil load, traffic load, and internal pressure in CFRP repaired damages pipeline

Figure 5. Comparison between circumferential stresses and internal pressure in pipeline without defect, with defect, and FRP repaired damaged pipeline

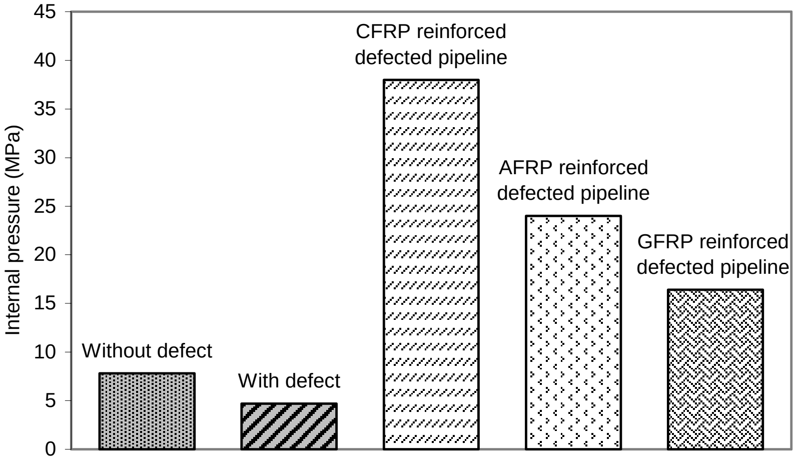


Figure 6. Comparison between pipeline status and ultimate internal pressure in pipe without defect, pipeline with defect, and FRP repaired damaged pipes

Figure 5 shows a comparison between the maximum circumferential stress σ_m $(\sigma_f + \sigma_s + \sigma_t)$ and internal pressure in pipe without defect, pipe with defect, GFRP, CFRP, and AFRP repaired damaged pipe. Under the same internal pressure, damaged pipeline repaired by CFRP sheets has less circumferential pressure which allows for more internal pressure.

Figure 6 compares the undamaged pipe, damaged pipe, and pipes repaired with the three different FRP sheets, to their ultimate internal pressure. Again it is clear that the pipe repaired with carbon fiber sheets has a higher stress threshold than those repaired with glass or aramid fibers.

CONCLUSIONS

As an effective mean for the repair and rehabilitation, the benefits of using fiber reinforced polymer composites have been established in this paper. This objective was reached by developing a theoretical model with stress expressions and circumferential stress curves. This stress expressions are based on the interactions among the different stresses (stress due to soil, traffic and internal pressure) exerted on pipelines and the reinforcement effect of different types of FRP (CFRP, AFRP and GFRP) on circumferential stress of damaged steel pipelines. The stress curves show that the damaged pipeline repaired by CFRP has less circumferential pressure level under the same internal pressure compared with stress curves of AFRP and GFRP repaired damaged pipelines. This makes the carbon fiber sheet provide a better performance than glass or aramid in improving the ultimate internal pressure capacity of pipes.

This study was focused on the application of fiber reinforced polymer on steel pipelines. No study shows any visible degradation when carbon fiber material contacts steel pipelines. But, the existing steel corrosion may get worse in the presence of carbon fiber material. Thus, before applying FRP on damaged steel pipelines, coating is suggested.

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