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Repair of through thickness corrosion/leaking defects in corroded pipelines using Fiber Reinforced Polymer overwrap

P Nitheesh Kumar¹, Vishwas Chandra Khan¹, G Balaganesan^{2,*}, A K Pradhan¹ and M S Sivakumar²

¹School of Mechanical Sciences, Indian Institute of Technology Bhubaneswar, Odisha, India 752 050.

²Department of Applied Mechanics, Indian Institute of Technology Madras, Tamil Nadu, India 600 036

*Corresponding author E mail: gbganesh@iitm.ac.in

Abstract. The present study is concerned with the repair of through thickness corrosion or leaking defects in metallic pipelines using a commercially available metallic seal and glass/epoxy composite. Pipe specimens are made with three different types of most commonly occurring through thickness corrosion/leaking defects. The metallic seal is applied over the through thickness corrosion/leaking defect and it is reinforced with glass/epoxy composite overwrap. The main objective of the metallic seal is to arrest the leak at live pressure. After reinforcing the metallic seal with glass/epoxy composite overwrap, the repaired composite wrap is able to sustain high pressures. Burst test is performed for different configurations of metallic seal and optimum configuration of metallic seal is determined. The optimum configurations of metallic seal for three different types of through thickness corrosion/leaking defects are further reinforced with glass/epoxy composite wrap and experimental failure pressure is determined by performing the burst test. An analytical model as per ISO 24817 has been developed to validate experimental results.

1. Introduction

The versatile nature and high pressure bearing capacity of the metallic pipes makes them to be largely used by most of the oil and gas companies in transporting oil, gas and other pressurized fluids over long distances around the world and are the safest and economical mode of transport [1]. Sometimes, these transmission pipelines are operated in harsh environmental conditions both inside and outside the pipe section and hence the pipe suffers a lot of damage scenarios. These damages are usually seen as non-leaking defects such as corrosion, dents, pitting, wall thinning, buckling and leaking defects such as cracks, through thickness corrosion, pit-holes, rupture etc., [2] The most common mode of damage in transmission pipelines used in oil and gas industries are due to the internal as well as external corrosion of the pipelines [3]. However, if the damage is not treated for a very long time, the surface corrosion may lead to higher wall loss causing detrimental effects in terms of reduced life span and pressure bearing capacity that could not only cause through thickness corrosion defect but could also risk the overall structural integrity of the pipe. The conventional and widely accepted repair methodology involves replacing the complete pipe section or only the damaged part with a new one or reinforcing it on the outer surface with a steel sleeve using welding/clamping [4]. But, if the medium flowing inside the pipe are hydrocarbons (oil and gas) then tools producing heat, sparks/fire are prohibited due to the risk of explosion. So, gas cutting and welding cannot be used. However, as there used to be no other alternative repair methodology to treat these defects, the oil and gas industries



continued using the steel sleeve repair methodology which involved shutting down the plant temporarily and removing the oil or gas in the pipeline and purging nitrogen gas into it to create an inert working atmosphere [5]. The installation process used to be cumbersome and lengthy which resulted in economic losses to the company. This created a need for developing a simple and more economical alternative repair methodology.

Recently, alternative repair methodologies based on FRP's are used to rehabilitate corroded or damaged pipelines. In this repair technique the defect portion is reinforced by applying a composite overwrap using glass/epoxy or carbon/epoxy around the transmission pipelines. The ability to inhibit corrosion and relatively high strength to weight ratio, load bearing capacity and stiffness makes these FRP's an ideal candidate to be used in rehabilitation of corroded steel pipelines and other mechanical structures. ASME [6] and ISO [7] codes have been formulated to find the appropriate qualification, design, testing, inspection and installation of FRP based repair methodologies. Costa-Mattos et al. studied these alternative repair techniques of corroded steel pipelines using epoxy resins. Their study suggests first filling the defect with epoxy resin and then reinforcing it with concentric coils of composite overwrap with appropriate sleeve thickness such that the level of structural integrity is optimum. However, these FRP overwrap techniques are not effective for leaking/through thickness corrosion defects as they generally cannot prevent leaking. The composite overwrap can assure an optimum level of pressure bearing capability and structural integrity in case of part through corrosion/part wall loss defects but are not effective to stop leakage as in the case of localised through thickness corrosion defects. So, if the transmission pipeline has localised through thickness corrosion/leaking defects then our first objective in repairing the defect should be to make sure that the repaired pipe doesn't leak under pressure and temperature. In most of the cases these transmission pipelines are not accessible. The rehabilitation of such corroded steel pipelines may require an industrial hanger or some supporting mechanical structure/fixture so that the damaged part can be made accessible and hence our second objective is to make the repair methodology much simpler [8,9]. Now focusing on these two objectives, a robust FRP based repair methodology using metallic seal has been developed.

In this repair methodology, we first use the metallic seal paste and apply it on the localised through thickness corrosion defect to stop the leak and then reinforce it with concentric coils of composite overwrap with appropriate sleeve thickness such that the level of structural integrity is optimum. After doing a rigorous literature survey, it is found that very little study on repair methodology using a rapid curing epoxy paste was done for rehabilitation of through thickness corrosion/leaking defects and the research on this area is not yet completely developed. Hence, a commercially available rapid curing epoxy paste i.e., metallic seal has been used to study the effectiveness of the repair methodology.

2.Experimental details

2.1 Specimen fabrication

API 5L X65 pipe specimens which have a length of 1000mm and outer diameter of 168.3mm and thickness of 7.11mm are used in the experimentation. Three pipe specimens, one with 10mm circular defect and one with 2mm circumferential slot defect and the other with 2mm axial slot defect is machined using CNC milling at the centre of the pipe section with all the three having same surface defect area of 78.54mm². The test pipe specimen with circular defect, circumferential slot defect and axial slot defect are in shown figure 1(a), (b) and (c) respectively. The repair is done in two phases. In the first phase of the repair, the metallic seal in the form of paste is applied over the defect in dry condition and certain amount of pressure is exerted onto to it so that it forms a plug in the defect hole and the interfacial bonding of the metallic seal with the test specimen is experimented with three different shapes of circular, elliptical and round cornered rectangle forms having same area of 6283 mm². The repair bonding paste (M-Seal Phataphat) is firmly held in place by applying pressure using a rubber tourniquet so that it forms a plug in the defect hole. The metallic seal is allowed to cure for three hours and burst test is conducted to find out the failure pressure. Prior to applying the metallic

seal over the defect, the pipe surface near the defect area is cleaned and made rough to have better interfacial bonding. The best result of the first phase i.e., the shape with which highest failure pressure is achieved goes through the second phase of the repair where the first phase of repair is done and then it is reinforced by wrapping four layers of bi-directional (woven roving) glass fiber mat of 560 gsm wetting with epoxy (Araldite LY556, Hardener HY951). Schematic arrangement of test pipe specimen after second phase of the repair is shown in figure 2. The wrap length and the axial width of the wrap are calculated as per ISO 24817 standards [7].

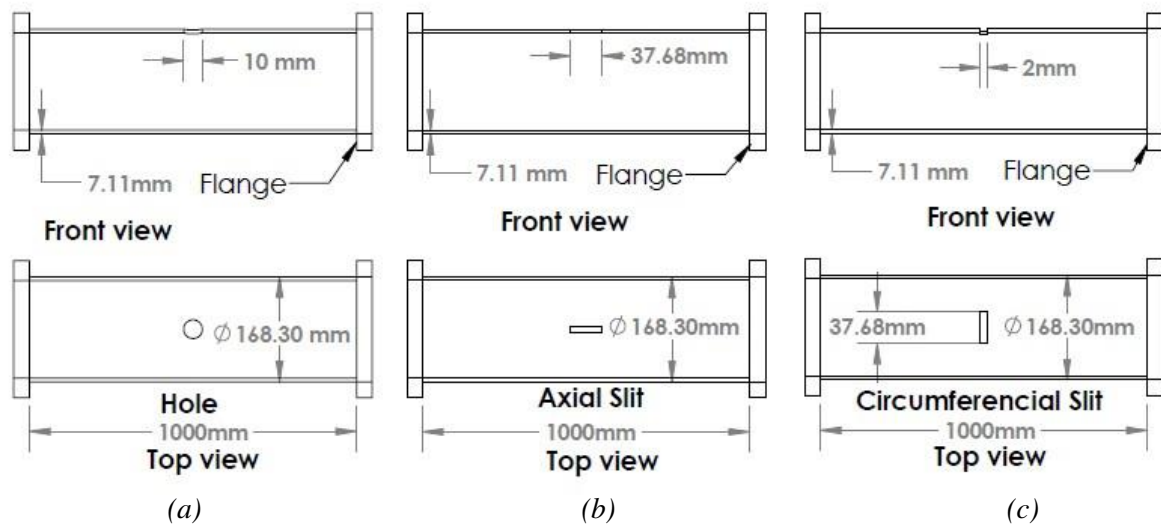


Figure 1. Pipe specimen with (a) defect as a hole (b) defect as slot in longitudinal direction (c) defect as circumferential slot

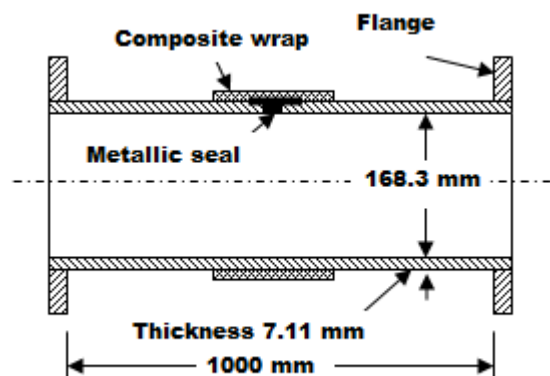


Figure 2. Schematic arrangement of pipe after repair with metallic seal and composite wrap

2.1.1 Burst Test experiment

Burst test of the test pipe specimens is conducted at room temperature with the defect repaired with metallic seal with and without composite wrapping. A high-pressure hydro pump is used to pressurize the fluid in the pipe section. The fluid used for conducting the experiment is water soluble coolant oil mixed with water. Strain gauges are mounted on the wrap in axial and hoop directions to measure the strain induced while performing the test and its output is fed to a computer using a data acquisition

system and a strain module. The test pipe specimen is pressurized until failure occurs. The layout of the burst test setup with the repaired pipe specimen is shown in figure 3.

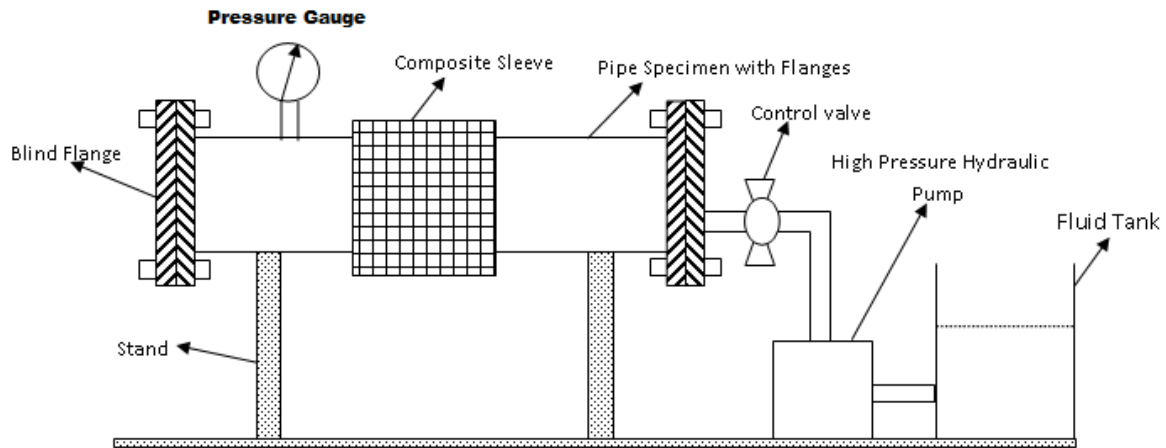


Figure 3. Schematic arrangement of pipe pressure testing set-up

3. Analytical Modelling

3.1 Thin-walled elasto-plastic test pipe specimen subjected to internal pressure

A thin-walled elasto-plastic test pipe specimen subjected to an internal pressure (P_{int}) and external pressure (P_{ext}) with an internal radius 'a' and external radius 'b' is considered. Neglecting the radial stresses, hoop stress for this condition can be written as

$$\text{Hoop Stress } (\sigma_{\theta}) = \frac{(P_{int} \times a) - (P_{ext} \times b)}{b - a} \quad (1)$$

As the repair is performed at zero live pressure i.e., at zero internal pressure, the minimum thickness of the repair laminate is given by following equation according to ISO 24817 [7]

$$t_{min} = \frac{1}{\epsilon_c E_c} \left(\frac{P_{eq} D}{2} - s t_s \right) \quad (2)$$

where, ϵ_c is the allowable repair laminate circumferential strain, E_c is the circumferential modulus of the repair laminate, P_{eq} is the equivalent internal pressure, D is the external diameter of the pipe section, s is the allowable stress of the substrate material i.e., the steel pipe and t_s is the minimum remaining substrate wall thickness.

4. Results and Discussion

4.1 Circular defect repaired with first phase and second phase repair

The test pipe specimen with circular defect of 10mm diameter is repaired with first phase repair using metallic seal in three different configurations circular, elliptical, round ended rectangle. The first phase repaired specimens of circular defect are shown in figure 4. Burst test is performed and all the configurations failed radially with elliptical configuration having the maximum failure pressure of 2.5MPa. So, the test pipe specimen with circular defect is repaired with metallic seal by applying metallic seal in elliptical configuration and is firmly held in place by applying pressure using a rubber tourniquet so that it forms a plug in the defect hole. The metallic seal is allowed to cure for three hours

and then it is reinforced by wrapping four layers of bi-directional (woven roving) glass fiber mat of 560 gsm wetting with epoxy (Araldite LY556, Hardener HY951). The test pipe specimen with circular defect after second phase repair is shown in figure 5. Burst test is performed and the repair failed at 12.5 MPa. The results of the burst test are tabulated in Table 1.

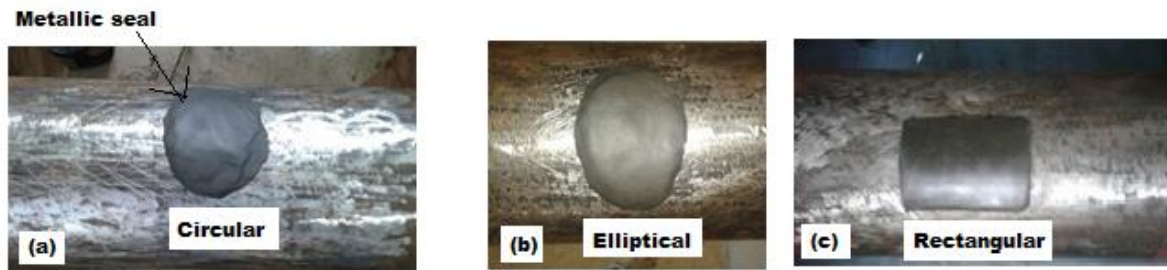


Figure 4. First phases repaired using metallic seal specimens of Circular defect with different configurations (a) Circular (b) Elliptical (c) rectangle



Figure 5. Circular defect repaired with elliptical configuration of metallic seal further reinforced with composite sleeve

4.2 Circumferential slot defect repaired with first phase and second phase repair

The test pipe specimen with circumferential slot defect which is 37.68mm long, 2mm wide and oriented in circumferential direction is repaired with first phase repair using metallic seal in three different configurations circular, elliptical, round ended rectangle. The first phase repaired specimens of circumferential slot defect are shown in figure 6. Burst test is performed and all the configurations failed radially with elliptical configuration having the maximum failure pressure of 4MPa. So, the test pipe specimen with circumferential slot defect is repaired with metallic seal by applying metallic seal in elliptical configuration and is firmly held in place by applying pressure using a rubber tourniquet so that it forms a plug in the defect hole. The metallic seal is allowed to cure for three hours and then it is reinforced by wrapping four layers of bi-directional (woven roving) glass fiber mat of 560 gsm wetting with epoxy (Araldite LY556, Hardener HY951). The test pipe specimen with circumferential slot defect after second phase repair is shown in figure 7. Burst test is performed and the repair failed at 15 MPa. The results of the burst test are tabulated in Table 1.



Figure 6. First phase repaired specimens of circumferential slot defect with different configurations (a) Circular (b) Elliptical (c) Rectangle



Figure 7. Circumferential slot defect repaired with elliptical configuration of metallic seal further reinforced with composite sleeve.

4.3 Axial slot defect repaired with first phase and second phase repair

The test pipe specimen with axial slot defect which is 37.68mm long, 2mm wide and oriented in axial direction is repaired with first phase repair using metallic seal in three different configurations circular, elliptical, round ended rectangle. The first phase repaired specimens of axial slot defect are shown in figure 8. Burst test is performed and all the configurations failed radially with elliptical configuration having the maximum failure pressure of 3.5MPa. So, the test pipe specimen with axial slot defect is repaired with metallic seal by applying metallic seal in elliptical configuration and is firmly held in place by applying pressure using a rubber tourniquet so that it forms a plug in the defect hole. The metallic seal is allowed to cure for three hours and then it is reinforced by wrapping four layers of bi-directional (woven roven) glass fiber mat of 560 gsm wetting with epoxy (Araldite LY556, Hardener HY951). The test pipe specimen with axial slot defect after second phase repair is shown in figure 9. Burst test is performed and the repair failed at 13.5 MPa. The results of the burst test are tabulated in Table 1.



Figure 8. First phase repaired specimens of axial slot defect with different configurations (a) Circular (b) Elliptical (c) Round ended rectangle



Figure 9. Axial slot defect repaired with elliptical configuration of metallic seal further reinforced with composite sleeve.

Table 1. Failure pressures of test specimens after performing burst test.

Defect geometry	Phase I repair by metallic seal shape of			Phase II repair Metallic Seal + Composite Overwrap
	Circular ^a	Elliptical ^b	Round ended rectangular ^c	
Circular defect	2 MPa	2.5 MPa	1.7 MPa	12.5 MPa
Circumferential slot defect	3 MPa	4 MPa	3 MPa	15 MPa
Axial slot defect	3 MPa	3.5 MPa	2.5 MPa	13.5 MPa

^a Dimensions of circular repair configuration – Diameter = 8.94cm

^b Dimensions of Elliptical repair configuration – Length of major axis = 10cm; Length of minor axis=8cm.

^c Dimensions of Round ended rectangular repair configuration – Length = 9cm; Breadth = 7cm

4.4 Effectiveness of bonding properties of Metallic Seal

The metallic seal used in the above experiments had very good interfacial bonding. After the first phase repair is done, burst test was performed. All the repair configurations failed radially i.e., there was no sign of leak from the edges of the repair. No debonding was observed in all the three different configurations after performing the burst test. It suggests that the metallic seal has good interfacial bonding with the steel substrate when compared to neat epoxy (Araldite LY556, Hardener HY951). Tensile strength and lap shear strength/adhesive strength of the metallic seal are experimentally found according to ASTM D638 [10] and ASTM D3163 [11] respectively. The maximum tensile stress of metallic seal is 20.24 MPa and lap shear strength of metallic seal is 34.58 MPa. The first phase repair with metallic seal failing radially is shown in figure. 10

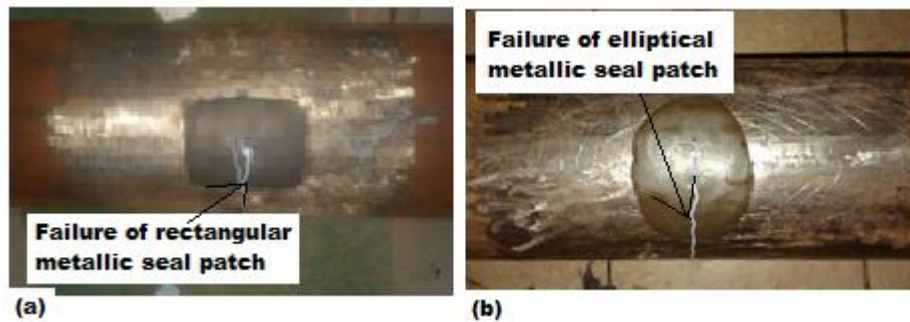


Figure 10. Metallic seal failing radially in (a) Rectangular (b) Elliptical configurations

4.5 Theoretical and experimental failure pressures

From equation (2), for a pipe with through thickness corrosion defect i.e., remaining substrate wall thickness at the defect is zero, the theoretical failure pressure is calculated as

$$P_t = (t_{min} \epsilon_c E_c) \frac{2}{D} \quad (3)$$

The theoretical failure pressure (P_t) from the above equation for a pipe with external diameter of 168.3mm and composite layer thickness of 2.4 mm is 25.668 MPa. The minimum repair thickness for different internal pressures is calculated as per equation 2 and the results are tabulated in Table 2.

Table 2. Minimum repair thickness of the laminate for different internal pressures

Specimen	Pipe Diameter[D] (mm)	Internal Pressure[P_{int}] (MPa)	Repair Thickness[t_{min}] (mm)
1.	168.3	5	0.48
2.	168.3	7.5	0.70
3.	168.3	10	0.94
4.	168.3	12.5	1.17
5.	168.3	15	1.40
6.	168.3	17.5	1.64
7.	168.3	20	1.87
8.	168.3	22.5	2.10
9.	168.3	25	2.34
10.	168.3	27.5	2.57

5. Conclusion

Most commonly and frequently occurring through thickness corrosion/leaking defects in metallic pipelines like circular, circumferential slot and axial slot defects are repaired using a repair methodology in which the defects are first sealed using a commercially available metallic seal and then reinforcing it with four layers of bi-directional glass fiber mat of 560 gsm wetting with epoxy (Araldite LY556, Hardener HY951). The effectiveness of the repair is studied by performing burst test of various configurations. The following findings were observed:

- The metallic seal is able to assure that the pipe doesn't leak under internal pressure.
- Elliptical configuration of repair with metallic seal for all the three defects i.e., circular, circumferential slot and axial slot defects is found to be effective.

- All the configurations failed radially i.e., the metallic seal has good interfacial bonding with the pipe specimen
- No debonding of the metallic seal was observed in all the burst test cases of different configurations on different defect types.
- The glass/epoxy composite overwrap provides load bearing effect to the force generated in the hole/defect due to internal pressure.
- The glass/epoxy composite overwrap increases the structural integrity of the pipe section and the pressure bearing capacity of the circular defect is enhanced by five times, for the circumferential slot defect is enhanced by 3.5 times and for the axial slot defect is enhanced by nearly 3.86 times.
- Failure pressure of the repaired specimen is predicted using an analytical modelling as per ISO 24817 standards and a good agreement is seen between the theoretical and experimental results.
- The failure is not catastrophic and has appeared in the form of leak that occurred in the axial direction at the edges of the composite overwrap.
- Failure is predominantly due to debonding between the composite overwrap and the steel substrate.

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