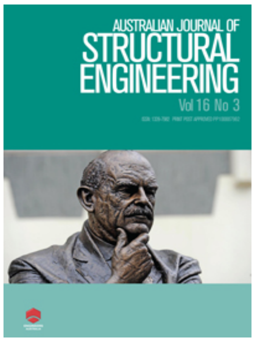

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Analysis of retrofitted corroded steel pipes using internally bonded FRP composite repair systems

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ABSTRACT
Steel pipelines play an important role in the oil and gas industry. Hence, corrosion of the steel pipe systems during its service life is a critical issue for the industry. Fibre-reinforced composites offer solutions with broad applicability and efficiency for the internal repair of these corroded pipelines. Understanding the behaviour of internal composite repair systems against different internal pressure regimes is an important aspect in the development of a repair system. This study develops the analyses of internal composite bonded repair systems for long steel pipes with an axisymmetric defect, based on Lame's equation. Various levels of bonding between the steel and composite are studied. Fully bonded optimum internal composite repair thicknesses are determined using biaxial carbon and glass fibre composites for different levels of corrosions, using the von Mises yielding and Tsai–Hill failure criterion approaches. Two case studies are illustrated using the design nomographs. The analysis technique used was found to be accurate when compared with finite element modelling results.

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KEYWORDS
GFRP; CFRP; composite repair; failure index; thick cylinder

1. Introduction

To supply the growing of energy demands, steel pipelines play a vital role in transporting oil and gas products. Over 1.7 million km of pipelines are 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). During the lifetime of a pipeline system, repairs may be required to reinstate pipeline to the required condition and maintain its reliability. Therefore, repair / maintenance of vast pipeline networks represent an essential part of oil and gas transportation.

Wide range of temperature variations (−50 to 130 °C), high pressure and chemical erosion are the major factors that affect the internal / external corrosion on transmission pipelines (Palmer and Paisley 2000). There are three broad chemical corrosion categories, namely sweet corrosion, sour corrosion and sulphate reducing bacteria (Palmer and Paisley 2000). The internal/external defect induced by chemical corrosion is one of the major causes of pipeline failure. Both external and internal corrosion can develop very quickly, which leads to pipeline leakage or rupture. The corrosion rate is affected by temperature, pressure, concentration of carbon dioxide and the flow rate of oil and gas.

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 2002). Composites are being used to rehabilitate internally corroded pipelines 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 the 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 (Toutanji and Dempsey 2001). In addition, the lightweight and flexibility of fibre composites makes them easy to handle during repair (Zhao and Zhang 2007).

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Three different classes of internal composite repairs are considered namely rigid bonded, rigid unbonded and flexible unbonded repairs (ASME PCC-2, 2008). For the rigidly bonded composite repair, the internal pipeline surface is cleaned and the composite materials are cured onto the pipe internal wall. The cured interface layer is very thin so that there is no relative deformation in the interface between the composite liner and steel pipe. Rigid unbonded repair can be achieved by inserting a cured composite pipe into a steel pipeline or alternatively curing a composite repair into a pipe but preventing the form of bonding to the inside of the pipeline. For flexible unbonded composite repair, the repair material is a reinforced unimpregnated membrane which remains flexible (Cosham and Hopkins 2004). Moreover, most internal repair technologies are cured in place and bonded to the wall of the existing pipelines. The resin (or grout) adhesive provide sufficient bond strength between the existing pipeline and the repair systems. Compared with the traditional repair systems like cutting of damaged pipelines and welding, composite repair systems are more reliable and versatile (Palmer and Paisley 2000).

There are limited studies and analysis conducted on the internal repair of steel pipelines using composite material systems and limited literature is available on its usage. Selection of the most appropriate repair thickness and the behaviour of a steel pipeline composite repair system, particularly the internal repair of high pressure pipeline, is a critical issue and needs to be investigated in detail. This article presents the analyses of internal composite bonded repair systems for an infinite length of steel pipe with axisymmetric defect based on Lame's Equation. Performance of steel pipe lines for various levels of corrosion is analysed first. How the behaviour of the steel pipe is affected due to various levels of bonding between the steel and composite is studied next. Optimum internal composite repair thicknesses using biaxial carbon and glass fibre composites are then determined for different levels of corrosion, using the von Mises yielding and Tsai–Hill failure criteria. Two case studies are presented demonstrating the applications of the developed nomographs. Finite element results are compared with the nomograph predictions.

2. Performance analysis of steel pipe with different levels of corrosions

Pristine steel pipe is analysed using Lame's approach (Kashani and Young 2008), which is based on the displacement differential equations and is applicable to any cylindrical vessel with any diameter-to-wall-thickness ratio. Equations for the hoop stress (σ_θ) and radial stress (σ_r) in a thick-walled cylinder, when subjected to internal and external pressures, are given by (Timoshenko and Goodier 1969)

$$\sigma_\theta = A + \frac{B}{r^2} \tag{1}$$

$$\sigma_r = A - \frac{B}{r^2} \tag{2}$$

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 a 150ND steel pipe having an internal and external radius r_i and r_o, respectively, subjected to an internal pressure P_i. In that case, following two boundary conditions of stresses enable us to determine the Lame's coefficients A and B.

At ***r* = *ri*, *σr* = −*Pi*** and ***r* = *ro*, *σr* = *0*.**

Substituting the above two boundary conditions in Equation (2) leads to the expressions of A and B as Equations (3) and (4), respectively.

$$A = \frac{P_i r_i^2}{(r_o^2 - r_i^2)} \tag{3}$$

$$B = \frac{P_i r_i^2 r_o^2}{(r_o^2 - r_i^2)} \tag{4}$$

σ_θ and σ_r can then be obtained in terms of the internal pressure P_i by utilising Equations (1) and (2). Assuming the pipe is of infinite length and plane strain condition, the axial strain ε_a is equal to zero. Using the generalised Hooke's law,

$$\epsilon_a = \frac{1}{E}\left[\sigma_a - \vartheta\left(\sigma_\theta + \sigma_r\right)\right] = 0 \tag{5}$$

where E and ϑ are Young's modulus and Poisson's ratio of the pipe material, respectively. Therefore axial stress (σ_a),

$$\sigma_a = \vartheta\left(\sigma_\theta + \sigma_r\right) \tag{6}$$

In an axisymmetrical cylindrical structure σ_θ, σ_r and σ_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, σ_V is given by,

$$\sigma_V = \sqrt{\frac{1}{2}\left[(\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_a)^2 + (\sigma_a - \sigma_\theta)^2\right]} \tag{7}$$

Equation (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 Equations (1)–(6).

Let us now explore the performance of steel pipe with different levels of corrosion (LOC) using Lame's approach as described earlier. Material properties and geometrical dimensions of a 150ND pipe (shown in Table 1) are used for the analysis. Throughout the analysis corrosion is assumed as axisymmetric internal corrosion and LOC is expressed as the percentage of thickness reduction with respect to the pristine pipe thickness. In the analysis, internal

Table 1. Pipe geometry and material properties.

Pipe geometrical properties							Steel material properties		
Type of pipe				150ND			Type of Steel	X42*	X65*
Outside diameter (mm)				168.3					
Original pipe thickness (mm)				7.11			Young's Modulus (E) - MPa	200000	200000
Internal corrosion	(LOC) %	0	20	40	60	80	Poisson's Ratio	0.29	0.27
	Internal radius (mm)	77.040	78.462	79.884	81.306	82.728	Specified Minimum Yield Strength-SMYS (MPa)	290	450
	External radius (mm)			84.15			Minimum Tensile Strength (MPa)	415	535
External corrosion	(LOC) %	0	20	40	60	80			
	Internal radius (mm)			77.04			Allowable Strain	0.001	0.002
	External radius (mm)	84.150	82.728	81.306	79.884	78.462			

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

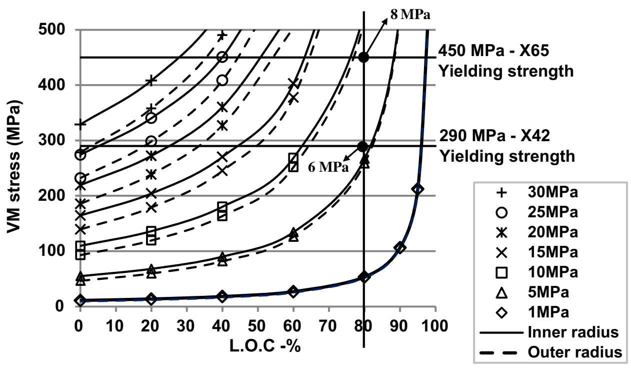

Figure 1. VM stress distribution for X42 150ND pipe against internal LOC and different internal pressures.

pressure corresponding to the yielding and bursting has been calculated by substituting the specified minimum yield strength (SMYS) and minimum tensile strength of steel, respectively in Equation 7. Internal/external radii with different LOC are given in Table 1. In addition two different pipe steel materials, X42 and X65 are considered in the analysis, which have a SMYS of 290 MPa (42000 Psi) and 450 MPa (65000 Psi), respectively.

Figure 1 shows VM stress distribution at inner and outer radii in 150ND steel pipe with different internal LOC against different internal pressures. From Figure 1, it can be observed that there are no significant VM stress variations in the internal and external radii for low internal pressures. But for higher internal pressures and low LOC, these differences are significant. Also noted that the VM stresses corresponding to the internal radius are always higher than those at the outer radius and yielding is initiated from the inner radius.

A previous study (Sirimanna et al. 2013) identified that when the LOC is greater than 80%, the VM stress increases exponentially even with low internal pressures. In addition, they concluded that, 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 Figure 1, for 80% LOC, X42 and X65 can withstand a maximum of 6 and 8 MPa internal pressure, respectively, without yielding. But for LOC higher than 80%, internal pressure corresponding to yielding decrease significantly due to the exponentially increase of VM stresses.

Figure 2(a) and (b) show effects of the internal and external corrosion with respect to yield and burst pressure against LOC percentage. By observing Figure 2, yield or burst pressure relating to the internal axisymmetric corrosion is always less than for external axisymmetric corrosion. Therefore yield or burst pressure corresponding to the internal axisymmetric corrosion is critical and it governs the design. Thus for the analytical solutions, only internal corrosion is considered. It is also noted there is no significant difference in yield or burst pressure between external and internal axisymmetric corrosion for 150ND pipe.

Figure 3(a) and (b) show the yield and burst internal pressures for X42 and X65 150ND pipes. 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. The project specified operating pressure for X42 and X65 150ND pipe is 18.4 and 28.5 MPa, respectively. According to Figure 3(a) and (b), both X42 and X65 pipes can withstand the original operating pressure until approximately 31% corrosion without yielding. If the LOC is greater than 31%, repair/replacement is required for both X42 and X65 steel pipes to resist the operating pressure limits or de-rate the pipe appropriately following the Figure 3(a) and (b) graphs. In addition, if the operating pressures are kept the same at 18.4 and 28.5 MPa for the X42 and X65 150ND pipes, respectively, they would burst at approximately 54 and 44% LOC.

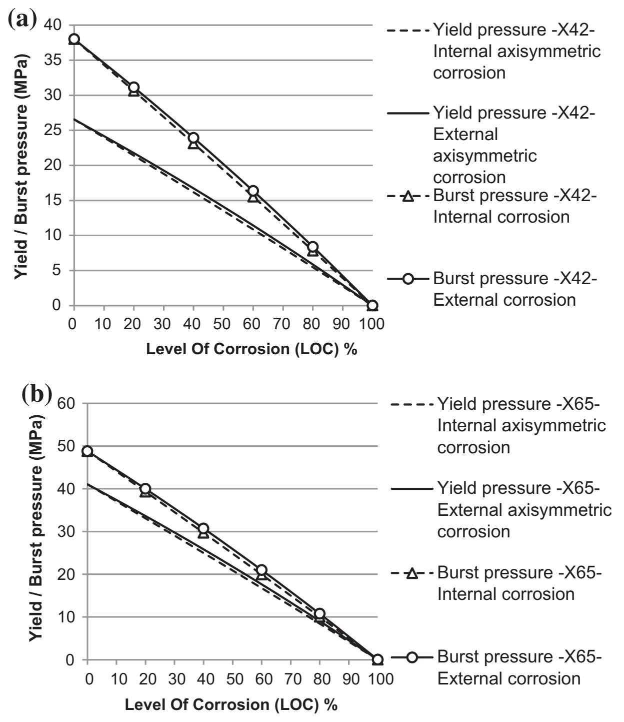

Figure 2. Comparisons of internal and external axisymmetric defect against yield and burst pressure for: (a) 150ND X42 steel pipe and (b) 150ND X65 steel Pipe.

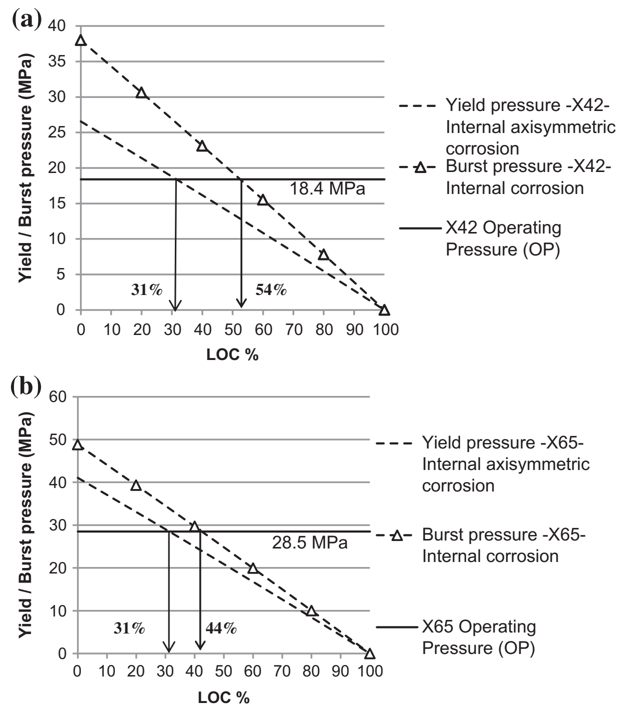

Figure 3. Operating pressure, burst pressure and yield pressure for: (a) 150ND X42 steel pipe and (b) 150ND X65 steel Pipe.

3. Analysis of steel pipe with internal composite repair system for various levels of bonding

Generally commercially available internal composite repair systems consist of three layers, namely the outermost steel pipe, middle fibre-reinforced polymer (FRP) layer and the innermost impermeable liner, as depicted in Figure 4(a). The innermost thin impermeable layer made out of polyethylene (PE), which protects the middle FRP layer from the corrosive materials being transported through the pipeline. The outermost steel layer and middle FRP layers structurally contribute to withstand the circumferential, radial and axial stresses generated due to the internal pressure of the fluid. Therefore, in Figure 4, the cross section is simplified by considering outermost steel layer and middle FRP layer.

It is assumed that the inner composite layer consists of a biaxial lamina having $E_1 = E_2$. Radial direction elastic modulus E_3 is low in composite. This low E_3 is critical, if tensile action is applied in the radial direction. 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 is relatively low when compared to the magnitude of hoop stresses. Therefore, despite the low E_3 value, in the analysis, hoop and axial elastic properties governs the design. Thus for the approximate analysis, the assumption, $E_1 = E_2 = E_3$, is made and Lame's approach for an isotropic material is used. Authors verified the above assumption and checked applicability using commercially available Stand 7 (Release 2.4.6 B2) FEA software package. Both orthotropic and isotropic cylinders subjected to internal pressure were analysed and good agreement was obtained with Lame's theoretical approach for thin ($D/t > 20$) and thick ($20 > D/t > 7.5$) composite cylinders, where D is external diameter and t is the thickness of the cylinder. Considering the static equilibrium of a cylinder, a bonded internal composite repair system can be divided into two parts associated with the contact pressure (P_s) as illustrated in Figure 4(b).

A and *B* Lame's coefficients for inner composite and outer steel cylinders can be found using the boundary conditions below along with Equation (2).

For outer steel pipe ➔ At $\boldsymbol{r = rs}$, $\boldsymbol{\sigma r = -P_s}$ and $\boldsymbol{r = ro}$, $\boldsymbol{\sigma r = 0}$

For inner composite cylinder ➔ At $\boldsymbol{r = ri}$, $\boldsymbol{\sigma r = -Pi}$ and $\boldsymbol{r = rs}$, $\boldsymbol{\sigma r = -Ps}$

Substituting *A* and *B* coefficients to the Equations (1) and (2) will lead to the general equations for inner composite cylinder and outer steel pipe.

At the inner composite cylinder

$$\begin{matrix}\sigma_{\theta_{outer}}\\ \sigma_{r_{outer}}\end{matrix} = \left\{\frac{\left(P_s r_s^2 - P_i r_i^2\right)}{\left(r_i^2 - r_s^2\right)}\right\} \pm \left\{\frac{\left[\left(P_s - P_i\right) r_s^2 r_i^2\right]}{\left(r_i^2 - r_s^2\right)}\right\}\frac{1}{r^2} \quad (8) \text{ and } (9)$$

At the outer steel pipe

$$\begin{matrix}\sigma_{\theta_{outer}}\\ \sigma_{r_{outer}}\end{matrix} = \left\{\frac{P_s r_s^2}{\left(r_o^2 - r_s^2\right)}\right\} \pm \left\{\frac{P_s r_s^2 r_o^2}{\left(r_o^2 - r_s^2\right)}\right\}\frac{1}{r^2} \quad (10) \text{ and } (11)$$

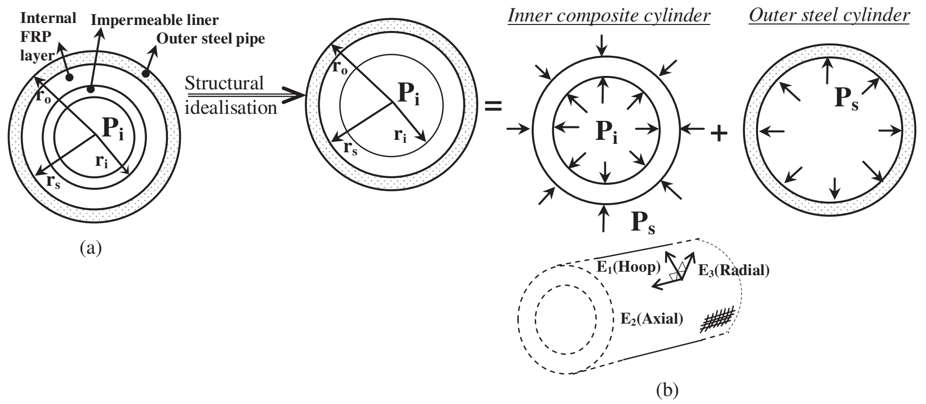

Figure 4. (a) Internal composite repair components, (b) structural idealisation, superposition approach and composite material axis system.

Table 2. GFRP and CFRP material properties (Daniel and Ishai 2006).

Material properties	GFRP (E glass/Epoxy (M103/3783))	CFRP (Carbon Epoxy (AGP370-5H/3501-6))
V_f (Fibre volume ratio)	0.5	0.62
$E_1 = E_2$ (MPa)	24500	77000
ν_{12}	0.11	0.06
σ_{1t} – Allowable tensile strength in longitudinal direction (MPa)	433	963
σ_{1c} – Allowable compressive strength in longitudinal direction (MPa)	377	900
Ultimate tensile strain ε_{1t}^{u}	0.017	0.012

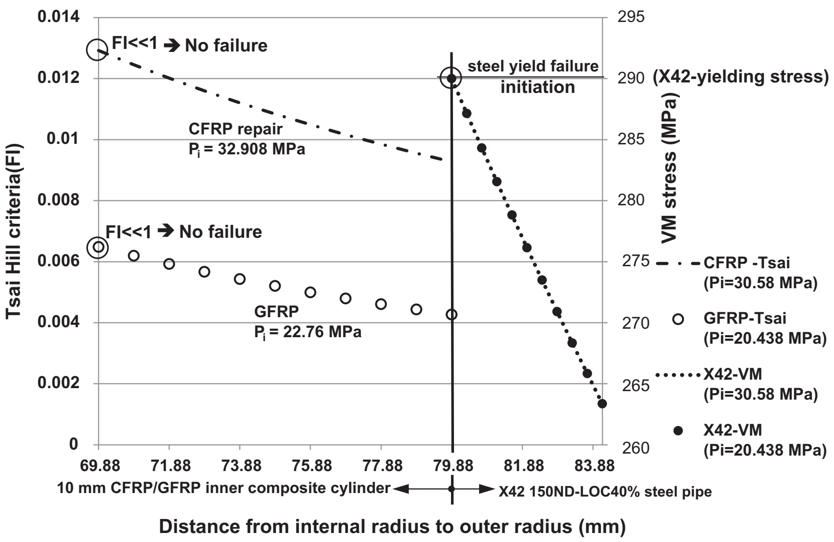

Figure 5. VM stress and Tsai–Hill FI variation for 10-mm GFRP and CFRP internal composite repair systems for X42 pipe with 40% LOC.

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

At $r = r_s$,

$$\varepsilon_{\theta_{\text{outer}}} = \mu\varepsilon_{\theta_{\text{inner}}} \rightarrow \frac{1}{E_o}\left[\sigma_{\theta_{\text{outer}}} - \vartheta_o\left(\sigma_{a_{\text{outer}}} + \sigma_{r_{\text{outer}}}\right)\right] = \frac{\mu}{E_i}\left[\sigma_{\theta_{\text{inner}}} - \vartheta_i\left(\sigma_{a_{\text{inner}}} + \sigma_{r_{\text{inner}}}\right)\right] \quad (12)$$

where μ is a bond coefficient. $\mu = 1$ represents the fully bonded condition between steel and composite. In this case, it is a two-material system and both the composite and the host steel pipe share hoop, radial and axial stresses. $\mu = 0$ denotes a special unbonded condition. In this scenario, there is no contribution from the steel side to withstand the internal pressure and all the stresses are to be carried by the composite. This condition can be used to design rigid unbonded internal repairs, where there is no load transfer between the internal composite pipe and the external steel pipe. The value of μ between 0

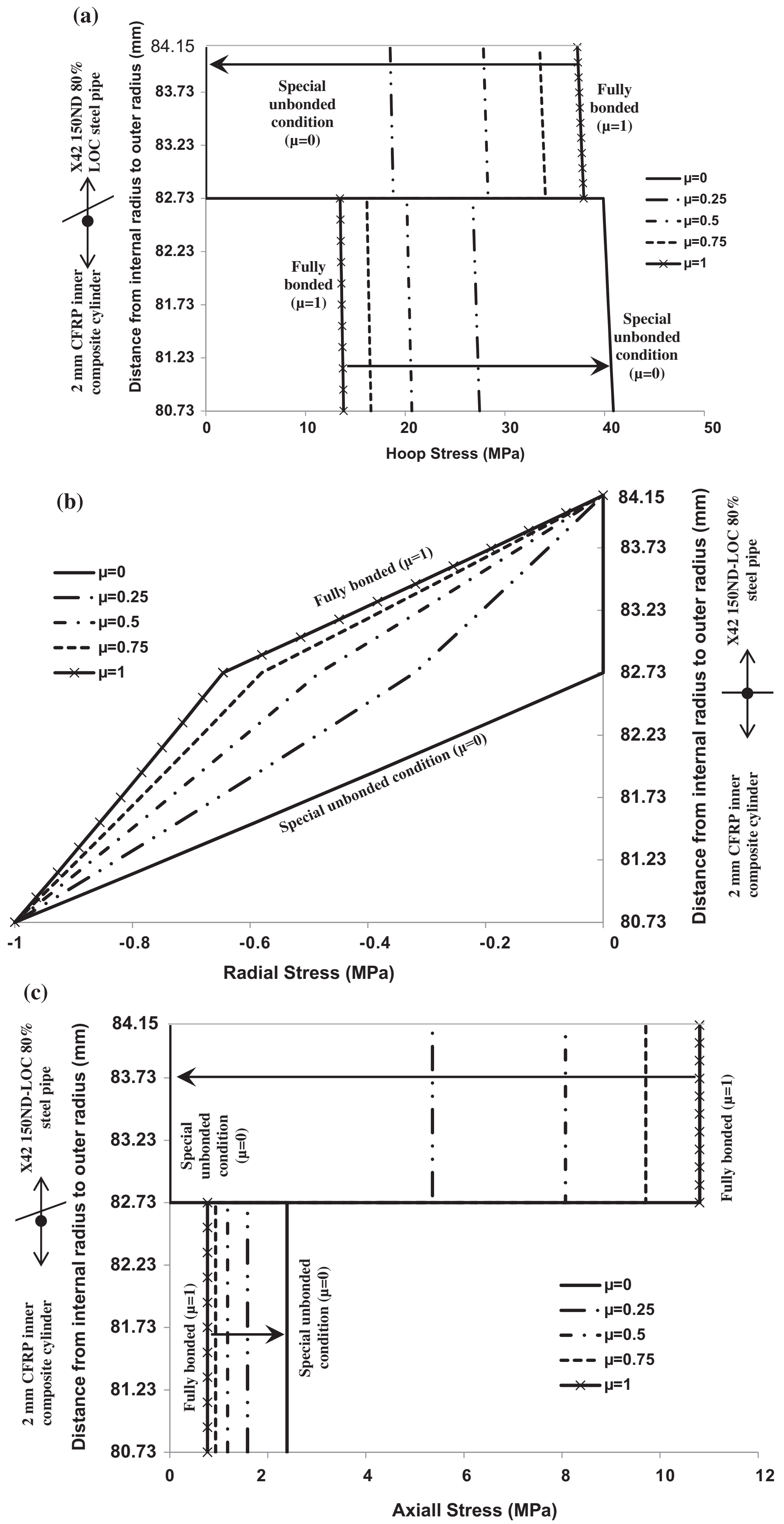

Figure 6. Through thickness stress variation against different bond coefficients (X42 150ND – 80% LOC, 2-mm CFRP internal repair, $P_i = 1$ MPa): (a) Hoop direction; (b) Radial direction and (c) axial direction.

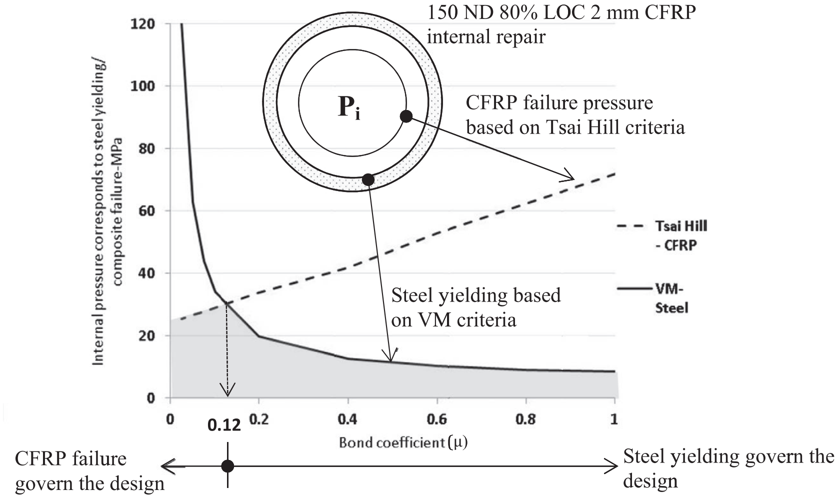

Figure 7. Design criteria against bond coefficient.

and 1 denotes partially bonded situation, where part of the load is shared between the internal composite pipe and the external steel pipe depending on the area of contact and the degree of bonding. The partial bonding scenario can happen over time due to the debonding or due to the poor workmanship leading to poor contact in some areas. It is noted here that the loading considered in this article is only the internal pressure in the pipe. If external axial load need to be considered in the design, it can be considered as a separate load case and the two cases can be combined later. Using Equations (6) and (12) is simplified and shown in Equation (13).

$$\frac{1}{E_o}\left[\sigma_{\theta_{\text{outer}}}\left(1-\vartheta_o^2\right)-\sigma_{r_{\text{outer}}}\vartheta_o\left(1+\vartheta_o\right)\right] = \frac{\mu}{E_i}\left[\sigma_{\theta_{\text{inner}}}\left(1-\vartheta_i^2\right)-\sigma_{r_{\text{inner}}}\vartheta_i\left(1+\vartheta_i\right)\right] \quad (13)$$

When $r = r_s$; $\sigma_{\theta_{\text{inner}}}$, $\sigma_{r_{\text{inner}}}$, $\sigma_{r_{\text{outer}}}$ and $\sigma_{\theta_{\text{outer}}}$ stress components can be evaluated using Equations (8)–(11) and back substituting to Equation (13) will lead to find P_s as Equation (14).

$$P_s = \frac{\frac{2P_i r_i^2\left(1-r_i^2\right)}{\left(r_i^2-r_s^2\right)}}{\left[\frac{\left(r_s^2+r_i^2\right)\left(1-\vartheta_i^2\right)}{\left(r_i^2-r_s^2\right)}\right]+\left[\vartheta_i\left(1+\vartheta_i\right)\right]+\left[\frac{E_i\left(1-\vartheta_o^2\right)\left(r_s^2+r_i^2\right)}{\mu E_o\left(r_s^2-r_o^2\right)}\right]-\left[\frac{E_i\left(1+\vartheta_o\right)\vartheta_o}{E_o}\right]} \quad (14)$$

Substituting this P_s to Equations (8)–(11) represent the Lame's equations for inner and outer cylinder subjected to internal pressure P_i. The VM criterion stated in the previous section is used to predict the failure of the steel pipe. Now the inner composite cylinder failure is investigated using the failure index (FI) based on Tsai–Hill criterion (Tsai 1985) given by the below equation.

$$\left(\frac{\sigma_1}{\sigma_{1,\beta}}\right)^2-\left(\frac{\sigma_1}{\sigma_{1,\beta}}\right)\left(\frac{\sigma_2}{\sigma_{2,\beta}}\right)+\left(\frac{\sigma_2}{\sigma_{2,\beta}}\right)^2+\left(\frac{\sigma_{12}}{\tau_{12}}\right)^2 = FI \quad (15)$$

In the above equation, β is used to determine $\sigma_{1\beta}$, which can be either tensile, (σ_{1t}) or compressive, (σ_{1c}), depending upon the sign of the stresses σ_1 and σ_2. According to the Tsai–Hill criterion, FI greater than 1 represents composite failure. According to Figure 4(b), the inner composite cylinder biaxial material axis σ_1 and σ_2 are aligned with the cylindrical coordinate axis system. Therefore σ_1 and σ_2 are acting on the principal directions and the shear stress σ_{12} becomes zero. Hence σ_1 and σ_2 are directly equal to the σ_θ, σ_a and σ_a as calculated using Equation (6) considering plane strain condition.

Two most common composites, namely glass fiber-reinforced polymer (GFRP) and carbon Fibre-reinforced polymer (CFRP) material systems are considered in the analysis with the material properties listed in Table 2.

For the initial analysis, a fully bonded ($\mu = 1$) 150ND X42 steel pipe, having 40% LOC, repaired internally with 10-mm-thick CFRP and GFRP composite systems are considered. FI and VM stress variation along the pipe thickness against different internal pressures are plotted in Figure 5. 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 the internal composite repair system. Therefore, the VM yielding criterion dominates the failure as compared to the Tsai–Hill criterion. According to Figure 5, VM yielding failure is initiated at the steel-composite junction. No composite failure is predominant according to the Tsai–Hill criteria and the corresponding FI is well below 1. Therefore, a fully bonded internal composite repair system, the maximum internal pressure can be withstood until the yields is initiated at the steel-composite bond line.

Figure 6 shows the hoop, radius and axial stress variations against different bond conditions for 150ND (LOC 80%) pipe with 2-mm-thick CFRP internal repair subjected to 1 MPa internal pressure. For the fully bonded case (μ = 1), hoop and axial stresses in the remaining steel is comparatively higher than CFRP, because fully

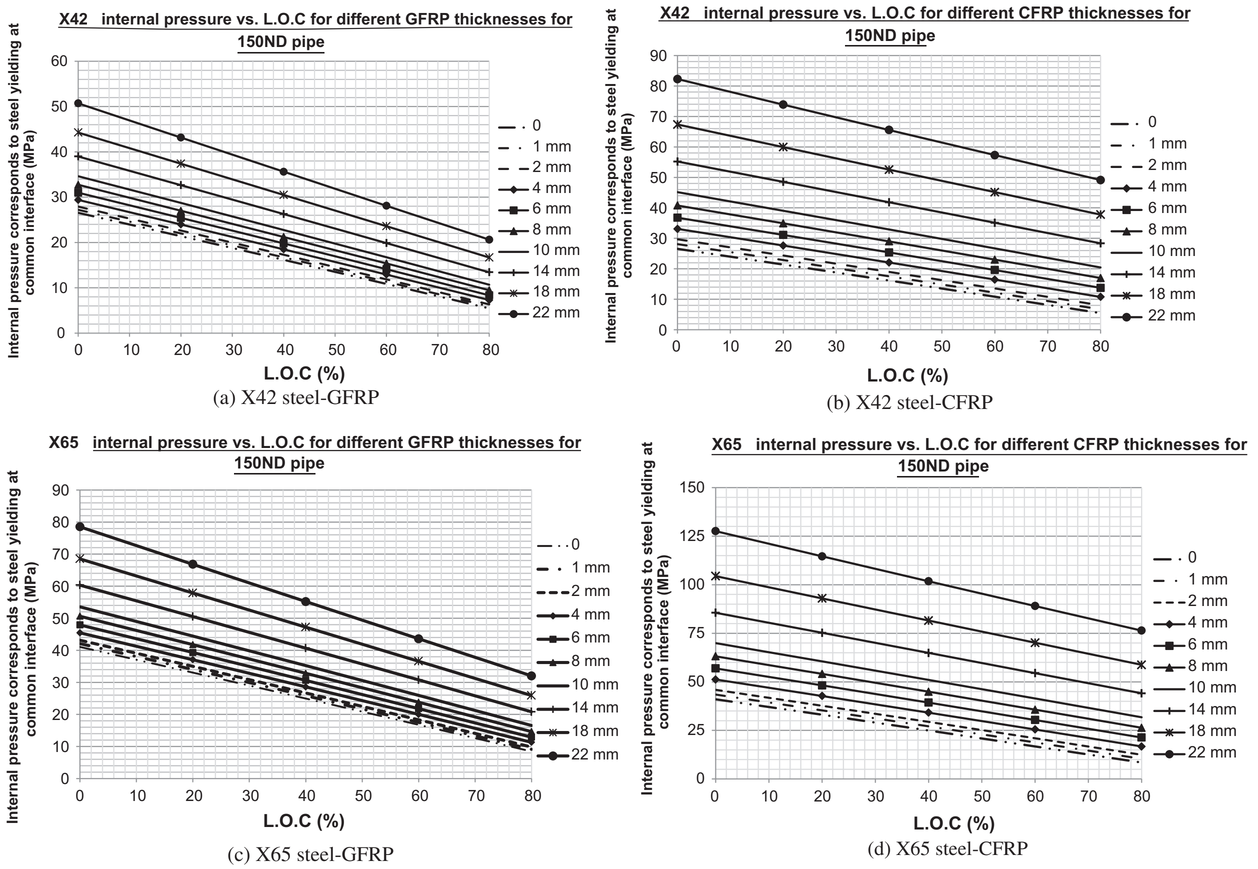

Figure 8. Internal composite repair design nomographs for 150ND pipe.

Table 3. Internal composite repair thickness needed to upgrade 60% LOC 150ND pipe.

Pipe	LOC%	Steel type	Existing internal pressure capacity (MPa)	Upgrade internal pressure – (MPa)	Composite type	Approximate internal composite repair thickness using nomographs (mm)	Percentage of original (150ND) internal area reduction %
150ND	60	X42	10.8	25	GFRP	20	36.67
					CFRP	9	11.91
		X65	16.7		GFRP	9	11.91
					CFRP	4	–0.69

strain compatibility is maintained at the bond line and the generated stress ratio is approximately proportional to the modular ratio. For $\mu = 1$, the plot shows the hoop stress in the steel and CFRP is around 38 and 14 MPa, respectively, which produces a 2.71 (38/14) stress ratio, which approximately equals the modulus ratio 2.59 (200000/77000). Therefore, as depicted in Figure 5, for the fully bonded case, the steel VM stress (Equation (7)) reaches SMYS at first and initiates the steel yielding. But for the partially bonded cases (μ = 0.75, 0.5 and 0.25) the hoop, axial and radial stresses in the steel portion reduce continuously and increase gradually in the CFRP portion. On the other hand in the special unbonded condition (μ = 0), no stresses transfer thorough the bond line and all hoop, axial and radial stresses are zero in the steel. Therefore in the unbonded internal repair case, no internal pressure is withstood by the remaining steel and full contribution is by the CFRP.

Figure 7 shows the behaviour of two failure criteria against the bond coefficient (μ) for 150ND 80% LOC pipe with 2-mm CFRP internal repair. For the fully bonded case (μ = 1), the internal pressure corresponding to steel yielding always governs the failure and is well below the CFRP failure pressure. From partially bonded (μ = 0.12) to fully bonded (μ = 1) region, steel yielding based on VM criteria governs the design. Unbonded (μ = 0) to partially bonded (μ = 0.12) region, CFRP failure pressure governs the design.

4. Application of nomographs

Using the yielding of steel at the bond line as the governing criteria, design nomographs were developed by (Sirimanna et al. 2013) to represent the relationship of internal pressure and LOC for different composite repair thicknesses as shown in Figure 8. In these graphs, zero thickness corresponds to pristine steel and the analysis was performed up to a composite repair thickness of 22 mm, where approximately 50% internal area of the pipe was reduced. The nomographs are only applicable

Table 4. Internal pressure upgrade using 10-mm internal bonded composite layer.

Pipe	LOC%	Steel type	Existing internal pressure capacity (MPa)	Internal bonded composite thickness (mm)	Composite type	Upgraded internal pressure (P_i) – using nomographs
150ND	60	X42	10.8	10	GFRP	16.5
					CFRP	26
		X65	16.7		GFRP	26
					CFRP	40

for X42 or X65 150ND steel pipes repaired using CFRP or GFRP materials with material properties shown in Tables 1 and 2. These nomographs can be used to find internal repair thicknesses corresponding to the maximum internal pressure (P_i) related to steel yielding, which needs to be downsized with some safety factors to obtain the serviceability operating pressure.

Let us consider a 150ND pipe having a 60% internal LOC which needs to be retrofitted using the bonded internal composite repair system. The following three cases are illustrated to demonstrate the usage of the nomographs.

Case 1

In Case 1, the internal pressure of the pipe needs to be upgraded to 25 MPa. Table 3 shows the corresponding internal repair thicknesses and percentage of internal area reduction obtained using Figure 8 nomograph results.

According to Table 3, the internal pressure can be upgraded to 25 MPa using minimum CFRP composite thicknesses of 10 and 4 mm for the X42 and X65 steel types, respectively. In addition, 4-mm CFRP internal repair thickness adds 0.69% extra area to the original 150ND pipe. This particular case, GFRP internal repair reduces more cross sectional area than the CFRP, which influence the flow rate of the pipe. Therefore, in terms of flow rate, internal repair using CFRP method is more suitable than GFRP.

Case 2

In Case 2, the same pipe as used in Case 1 is repaired using 10-mm internal bonded composite repair thickness. Corresponding upgradable internal pressures were evaluated using nomographs and shown in Table 4.

According to Table 4, a maximum internal pressure of 40 MPa can be sustained using CFRP internal repair, which is 2.4 times higher than it is original capacity (X65 150ND 60% LOC pipe).

Case 3

This section investigates the internal composite thicknesses required to withstand project specified operating pressure for different LOC. The project specified operating pressure for X42 and X65 150ND pipe are 18.4 and 28.5 MPa, respectively. Figure 9 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 the nomographs depicted in Figure 8. Both X42 and X65 150ND pipes can withstand 18.4 and 28.5 MPa operating pressures, respectively, until approximately 31% corrosion without any internal repair. The same conclusion was arrived earlier by analysing the pristine steel pipe with different LOC. Figure 9 shows that GFRP internal repair required roughly two times thicker repair than CFRP. This is due to the high Young's modulus of CFRP.

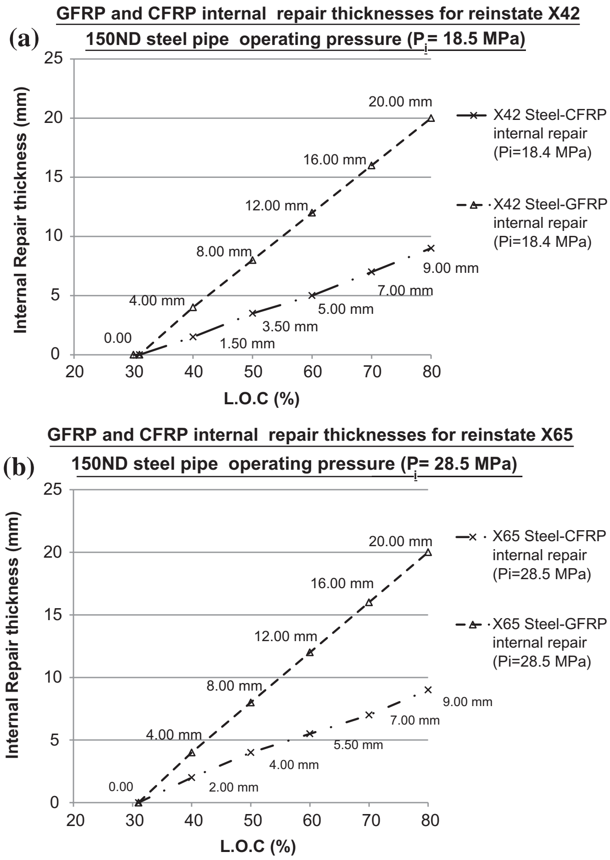

Figure 9. Required internal composite repair thicknesses for rectify operating pressure (a) 28.5 MPa for X65 steel and (b) 18.5 MPa for X42 steel.

5. The finite element comparisons with the nomograph predictions

The nomograph predictions were compared to numerical simulations, which were performed using Strand 7 (v 2.4.5). Four different internal repair combinations were selected using Case 2 and the details are shown

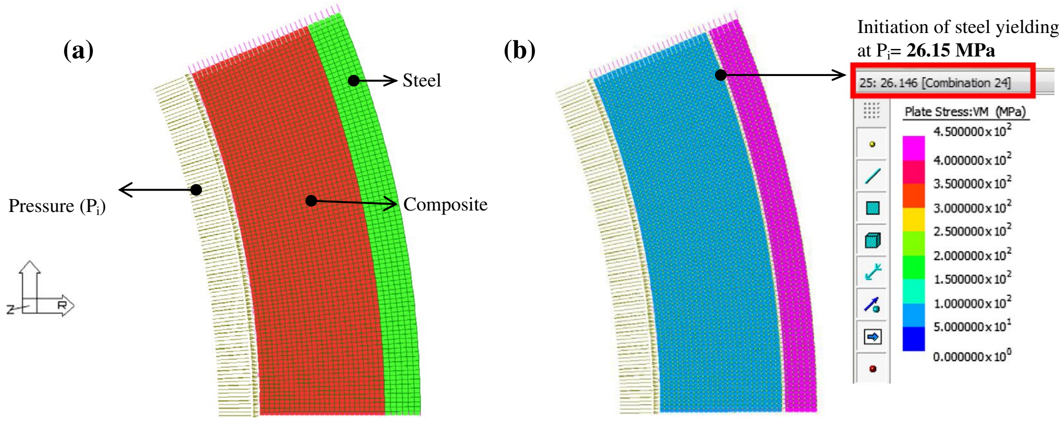

Figure 10. FEA model (a) Plane strain model and (b) Initiation of yielding for X65-GFRP Case 3.

Table 5. Comparison of the nomograph results (Analytical) and FEA results for the four cases mentioned in Table 4.

Cases		Internal Pressure (P_i) – using nomographs (Analytical results) (MPa)	Internal Pressure (P_i) – Using FEA approach (MPa)	Percentage difference with respect to Analytical results (%)
1	X42-GFRP	16.50	16.65	0.88
2	X42-CFRP	26.00	26.13	0.49
3	X65-GFRP	26.00	26.15	0.56
4	X65-CFRP	40.00	40.12	0.31

in Table 4. Pipe geometry and the material properties were selected using Table 1 and 2. A 60 % LOC FEA model was created and four cases were evaluated against different material combinations as mentioned in Table 4. In order to simulate an infinitely long cylinder, quadratic four 2D plane strain elements were selected. A one-sixteenth section (22.5-degrees) of the full cylinder was modelled. Symmetric boundary conditions (circumferential displacement and nodal rotations are not allowed) were applied at the ends to ensure that the behaviour of the full cylinder was represented. Initially 1 MPa pressure is applied internally and linear load combinations were introduced to identify the maximum internal pressure corresponds to steel yielding based on the VM criterion. Figure 10(a) shows general FEA plane strain model and (b) represents steel yielding at the composite steel junction (white colour stripe indicates VM stress > SMYS condition) corresponds to Case 3 (X65-GFRP) in Table 5. The pressure corresponds to initiation of steel yielding is 26.15 MPa and depicted in Figure 8(b).

According to Table 5, the nomograph results are in excellent agreement with the FEA results with less than 1% error. Therefore, these nomographs can be used to design 150ND internal fully bonded composite repair systems.

6. Conclusion

The analyses of an internal composite bonded repair system for an infinite length of steel pipe with an axisymmetric corrosion defect are presented. Optimum internal composite repair thicknesses were investigated using biaxial carbon and glass fibre composites, for different levels of corrosion for bonding on steel pipelines. Design nomographs were developed for 150ND pipe. These can be used to design fully bonded internal composite repair systems. Results obtained from the nomographs were found to be accurate when compared with finite element analysis results. The following conclusions can be drawn from this study:

- There is no significant difference in yield/burst pressure between external and internal axisymmetric corrosion for 150ND pipe with any LOC. Yield/burst pressure for internal axisymmetric corrosion is always lower than for external axisymmetric corrosion. Therefore internal axisymmetric corrosion is crucial and governs the design.
- The results show that both X42 and X65 150ND pipes can withstand an operating pressure of 18.4 and 28.5 MPa, respectively, without any internal repair until around 31% corrosion.
- For the fully bonded case, the hoop and axial stresses in the remaining steel pipe is comparatively higher than those in the internal composite repair system. Therefore, the VM yielding criterion governs and steel yielding is initiated at the steel-composite junction. No composite failure is noticeable and FI is well below 1. Hence, for a fully bonded internal composite repair system, the maximum internal pressure can be withstood until steel yield failure at the steel-composite bond line.
- For the unbonded internal composite repair, total internal pressure is withstood by the composite without any contribution from the remaining steel pipe.

- For the fully internal bonded repair, a GFRP composite repair needs approximately twice the repair thickness of an equivalent CFRP repair.

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Lance McGarva 14 year career in advanced composites began with his PhD in Lightweight Structures at the Royal Institute of Technology in Sweden, investigating rapid manufacture of thermoplastic composite sandwich structures. Lance worked at LUSAS, first as a Composite Application Engineer and later as an Engineering Analyst. Part of the work involved development of a finite element analysis tool for predicting manufacturing induced distortion of composite components for the aerospace industry. Consultancy work involved linear and non-linear finite element analysis of a variety of composite structures and components. Dr. McGarva then moved to Airbus UK as a Composite Stress Engineer in the Composite Structures Development Centre. In this role, he provided stress support for the ALCAS project, aimed at developing composite wing structures and technologies for future aircraft. Lance joined CRC-ACS in 2008, and was a project leader within the helicopter program, primarily working on the development of alternative manufacturing methods for, and repair of, composite helicopter components. In his current role at ACS Australia, Lance leads operations in the Brisbane office.

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