ANALYSIS OF INTERNAL BONDED FIBRE REINFORCED COMPOSITE REPAIR SYSTEMS FOR CORRODED STEEL PIPELINES

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ABSTRACT

Steel pipelines are widely used in the oil and gas industry. Over time, many pipelines experience internal metal loss, mainly due to corrosion, and some form of repair is required in order to reinstatethe original operating capacity and maintain structural integrity. Fibre reinforced composites offer solutions with broad applicability and efficiency for internal repair of these pipelines. Analysing and understanding the behaviour of composites is important in order for them to be used effectively as an internal repair system for corroded steel pipelines. This paper presents the analyses of internal composite bonded repair systems for long steel pipes with an axisymmetric defect, based on Lame’s equation. Optimum internal composite repair thicknesses using biaxial carbon and glass fibre composites were determined for different levels of corrosion, following the Von Mises yielding and Tsai-Hill failure criterion approaches. Design nomographs for internal composite repair systems have been developed.

KEYWORDS

GFRP, CFRP, composite repair, failure index, thick cylinder.

INTRODUCTION

Steel pipelines play a vital role in transporting oil and gas. Over 1.7 million km pipelines transporting gas, crude oil, and petroleum products throughout the world (Mohitpour et al. 2003). Many of these pipelines have been in operation since the 1940s and 1950s (Chapetti et al. 2001). Consequently, every year between $2 and $3.3 billion in the United States alone is lost due to corrosion in gas and petroleum pipelines that need to be repaired or replaced (Koch et al. 2001). Therefore, maintenance of vast pipeline networks represents an essential part of oil and gas transportation.

High pressure, a wide range of temperature variation (-50 to 130°C) and chemical erosion are the major factors that affect the internal corrosion on transmission pipelines for oil and gas industry (Palmer et al. 2000). As a result, the pipeline walls continue to corrode and this eventually leads to pipeline leakage or rupture. In the oil and gas industry, the usage of fibre composite materials is continually growing along with the development of new piping systems, pressure vessels and other structural components (Price et al. 2002). Composite is being used to rehabilitate internally corroded pipeline to prevent further corrosion. The high tensile strength, lightweight, durability and versatility of fibre composites makes them the material of choice for many repair and rehabilitation projects (Elsani 2009). These properties combined with the direction dependency allow the material to be fit through the inside of the pipe and then be reshaped so it can be placed against the wall in the area where repair is required (Bruce et al. 2006). This exceptional advantage of fibre composites has motivated the oil and gas industry in using this material for the internal repair and rehabilitation. Pipe diameter is not excessively reduced and flow capacity has been known to increase in some cases due to the smooth final coating that causes less friction than some pipe material such as concrete (Toutanjii et al. 2001). In addition, the lightweight and flexibility of fibre composites makes them easy to handle during repair. Compared with the traditional repair systems like cutting of damaged pipelines and welding, composite repair systems are more reliable and versatile.

There are limited studies conducted on the internal repair of steel pipelines using composite material systems and little literature is available on its usage. The selection of the most appropriate repair thickness and the behaviour of a steel pipeline – composite repair system, particularly the internal repair of high pressure pipelines is an issue.
and needs to be investigated in detail. This paper presents the analyses of internal composite bonded repair systems for infinite length of steel pipe based on Lame’s Equation. Optimum internal composite repair thicknesses using biaxial carbon and glass fibre composites were determined for different levels of corrosion on steel pipelines, using the Von Mises yielding and Tsai-Hill failure criterion. Design nomographs suitable for internal bonded composite repair systems development are presented.

ANALYTICAL SOLUTIONS

Analysis of steel pipe without corrosion

Steel pipe without corrosion is analysed using Lame's approach (Kashani et al. 2008), which is based on displacement differential equations and is applicable to any cylindrical vessel with any diameter-to-wall-thickness ratio. Equations for the hoop stress and radial stress in a thick-walled cylinder, when subjected to internal and external pressure, were developed by Lame in the early 19th century (Timoshenko et al. 1969). Expressions of the hoop stress \( \sigma_\theta \) and radial stress \( \sigma_r \) in a thick cylinder are given by (Timoshenko et al. 1969)

\[
\begin{align*}
\sigma_\theta &= A + \frac{B}{r^2} \\
\sigma_r &= A - \frac{B}{r^2}
\end{align*}
\]

where, \( A \) and \( B \) are Lame’s coefficients based on the boundary conditions and \( r \) is radius of any point in a thick-walled cylinder. Let us consider 150ND steel pipe having an internal and external radius \( r_i \) and \( r_o \), respectively, subjected to an internal pressure \( P_i \). The following two known boundary conditions of stress enable us to determine the Lame’s coefficients \( A \) and \( B \).

At \( r = r_i, \ \sigma_r = -P_i \) and \( r = r_o, \ \sigma_r = 0 \).

Substituting the above two boundary conditions in Eq. 2 leads to the expressions of \( A \) and \( B \) as Eqs. 3 & 4 respectively.

\[
\begin{align*}
A &= \frac{P_i r_i^2}{(r_o^2 - r_i^2)} \\
B &= \frac{P_i r_i^2 r_o^2}{(r_o^2 - r_i^2)}
\end{align*}
\]

\( \sigma_\theta \) and \( \sigma_r \) can then be obtained in terms of the internal pressure \( P_i \) by utilising Eqs. 1 and 2. Assuming the pipe is of infinite length and plane strain condition, the axial strain \( \varepsilon_a \) is equal to zero. Using the generalized Hooke’s law,

\[
\varepsilon_a = \frac{1}{E} [\sigma_a - \nu(\sigma_\theta + \sigma_r)] = 0
\]

where, \( E \) and \( \nu \) are Young’s modulus and Poisson’s ratio of the pipe material, respectively. Therefore,

\[
\sigma_a = \nu(\sigma_\theta + \sigma_r)
\]

In an axisymmetrical cylindrical structure \( \sigma_\theta, \sigma_r \) and \( \sigma_a \) are the principal stresses, because they are acting in the principal directions. Therefore, all the shear stresses are equal to zero and the corresponding Von Mises (VM) stress, \( \sigma_V \) is given by,

\[
\sigma_V = \sqrt{\frac{1}{2}[(\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_a)^2 + (\sigma_a - \sigma_\theta)^2]}
\]

Eq. 7 consists of hoop, radial and axial stresses, which can be expressed in terms of the internal pressure \( P_i \), internal radius \( r_i \) and external radius \( r_o \). Using the pipe material properties and geometrical dimensions of a 150ND pipe, given in Table 1, the optimum repair thickness is determined for different Level of Corrosion (LOC).

<table>
<thead>
<tr>
<th>Type of Steel</th>
<th>X42*</th>
<th>X65*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (E) - MPa</td>
<td>200000</td>
<td>200000</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.29</td>
<td>0.27</td>
</tr>
<tr>
<td>Specified Minimum Yield Strength-SMYS (MPa)</td>
<td>290</td>
<td>450</td>
</tr>
<tr>
<td>Minimum Tensile Strength (MPa)</td>
<td>415</td>
<td>535</td>
</tr>
<tr>
<td>Allowable Strain</td>
<td>0.001</td>
<td>0.002</td>
</tr>
</tbody>
</table>

* Steel properties according to API Specification 5L and ASME B31.4-2002 standards

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<table>
<thead>
<tr>
<th>Type of pipe</th>
<th>150ND</th>
<th>Type of Steel</th>
<th>X42*</th>
<th>X65*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside diameter (mm)</td>
<td>168.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original pipe thickness (mm)</td>
<td>7.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(% LOC)</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Young’s Modulus (E) - MPa</td>
<td>200000</td>
<td>200000</td>
<td></td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.29</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal radius (mm)</td>
<td>77.040</td>
<td>78.462</td>
<td>79.884</td>
<td>81.306</td>
</tr>
<tr>
<td>External radius</td>
<td>84.15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1(a) shows the VM stress variation from inner to outer radius for different LOC and internal pressure ($P_i$) of 1 MPa. Irrespective of LOC, the VM stress at the inner radius is higher than at the outer radius. Therefore, an increase in internal pressure leads to yielding of the pipe material initiating at the inner radius.

According to Figure 1(b), when the LOC is greater than 80%, the VM stress increases exponentially and the corresponding internal pressure for yielding is minimal. Therefore, from a rehabilitation point of view, if the steel pipe has less than 80% LOC, rectification can be done using an internal composite repair; but replacement is necessary when LOC is greater than 80%. According to ISO/TS 24817, in serviceability state, the pipe is not allowed to yield and the corresponding pressure should be downsized by introducing some safety factors. In the analysis, internal pressure corresponding to the yielding and bursting has been calculated, substituting the specified minimum yield strength and minimum tensile strength of steel, respectively in Eq 7.

Figures 1(c) and (d) show the internal pressure corresponding to yielding and bursting for X42 and X65 150ND pipe. The operating pressure for X42 and X65 150ND pipe is 18.4 MPa and 28.5 MPa, respectively. According to Figures 1(c) and 1(d), both X42 and X65 pipes can withstand the original operating pressure until around 20% corrosion. If the level of corrosion is greater than 20%, repair or replacement is required for both X42 and X65 steel pipes to resist the operating pressure limits.

Analysis of a full bonded internal composite repair system

The pipe and internal composite repair system considered, consists of three layers, namely the outermost steel pipe, middle Fibre Reinforced Polymer (FRP) layer and the innermost polyethylene (PE) liner, as depicted in Figure 2(a). The innermost thin PE layer acts as an impermeable layer which protects the middle FRP layer from the corrosive materials being transported through the pipeline. Only the outermost steel layer and middle FRP layers structurally contribute to withstand the circumferential and axial stresses generated due to the internal pressure of the fluid. Therefore, only the outermost steel layer and middle FRP layer are considered in the following analysis.

It is assumed that the inner composite layer consists of a biaxial lamina having $E_1=E_2$. In the analysis, only the positive internal pressure ($P_i$) is considered and a positive pressure gradient is maintained from inner to outer radius. Hence, stress in the radial direction is always in compression and insignificant compared to the magnitude of hoop and axial stresses. Therefore the approximate analysis, the assumption, $E_1=E_2$ is made and Lame’s approach for an isotropic material is used. Using static equilibrium of the cylinders, a fully bonded
internal composite repair system can be divided into two parts associated with contacted pressure \(P_s\) as illustrated in Figure 2(b).

\[
\sigma_{\text{outer}} = \left( \frac{(P_x x^2 - P_i r^2)}{(r^2 - r_x^2)} \right) + \left( \frac{(P_x x^2 r_s)}{(r_s^2 - r_x^2)} \right) \frac{1}{r^2} 
\]

(8) & (9)

At the inner composite cylinder

\[
\sigma_{\text{inner}} = \left( \frac{(P_x x^2 - P_i r^2)}{(r^2 - r_x^2)} \right) + \left( \frac{(P_x x^2 r_s)}{(r_s^2 - r_x^2)} \right) \frac{1}{r^2} 
\]

(10) & (11)

The unknown contact pressure \(P_s\) can be found using the circumference strain compatibility at steel FRP interface. Using the generalized Hooke’s law, the circumference strain compatibility at steel FRP interface can be expressed as Eq. 12.

\[
\frac{1}{E_x} [\sigma_{\text{inner}}(1 - \theta_1^2) - \theta_1 \sigma_{\text{inner}}(1 + \theta_1)] = \frac{1}{E_o} [\sigma_{\text{outer}}(1 - \theta_o^2) - \theta_o \sigma_{\text{outer}}(1 + \theta_o)] 
\]

(12)

Using Eq. 6, Eq.12 is simplified and shown in Eq.13

\[
\frac{1}{E_x} [\sigma_{\text{inner}}(1 - \theta_1^2) - \theta_1 \sigma_{\text{inner}}(1 + \theta_1)] = \frac{1}{E_o} [\sigma_{\text{outer}}(1 - \theta_o^2) - \theta_o \sigma_{\text{outer}}(1 + \theta_o)] 
\]

(13)

When \(r = r_s\), \(\sigma_{\text{inner}}, \sigma_{\text{inner}}, \sigma_{\text{outer}}, \text{ and } \sigma_{\text{outer}}\) stress components can be evaluated using Eqs. 8, 9, 10, 11 and back substituting to Eq.13 will lead to find \(P_s\) as Eq. 14.

\[
P_s = \frac{2P_x r_s^2 (1 - r_x^2)}{(r_s^2 - r_x^2)} + \left[ \theta_1 (1 + \theta_o) \right] + \frac{E_i (1 - \theta_1^2) (r_s^2 + r_x^2)}{E_o (r_s^2 - r_x^2)} - \frac{E_i (1 + \theta_o) \theta_o}{E_o} 
\]

(14)

Substituting this \(P_s\) to Eqs. 8, 9, 10, 11 and 12 represent the Lame’s equations for inner and outer cylinder subjected to internal pressure \(P_i\). The inner composite cylinder failure is investigated using the Failure Index (FI) based on Tsai-Hill criterion (Tsai, 1985) given by the below Equation.

\[
\left( \frac{\sigma_1}{\sigma_{1, \beta}} \right)^2 - \left( \frac{\sigma_1}{\sigma_{1, \beta}} \right) \left( \frac{\sigma_2}{\sigma_{2, \beta}} \right) + \left( \frac{\sigma_2}{\sigma_{2, \beta}} \right)^2 + \left( \frac{\sigma_{12}}{\tau_{12}} \right)^2 = FI 
\]

(15)
In the above equation the $\beta$ which is used in determine $\sigma_{th}$ can be either in tensile, ($\sigma_{th}$), or compressive, ($\sigma_{th,c}$), depending upon the sign of the stresses $\sigma_1$ and $\sigma_2$. According to Tsai-Hill criterion, a FI greater than 1 represents composite failure. According to Figure 2 (b), the inner composite cylinder biaxial material axis $\sigma_1$ and $\sigma_2$ are aligned with cylindrical coordinate axis system. Therefore $\sigma_1$ and $\sigma_2$ are acting on the principal direction and the shear stress $\sigma_{12}$ becomes zero. Hence $\sigma_1$, $\sigma_2$ are directly equal to the $\sigma_y$, $\sigma_a$ and $\sigma_a$ as calculated using Eq. 6 considering plane strain condition.

Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) material systems are considered in the analysis with the material properties listed in Table 2.

<table>
<thead>
<tr>
<th>Material properties</th>
<th>GFRP (E glass/Epoxy (M103/3783))</th>
<th>CFRP (Carbon Epoxy (AGP370-S1/3501-6))</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_f$ (Fibre volume ratio)</td>
<td>0.5</td>
<td>0.62</td>
</tr>
<tr>
<td>$E_1/E_2$ (MPa)</td>
<td>24500</td>
<td>77000</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>$\sigma_{1u}$ - Allowable tensile strength in 1 direction (MPa)</td>
<td>433</td>
<td>963</td>
</tr>
<tr>
<td>$\sigma_{1c}$ - Allowable compressive strength in 1 direction (MPa)</td>
<td>377</td>
<td>900</td>
</tr>
<tr>
<td>Ultimate tensile strain ($\sigma_{ut}$)</td>
<td>0.017</td>
<td>0.012</td>
</tr>
</tbody>
</table>

For the initial analysis, 150ND X42, X65 steel pipes, having 40% LOC, repaired internally with 10 mm thick GFRP, CFRP composite systems are considered, respectively. FI and VM stress variation along the pipe thickness against different internal pressures are plotted in Figure 3. From the analysis, it was observed that for the fully bonded case, hoop and axial stresses in the remaining steel pipe is comparatively higher than internal composite repair system. Therefore VM yielding criteria is more predominate than Tsai Hill criteria. According to Figure 3 (a) and (b), VM yielding failure is initiated at the steel composite junction in all four cases. No composite failure is predominant according to the Tsai-Hill criteria and the corresponding FI well below 1. Therefore, a fully bonded internal composite repair system, the maximum internal pressure can be withstood until the yield failure at the steel composite bond line.

![Figure 3. VM stress and Tsai Hill FI variation for10 mm GFRP and CFRP internal composite repair systems. (a) X42, 40% LOC, (b) X65, 40% LOC](image)

Using the yielding of steel at the bond line as the criteria, design nomographs were developed to represent the relationship of internal pressure and LOC for different composite repair thickness results are shown in Figure 4. Zero thickness corresponds to pure steel pipe as described in preceding section. The analysis was done up to 22 mm composite repair thickness, or approximately 50% internal area of the pipe is reduced. Figure 4 nomographs are only applicable for X42 or X65 150ND steel pipes repaired using CFRP or GFRP materials with material properties shown in Tables 1 and 2. Designers can utilize these nomographs to find internal repair thicknesses correspond to maximum internal pressure ($P_i$) related to steel yielding, which needs to be downsized with some safety factors to obtain the serviceability operating pressure.

Figure 5 shows the required internal composite thicknesses to resist the operating pressure for X42 and X65 150ND steel pipe with different LOC, which is derived from nomographs developed in Figure 4. Both X42 and X65 150ND pipes can withstand 18.4 MPa and 28.5 MPa operating pressure respectively until around 20% corrosion without any internal repair. From the graphs, it is obvious that GFRP internal repair required roughly two times thicker repair than CFRP. This is due to high Young’s modulus in CFRP compare to GFRP. For the particular reinstate pressure, GFRP internal repair reduces more cross sectional area than CFRP, which finally affect the flow rate of the pipe. Therefore in terms of flow rate, CFRP internal repair method is more efficient.
than GFRP. In addition to corrosion point of view, direct contact between CFRP and steel in presence of an electrolyte, the wet corrosion cell could accelerate the galvanic corrosion of steel and create possible blistering and subsequent delamination or debonding. To prevent this galvanic corrosion, GFRP layer is introduced to separate contact between CFRP and steel.

![Graphs showing internal composite repair design nomographs for 150ND pipe](image)

Figure 4. Internal composite repair design nomographs for 150ND pipe

![Graphs showing required internal composite repair thicknesses for rectify operating pressure](image)

Figure 5. Required internal composite repair thicknesses for rectify operating pressure (a) 28.5 MPa for X65 steel, (b) 18.5 MPa for X42 steel

**CONCLUSIONS**

This paper has presented the analyses of an internal composite bonded repair system for an infinite length of steel pipe with axisymmetric defect using the Lame’s equation. Optimum internal composite repair thicknesses were investigated using biaxial carbon and glass fibre composites, for different levels of corrosion on steel pipelines. The results show that both X42 and X65 150ND pipes can withstand an operating pressure 18.4 MPa and 28.5 MPa respectively, without any internal repair until around 20% corrosion. It was found that the fully bonded internal composite repair system, the maximum internal pressure can be withstood until the yield failure at the steel composite bond line. For the internal bonded repair, GFRP composite needs twice repair thickness than CFRP composite. Design nomographs were developed and can be used to design internal composite repair systems.
ACKNOWLEDGMENTS

This work was undertaken as part of a CRC-ACS research program, established and supported under the Australian Government’s Cooperative Research Centres Program

REFERENCES


