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Cyclic Loading on Composite Repair of Corroded Steel Pipelines

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ABSTRACT

The study aims to determine how cyclic loading affects the structural integrity and lifespan of composite repair systems used to restore corroded steel pipelines. As specified in Annexure C of the ISO 24817 repair code, pipe specimens are machined to produce flaws with 80 % wall loss. Testing under static and cyclic pressure loading is done as per ASTM D2992 and ASTM D2143. Static pressure loading is accomplished by continually pressurizing the pipe specimen, and burst pressure is assessed. Various Rc-ratios or levels of cyclic loading severity are used in cyclic pressure loading tests. Each case's number of cycles before failure is determined experimentally, and the service de-rating factor is assessed in accordance with ISO 24817. The 235 bar pressure was sustained by the static-loaded repaired pipe specimens with 80 % wall loss, and the failure was catastrophic. At around 7000 cycles, the cyclically loaded repaired samples with 80 % wall loss failed, and the failure manifests as debonding or a leak.

Keywords: Cyclic loading; Composite repair systems; Corroded pipelines; Life prediction; Service de-rating factor

1. INTRODUCTION

Steel pipelines are primarily used to transmit highly pressurized fluids over long distances. These transmission pipelines generally operate at or are exposed to corrosive environments leading to internal and external corrosion defects. Also, these transmission pipelines are subjected to combined pressure and temperature fatigue/cyclic loading of $1x10^4$ to $1x10^8$ cycles with frequencies ranging from 10^{-6} to 10^{-1} Hz in their average lifetime. Cunha[1], *et al.* studied the effect of fatigue loading in corroded pipelines using a strain life (ε-N) approach and concluded that fatigue might become an essential factor for failure if the corroded pipelines are left unrepaired or un replaced. Kara[2], *et al.* studied the effects of cyclic loading on the impact behaviour of glass-reinforced epoxy GRE pipes. They concluded that the bonding between fibre and matrix has weakened due to fatigue. Langer[3], *et al.* Have investigated the designs of pressure vessels for low-cycle fatigue through stress and strain-based approaches and concluded that strain-based strain fatigue data is more accurate.

These defects must be repaired to enable pipelines to function at their desired capacity. Recently, composite repair methodology has been widely used due to its inherent advantages such as high strength-to-weight ratio, ability to inhibit corrosion, no risk of fire and explosion, ease of installation, and economical, etc., over traditional means of repair such as cutting welding and sleeving[4–6]. As part of these composite repair methodologies, a defective piece of the pipe is strengthened by overwrapping it with layers of composite materials such as glass/epoxy, carbon/epoxy, or kevlar/epoxy around the pipelines. Duell[7], *et al.* studied the pipeline repair overwrap system using carbon composites on various corrosion defect types in a steel pipe with the help of finite element methods. They concluded that the failure pressure was not significantly affected by the change in the defect size in the hoop direction, but stress fields in the pipe got affected. Vishwas[8], *et al.* investigated the impact of nano clay filler reinforcement in the FRP composite wrapping repair system. The investigation improved the interfacial bonding strength and bursting resistance of composite wrapping over the outer surface of a corroded steel pipe.

Nitheesh[9], *et al.* investigated the optimum configuration and bonding area for a composite repair to have maximum bursting resistance. They concluded that the elliptical configuration and bonding area consisting of 80 times the defect area gives maximum bursting resistance in a composite sealant paste-based repair of leaking-type defects in corroded pipelines. Composite repair techniques for offshore or underwater steel pipeline repair have recently been developed by researchers[10-11].

Mally[10], *et al.* investigated the performance of an underwater-installed carbon/epoxy composite repair system. To examine the changes in characteristics caused by aqueous submersion, they conducted coupon levels and a full-scale trial. Their findings demonstrated that applying a composite repair system utilized underwater did not result in appreciable changes in the composite's properties. Still, they did see a considerable reduction in burst pressures due to inadequate interfacial bonding. Nariman Saeed[12], *et al.* conducted an

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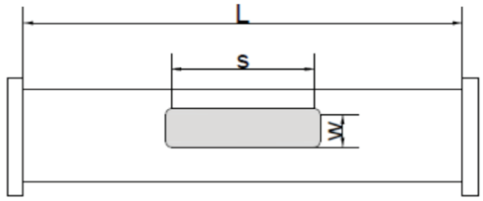
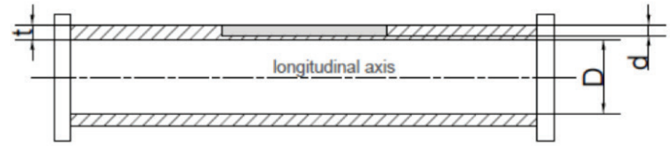


(a)



(b)

Figure 1. Pipe specimen with non-leaking wall loss defect (a) Top view (b) Front cut-sectional view.

analytical and numerical study of composite pipeline repairs to comprehend the impact of live pressure on the repair. In circumferential weld joints in pipelines spanning up to 50 % of the circumference of the weld, Watanabe[13], *et al.* explain the methods to fix part wall loss and through wall loss faults. A hydraulic burst test of repaired specimens is used to assess the success of the repair process, and an effort has been made to validate the results against those obtained analytically. Subbalakshmi[14], *et al.* assessed the performance of glass/epoxy composite overwrap to rehabilitate damaged pipelines exposed to harsh environmental conditions. They predicted the life of composite repair to be a minimum of 2 decades. Vishwas[15], *et al.* developed a rapid curing leak sealant paste using the design of experiments and response surface optimization to repair live leaking defects in the pipelines. Also, they proposed and tested various composite repair methodologies with enhanced pressure-bearing capabilities and adhesion properties to repair leaking defects. All these studies indicate the extent of studies conducted in different areas of pipeline repair using composite repair methodology. However, literature suggests that no studies have been done to estimate the fatigue life of composite repair of corroded steel pipelines. The combined pressure and temperature cyclic loading have detrimental effects on the structural integrity and lifetime of the repair.

In this present study, the effect of pressure cyclic loading at a constant frequency of 0.416 cycles per sec. or 25 cycles per minute and a varying cyclic loading severity or R_c ratio on the structural integrity and lifetime of the repair is being investigated as per ASTM D2143[16] and ASTM D2992[17]standards. To enhance the interfacial bonding between the repair and the substrate, pre-impregnated chopped strand mat (CSM) glass fiber is applied prior to applying the pre-impregnated woven-roven mat (WRM) glass fiber. CSM and WRM glass fiber are combined to repair the non-leaking defects in corroded pipelines, as suggested by past researchers[18]. A setup has been designed and fabricated to experiment with the cyclic pressure loading in the test specimens.

The present study offers numerous advantages over previous research conducted on the subject matter. The proposed composite repair methodologies are straightforward and easily implementable in practical conditions, resulting in lower repair costs. Unlike costly fibers such as Carbon or Kevlar, the study utilizes readily available and affordable Glass fibers, along with accessible epoxy resins. Additionally, the study validates the repair against cyclic pressure loading, providing an extra advantage compared to previous studies.

2. EXPERIMENTAL PROCEDURE

2.1 Specimen Preparation and Repair Code

According to Annexure C of ISO 24817 repair code, API 5L X65 pipe specimens are CNC milled to provide a non-leaking flaw notch with 80 % wall loss. The notch is 90 mm by 50 mm, and the edges are filleted to disperse stress. Figure 1 depicts the test pipe specimen with the non-leaking flaw, and Table 1 lists the dimensions. The test pipe specimens are strengthened with composite repair using a wrapping code made up of two layers of epoxy reinforced with chopped strand mat (CSM) and four layers of epoxy reinforced with woven-roven mat (WRM). Prior to filling the notch with epoxy and allowing it to cure until it becomes rock solid, the surface is first prepared around the defect area according to SSPC guidelines. The epoxy is then once more roughened, and its surface is rendered tangential to the pipe's surface. After being impregnated with a resin system composed of VAS-ER-1801 (part A) and VAS-HR-1811 (part B), two layers of Chopped Strand Mat (CSM) glass fiber of 300 GSM and four layers of Woven-Roven Mat (WRM) glass fiber of 610 GSM are then wrapped around the flaw. Figure 2 depicts the repaired test pipe specimen.

Table 1. Test pipe specimen and defect dimensions (mm)

Test pipe specimen length (L)	1000.0
Test pipe specimen Internal diameter (D)	101.6
Defect axial length (s)	90.0
Defect circumferential width (w)	50.0
Wall loss depth (d)	5.7
Pipe Thickness (t)	7.11

Figure 2. Test pipe specimens repaired with CSM + WRM (2+4) composite wrap.

2.2 Pressure Cyclic Loading Setup Layout

A Pressure Cyclic Loading Setup consisting of a hydraulic power pack with a reciprocating cylinder setup has been designed as per ASTM D2143 standard[16]. The schematic is shown in Fig. 3. The Cyclic Loading setup for the pipe specimen consists of a star delta starter, hydraulic power pack,

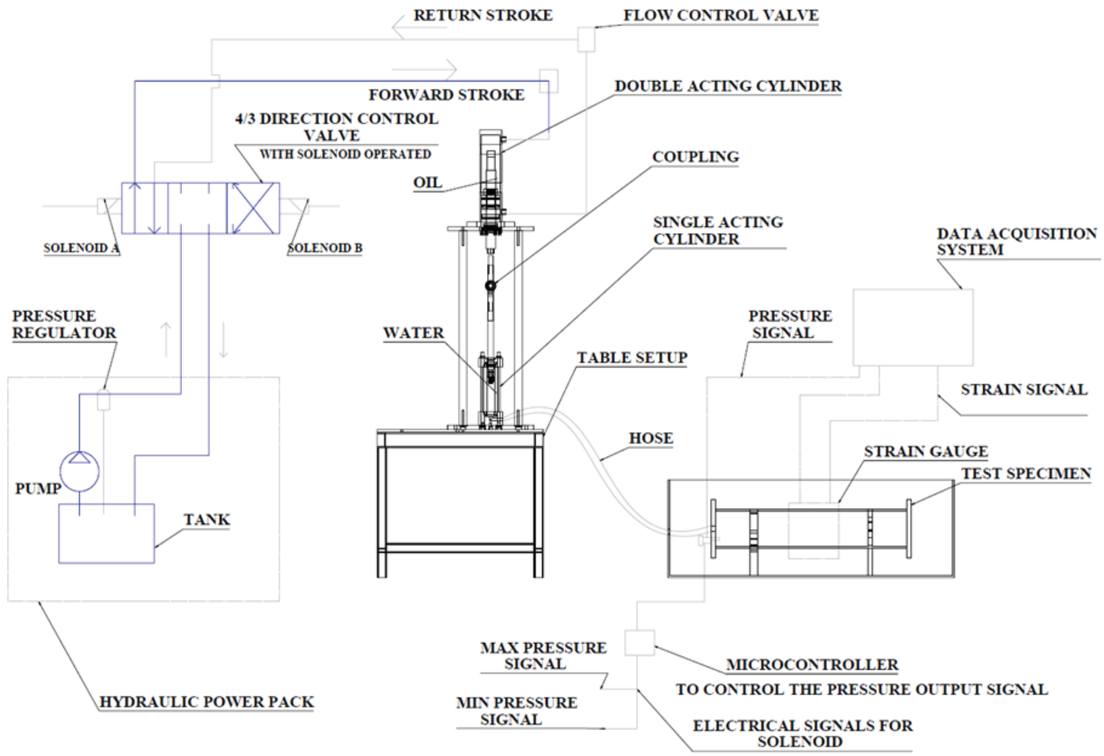


Figure 3. Schematic Layout of Cyclic Loading Setup.

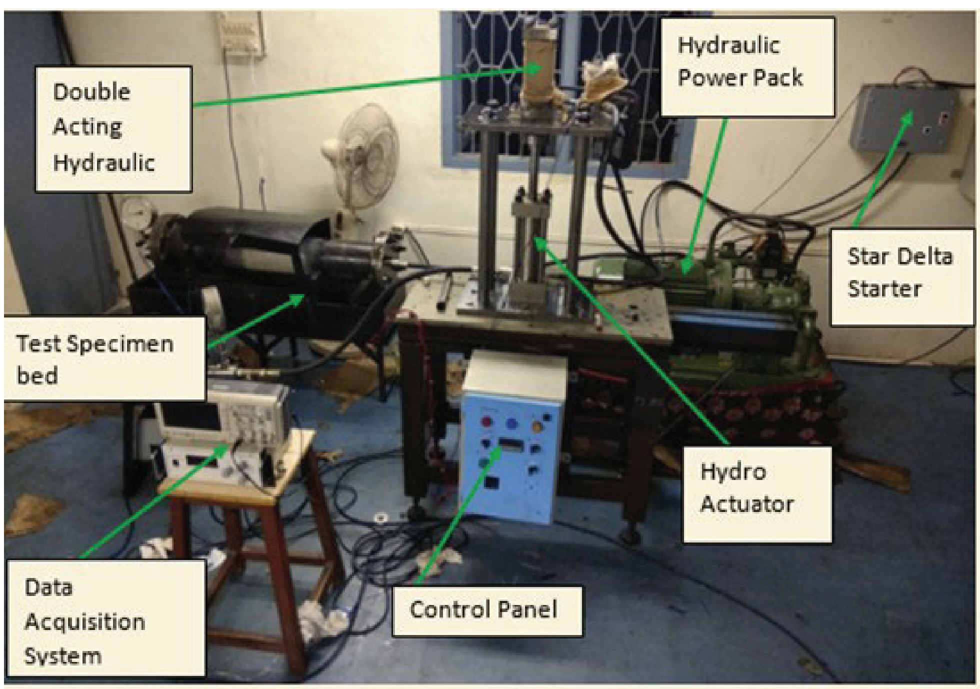


Figure 4. Cyclic Loading Setup.

direction control valve, hydraulic actuator (double acting cylinder), Stainless Steel cylinder (single acting cylinder), table setup (for mounting actuator and cylinder), specimen setup (for mounting the specimen), pressure switch, four-way valve, one-way flow control valve, check valve and hand pump. The designed cyclic loading setup layout is shown in Fig. 4.

2.3 Static and Cyclic Loading Tests

Two types of tests are performed in this study. A static loading test in which the test pipe specimen is mounted onto the setup and the fluid inside the pipe is pressurized until the failure, and thus burst pressure is evaluated. Four cycling loading tests are done at a constant frequency of 0.416 cycles per second or 25 cycles per minute and with a varying cycling loading severity or R_c ratio, as shown in Table 2. They are loaded from a minimum pressure (P_{min}) to a maximum pressure (P_{max}) until the repair fails or up to a threshold limit of 10000 cycles. If the repair does not fail before 10000 cycles, it is subjected to

Table 2. Cyclic loading tests to be performed

Test	Frequency	Minimum Pressure (P_{min}) (bar)	Maximum Pressure (P_{max}) (bar)	Cyclic Loading Severity or R_c– ratio (P_{min}/P_{max})
C1	0.417	20	60	0.33
C2	0.417	20	80	0.25
C3	0.417	20	100	0.2
C4	0.417	40	120	0.33

static loading to evaluate its burst pressure after cyclic loading. The chosen cycling loading severity, i.e., from P_{min} to P_{max}, in this study reflects the pressure variation observed in practical scenarios during shutdown and subsequent restoration to full capacity. In typical cross-country pipelines, the operating pressure is around 100 bars, and during shutdown or reduced capacity operation, the pressure (P_{min}) may decrease to 20 bars. This study aims to simulate these more severe scenarios involving shutdown and subsequent return to full operating capacity.

This can be used as a factor to discuss the loss of structural integrity due to cyclic loading. In this study strain-life fatigue (ε-N) approach is used to estimate the life of the repair. While performing the tests, strain gauges are mounted in the circumferential direction on the defect region, as shown in Fig. 5. A pressure gauge is also mounted on the blind flange opposite the pressurizing side. A data acquisition system consisting of a strain indicator and an oscilloscope is used to acquire the live strain data from the strain gauge mounted on the test pipe specimen, as shown in Fig. 6. Plots of varying strain vs. time can be used to predict the number of cycles required for failure.

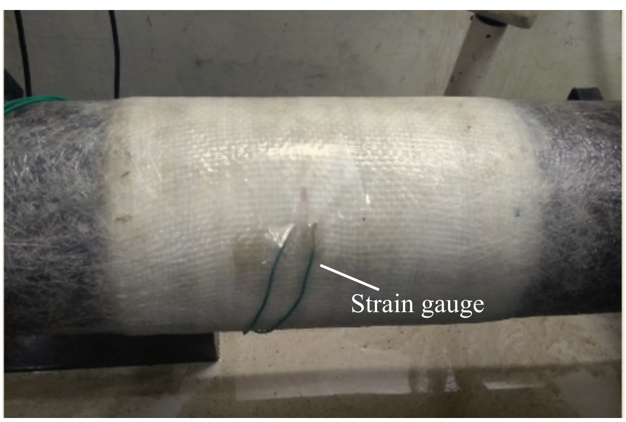


Figure 5. Strain gauge mounted in the circumferential direction over the defect.

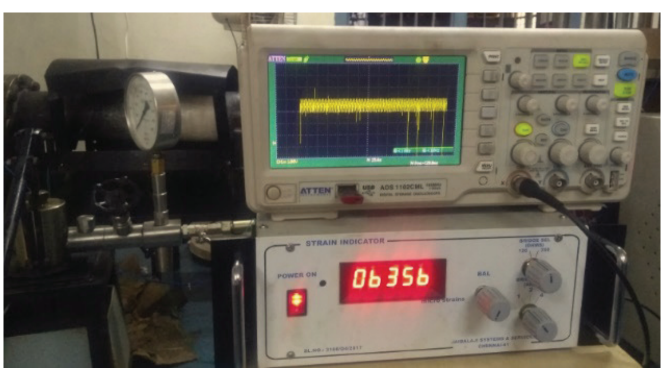


Figure 6. Data Acquisition System.

3. ANALYTICAL MODELLING

3.1 An Elastic Thin-Walled, Internally Pressurized Test Pipe Spool

The analytical model proposed in the paper is as per ISO 24817:2017 & ASME PCC-2:2022[19-20]. An elastic thin-walled test pipe specimen is subjected to external pressure (P_{ext}) and internal pressure (P_{int}) with an external radius 'b' and internal radius 'a'. Assuming the radial stresses are to be negligible, hoop stress (σ_θ) can be written as shown in Eqn. 1.

$$\sigma_\theta = \frac{(P_{int} \times a) - (P_{ext} \times b)}{b - a} \tag{1}$$

The Eqn. 2 provides the minimal thickness for the repair laminate with no live pressure.

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

where, ϵ_c is the allowable hoop strain of the repair laminate, E_c is the repair laminate modulus in hoop direction, P_{eq} is the equivalent internal pressure, D is the external diameter of the pipe spool, s is the allowable strength of the pipe substrate, and t_s is the minimum remaining wall thickness of the substrate[9].

3.2 Cyclic Loading of Non-Leaking Type Defects

As per ISO 24817 & ASME PCC-2[19-20], for a test pipe specimen subjected to cyclic loading from a minimum pressure P_{min} to maximum pressure P_{max}, the composite allowable strain in the circumferential direction is de-rated by a factor f_c as shown in Eqn. 3.

$$\epsilon_c = f_c \epsilon_{c,\ non-cyclic} \tag{3}$$

where, $\epsilon_{c,\ non\text{-}cyclic}$= allowable strain before de-rating for cyclic loading (mm/mm)

f_c= Cyclic de-rating factor given as per Eqn. 4.

$$f_c = \sqrt{\left(R_c^2 + \frac{1}{(2.888 * Log(N)) - 7.108} * (1 - R_c^2)\right)} \tag{4}$$

Here, R_c = Cyclic loading severity= P_{max}/P_{min}

N = number of loading cycles until failure

4. RESULTS AND DISCUSSIONS

4.1 Static Loading Tests

The test pipe specimen with 80 % wall loss has been repaired with the specified wrap code of two layers of CSM-reinforced epoxy and four layers of WRM-reinforced epoxy. The repaired test specimen is mounted onto the cycling loading setup and is pressurized incrementally until failure. The repaired sample failed at a pressure of 235 bar. The complete notch portion has opened up, breaking the epoxy filled in it into pieces, and fiber failure is observed along with debonding. The failed specimen is shown below in Fig. 7.

Figure 7. Failed specimen with 80 % wall loss.

4.2 Cyclic Loading Tests

4.2.1 Cyclic Loading Test of C1: 20 - 60

The cyclic pressure loading test is performed at a constant frequency of 25 cycles per minute with the test pipe specimen loaded from a minimum pressure of 20 bar to a maximum pressure of 60 bar and with the cyclic loading severity or R_c ratio value of 0.33 until the specimen fails. In this case, cyclic loading is performed for 12300 cycles, and the repair remains intact. The micro-strain versus number of cycles is plotted, as shown in Fig. 8. The strain increased rapidly from the first cycle to the 1465 cycle from 160 micro-strain to 502 micro-strain. And from the 1465 cycle to the 11250 cycles, the strain decreased slowly from 502 micro-strain to 419 micro-strain. And from the 11250 cycles until the 12300 cycle, the strain again increased rapidly from 419 micro-strain to 575 micro-strain. The maximum strain noticed is 575 micro-strain. As the repair has sustained more than 10000 cycles, the burst test or static loading test is performed on the cyclically loaded specimen, and it failed at a burst pressure of nearly 230 bar, as shown in Fig. 9. The failure mode is catastrophic, with fibers breaking from the edges of the notch, and part of the metal notch is sheared together with the wrap. So, the loss of structural integrity in the cyclic loading from 20 bar to 60 bar and with a cyclic loading severity or Rc ratio value of 0.33 is not significant. The cyclic de-rating factor, as calculated from Eqn. 4, is 0.55.

4.2.2 Cyclic Loading Test of C2: 20 – 80

The cyclic pressure loading test is performed at a constant frequency of 25 cycles per minute with the test pipe specimen loaded from a minimum pressure of 20 bar to a maximum

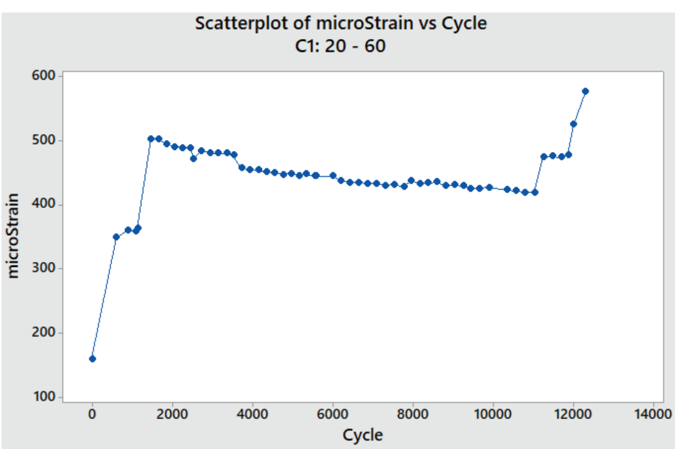


Figure 8. Micro-strain vs. number of cycles plot for C1: 20 – 60.

Figure 9. Failed specimen with 80 % wall loss after cyclic loading of 20 bar to 60 bar.

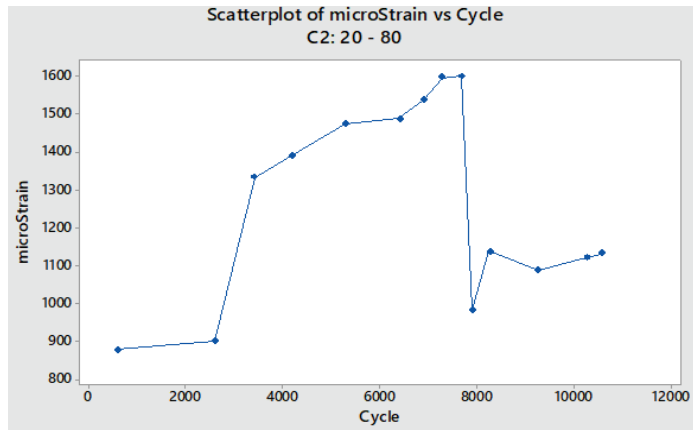


Figure 10. Micro-strain vs number of cycles plot for C2: 20 – 80.

pressure of 80 bar and with the cyclic loading severity or R_c ratio value of 0.25 until the specimen fails. In this case, cyclic loading was performed for 10600 cycles. The micro-strain versus number of cycles is plotted, as shown in Fig.10. The strain increased until 7800 cycles, and at 7800 cycles, debonding happened, and the strain dropped suddenly. The maximum strain noticed was 1600 micro-strain. The cyclic de-rating, as calculated from Eqn. 4, is 0.54. The failed specimen is shown in Fig. 11, and the failure mode is in the form of axial leaks from the end of the repair at the pipe interface to the overwrap.

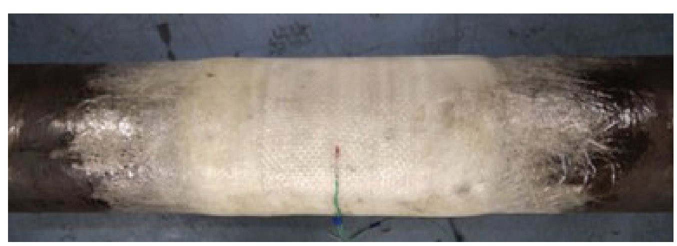


Figure 11. Failed specimen with 80 % wall loss due to cyclic loading of 20 bar to 80 bar.

4.2.3 Cyclic Loading Test of C3: 20 – 100

The cyclic pressure loading test is performed at a constant frequency of 25 cycles per minute with the test pipe specimen loaded from a minimum pressure of 20 bar to a maximum

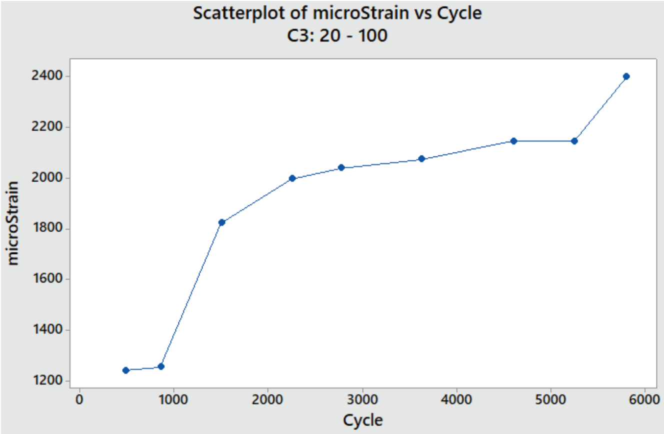


Figure 12. Micro-strain vs number of cycles plot for C3: 20 – 100.

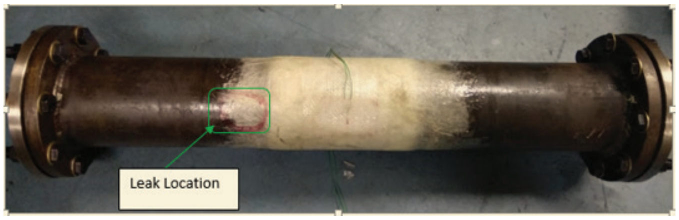


Figure 13. Failed specimen with 80 % wall loss due to cyclic loading of 20 bar to 100 bar.

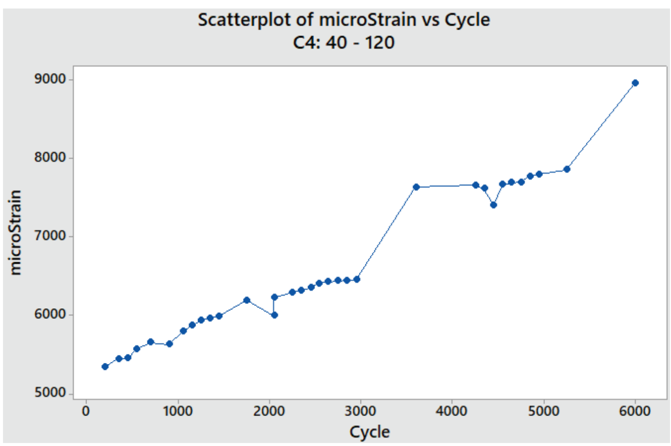


Figure 14. Micro-strain vs number of cycles plot for C4: 40 – 120.

Figure 15. Failed specimen with 80 % wall loss due to cyclic loading of 40 bar to 120 bar.

pressure of 100 bar and with the cyclic loading severity or R_c ratio value of 0.2 until the specimen fails. In this case, cyclic loading was performed for 5800 cycles. The micro-strain versus the number of cycles is plotted, as shown in Fig. 12. The strain increased until 5800 cycles, and at 5800 cycles, a small leak appeared from the edges of the repair, failing the specimen. The maximum strain noticed was 2400 micro-strain. The cyclic de-rating, as calculated from Eqn. 4, is 0.54. The failed sample is shown in Fig. 13, and its failure mode is debonding at the pipe to the overwrap interface, like the failed specimen for cyclic loading of 20 - 80 bars case.

4.2.4 Cyclic Loading Test of C4: 40 – 120

The cyclic pressure loading test is performed at a constant frequency of 25 cycles per minute with the test pipe specimen loaded from a minimum pressure of 40 bar to a maximum pressure of 120 bar and with the cyclic loading severity or R_c ratio value of 0.33 until the specimen fails. In this case, cyclic loading is performed for 6000 cycles. The micro-strain versus the number of cycles is plotted, as shown in Fig. 14. The strain increased until 6000 cycles, and at 6000 cycles, a small leak appeared from the edges of the repair resulting in the failure of the specimen. The maximum strain noticed was 8700 micro-strain. The cyclic de-rating factor, as calculated from Eqn. 4, is 0.59. The failed sample is shown in Fig. 15.

5. CONCLUSIONS

To repair non-leaking type defects with 80 % wall loss, the notch region is first filled with the resin system (VAS-ER-1801 + VAS-HR-1811), followed by a wrapping code comprising two layers of CSM-reinforced epoxy and four layers of WRM-reinforced epoxy. On the test specimen replicas, static and cyclic loading tests are carried out, and the impact of the cyclic loading on the structural integrity and longevity of the composite repair is examined. The following findings are drawn after extrapolating the strain behavior with the number of cycles in accordance with the strain life fatigue (ε-N) approach:

- A statically loaded repaired pipe specimen with 80 % wall loss can sustain a maximum pressure of 235 bar.
- The failure of static loading specimen is predominantly debonding, delamination, and breaking of epoxy into pieces.
- For the cyclically loaded repaired pipe specimens with 80 % wall loss subjected to four different pressure loadings and cyclic loading severity or Rc ratio at a constant frequency of 25 cycles per minute and results of the same are provided in Table 3.
- The effect of Cyclic loading reduces the lifetime of a repaired pipe specimen.
- The failure of cyclic loading specimens predominantly occurs due to through-thickness failure of the remaining substrate thickness at its weakest point, along with debonding of the repair.
- The failure of the cycling loading specimens is not catastrophic and appears in the form of a small leak at the edges in the axial direction.
- The repaired pipe specimen can sustain a minimum of 7000 cycles in its average lifetime.
- For the same cyclic loading severity or Rc ratio of 0.33, the lifetime, maximum strain, and cyclic de-rating factor vary significantly.
- For a decrease in cyclic loading severity or Rc ratio,

Table 3. Summary of the results of cyclic pressure loading tests performed

Test	Minimum Pressure (P_{min}) (bar)	Maximum Pressure (P_{max}) (bar)	Cyclic Loading Severity or R_c – ratio (P_{min}/P_{max})	Number of Cycles Sustained	Maximum Strain (micro-strain)	Cyclic de-rating factor
C1	20	60	0.33	12300	575	0.5478
C2	20	80	0.25	7800	1600	0.5379
C3	20	100	0.2	5800	2400	0.5433
C4	40	120	0.33	6000	8700	0.5872

the repaired pipe specimen's lifetime decreases, the maximum strain increases and the service de-rating factor almost remains the same.

- The effect of variance in pressure loading (P_{min}& P_{max}) is more significant than the variance in the cyclic loading severity or Rc ratio.

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CONTRIBUTORS

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In this paper he is responsible for designing and developing the cyclic pressure loading test setup. He has proposed and carried out various experiments as part of this manuscript. Further, he interpreted the results and prepared and finalized this manuscript.

Mr Nitheesh Kumar P. obtained his BTech from the Indian Institute of Technology Bhubaneswar.
In the current study he has assisted in conducting the experiments and played a pivotal role in the results interpretation and the generation of the manuscript.

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In the current study he first conceptualized the cyclic pressure loading test setup and helped design and fabricate the same. Further, he is responsible for the results interpretation and overall article review.

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