Investigation of the Failure Behavior of Fiber-Reinforced Patches in the Repair of Locally Damaged Steel Pipes

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Investigation of the failure behavior of fiber-reinforced patches in the repair of locally damaged steel pipes

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Abstract: In the present work, we investigate the performance of fiber-reinforced patches in the repair of a locally damaged steel pipe. The specimen of the study was presented for hydrostatic tests before damage and after repair. Damage was generated as a through-thickness cut acting diagonally to the pipe axis. The repair patch comprised twelve layers of fiberglass plain weave fabric aligned orthogonally to the pipe axis. The layers were divided into four distinct sizes and overlapped in a stepped configuration. The inner layers (one to four) covered a surface equivalent to 120% of the damaged area, the subsequent layers (five to seven) covered 160% and then (eight to ten) 200%, and the top layers (eleven and twelve) covered 240%. The hydrostatic tests were conducted until the maximum admissible pressure for the undamaged steel pipe. Two piezoelectric sensors and four strain gages were used in the pipe's instrumentation. The signal obtained during the successive tests was processed in terms of acoustic emission. The repair patch successfully survived the test scenario and acoustic emission detected no significant events. The repair patch robustness was accessed by incrementally degrading its surface and resubmitting the repaired pipe to the hydrostatic test. In the first repair degradation phase, a quarter of the patch's surface (three top layers) was removed through mechanical abrasion. The test was re-conducted, and the patch proved efficient, supporting the maximum admissible pressure once again. The repair patch only failed after degrading half of its surface (middle and top layers). A liquid penetrant test was used to demonstrate the patch's failure, which occurred in the borders of the through-thickness cut. Furthermore, the damage presence was not detected using a borescope.

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1. Introduction

Fiber-reinforced repair patches are an excellent tool to extend the operational lifespan of locally damaged primary components [1]. Such a tool is popular in the military sector since the `70s [2], and during the last decades, its use has expanded to commercial aircraft [3]. However, despite the fast increase in the demand for such a tool, the use of composite patches is still limited in conservative fields such as Oil & Gas, where the lack of norms and regulations prevents a broader use of adhesively bonded structural repairs. This industrial sector is particularly prone to costly maintenance breakdowns to correct faulty pipelines. During such events, conventional repair procedures, e.g., welding, involve long downtimes, which could be avoided by the use of adhesively bonded repair patches.

1.1. Fiber-reinforced repair patches

Adhesively bonding composite textiles to the surface of locally damaged components is an efficient way to increase the superficial strength of such components. However, despite the broad use of such a tool in the last decades, there is no consensus on the best practices for achieving an “optimum” repair patch. Parameters such as patch thickness, number of layers, fiber’s orientation, and patch’s geometrical shape and size are still subject of debate [1]. The only point of agreement between different authors is that smaller patches are the best patches, i.e., minimal surface interference results in minor alterations of the original structure’s inertia/stiffness and, consequently, minimal change in the structure’s intrinsic mechanical response.

1.2. In-situ repairing operations

If correctly applied, fiber-reinforced patches allow for a faster and easier way to perform field repairs of locally damaged metallic structures. Such a tool is an alternative to conventional welding operations, which inexorably result in costly maintenance breakdowns. However, despite the potential of adhesively bonded repair patches, their use in the Oil & Gas sector is still limited to the very minimum. Composite repair techniques are, commonly, restricted to onshore applications [4]. Furthermore, these are usually carried out without assuring that the repair itself does not locally over increase the pipe stiffness making it prone to fracture due to stress concentrations at end of the pipe-repair connection. Thus, due to the lack of standardization for the use of small fiber-reinforced repair patches to locally restore degraded/damaged pipelines, the Oil & Gas sector represents a great field to test unorthodox approaches to increase the operational life of structures such as steel pipelines.

2. Methodology

To access the efficiency of repair patches with minimal surface extension, and, consequently, minimal stiffness/inertia modification of the substrate, a stepped repair patch was designed to repair a steel pipe. The specimen consisted of a segment of hydrocarbon pipeline, in accordance with specifications from [5], with a nominal diameter equal to $101.60\mathrm{mm}$. The pipe length was defined as $1.50\mathrm{m}$ and a wall thickness of $6.02\mathrm{mm}$. The specimen was prepared for hydrostatic tests, as defined by [6] and [7]. The specimen is presented in Fig.1(a) prior to the damage, Figs. 1(b) and 1(c) detail the pipe instrumentation, which will be better discussed henceforward.

The damaged component is presented in detail in Fig.2(a), which illustrates the through-thickness cut diagonally to the pipe axis. Figs.2(b) to 2(c) show the crack-like damage dimensions, which are given by the schematic of Fig. 2(d): 49mm x 5mm on the outer surface and 21mm x 5mm on the inner surface. The pipe surface was cleaned with acetone and sanded (#400 grit) to remove irregularities produced during the cutting operation. Fig.2(e) presents the damaged region previously to the patching operation.

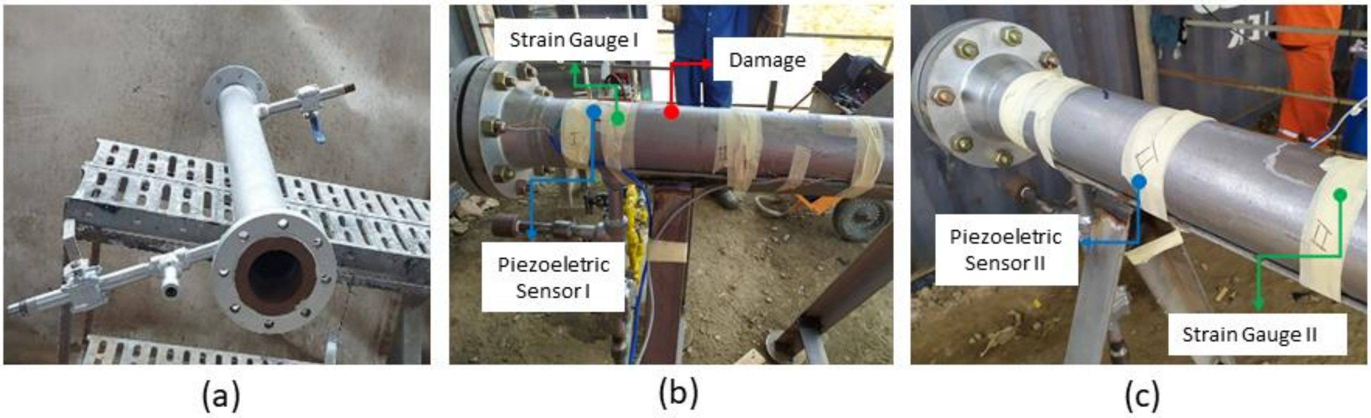

Fig. 1. Specimen prepared to field tests: (a) pipeline segment prior to damage; (b) instrumentation attached to the pipe; and (c) sensors positioning and identification.

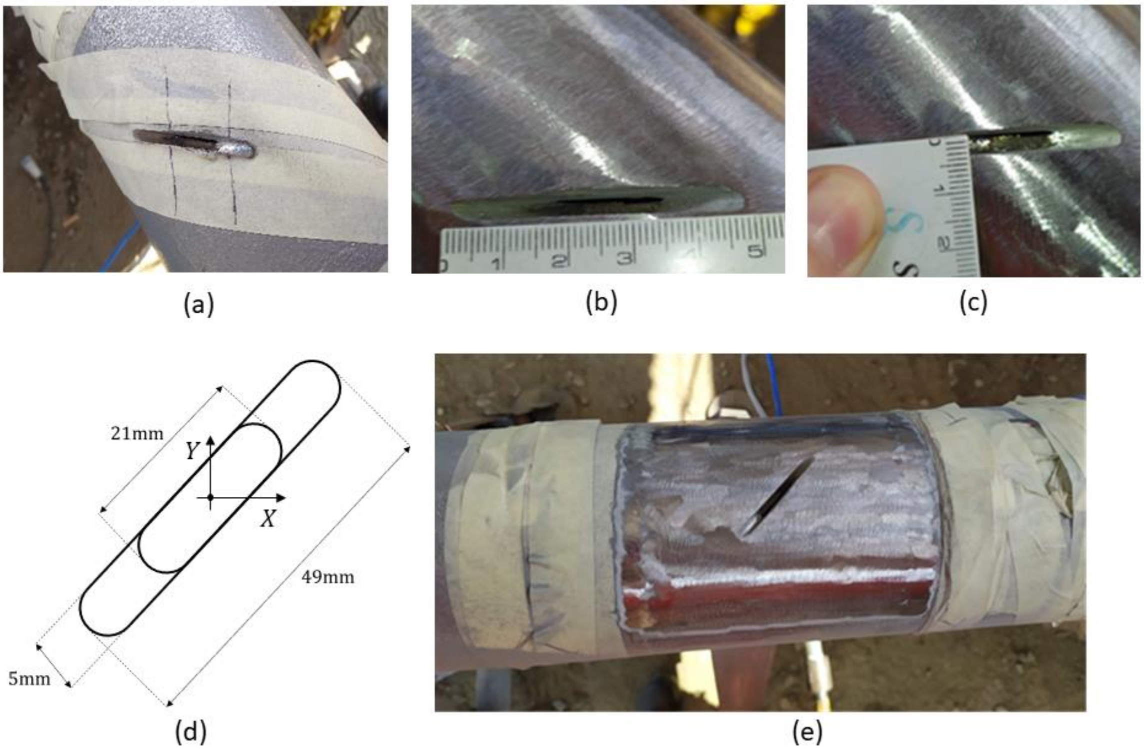

Fig. 2. Crack-like, through-thickness cut, damage: (a) overall view; (b) length in detail; (c) crack opening in detail; (d) crack schematic; and (e) region prepared to receive the repair patch.

The fiber-reinforced patch was defined as twelve layers of fiberglass plain weave fabric stacked in a stepped configuration. The patch fabric's main directions (0/90) were aligned coincident to the pipe's axial (X) and tangential (Y) directions. The patch was designed as four overlapping slabs containing a specific number of layers per slab. The first slab (smaller in terms of area) comprised layers one to four, the subsequent slab encompassed layers five to seven, the third slab was formed by layers eight to ten, and the last slab was the largest, with layers eleven and twelve. The repair patch lay-up was defined as follows:

Table 1. Repair patch lay-up.

Patch slab	Number of layers/slab	Layer size ($l_p \times l_p$)
1st (base)	4 layers (0/90)	$3600\ \mathrm{mm}^2$
2nd (mid)	3 layers (0/90)	$6400\ \mathrm{mm}^2$
3rd (mid)	3 layers (0/90)	$10000\ \mathrm{mm}^2$
4th (top)	2 layers (0/90)	$14400\ \mathrm{mm}^2$

Fig. 4 presents the specimen after the repairing operation. The patch was constituted of a plain weave fiberglass fabric ($200\ ^{\mathrm{g}}/_{\mathrm{m}^2}$) and an epoxy resin with micro-steel particulate reinforcement (4:1 mixture ratio). This type of resin [8] was selected due to its fast curing characteristics, i.e., the whole curing process took twelve hours at room temperature ($\approx 23°\mathrm{C}$). The patching process was defined in a similar manner to the suggested by [9].

Fig. 3. Repaired region after the patch cure.

The testing scenario consisted of hydrostatic tests (HT) until the maximum admissible testing pressure. Four sensors were used to monitor the structure: two piezoelectric sensors at the surroundings of the damaged region, and two strain gauges applied directly on the pipe surface, one at the middle pipe and the other close to the damaged region. Figs. 1(b) and 1(c) show the positioning of the aforementioned sensors. Considering the pipe segment used as the test specimen, and according to the norms [6] and [7], the maximum allowable working pressure for such specimen was computed as $2.94\mathrm{MPa}$ and the maximum admissible testing pressure was $7.84\mathrm{MPa}$. Four consecutive hydrostatic tests were done, for each HT, the specimen was under different conditions:

1st – Specimen undamaged: prior to damage and consecutive repairing operation;

2nd – Specimen repaired with fiber-reinforced patch: patch as-applied without superficial degradation;

3rd – Specimen with repair patch surface degraded by means of mechanical abrasion: 25% of the layers removed;

4th – Specimen with repair patch further degraded: 50% of layers removed.

All tests were conducted alongside Acoustic Emission (AE) monitoring. The postprocessing of the acquired signal was performed using a tailored software [10] developed especially for the signal conditioning and postprocessing needed in the present work. The AE employed a bandpass filter of type butterworth in the range of 20 kHz and 100 kHz.

3. Results and Discussions

After the 2nd HT test, the repair patch surface was degraded after each testing regime. The specimen and the repair patch remained intact and without any deformation behavior suggesting internal crack/failure, this statement is true even after the 3rd test, at which only 75% of the patch's layers were resisting load. The patch only failed during the 4th HT, at a pressure equal to $\cong 3.5\mathrm{MPa}$. It is very important to stress that even after the patch was reduced to half its design thickness and 40% of its original area, it resisted the maximum allowable working pressure. Fig. 4 presents the signal obtained using AE at two distinct conditions. Fig. 4(a) presents the signal at the maximum pressure of 7.84MPa during the 1st HT. Fig. 4(b) shows the same result, but now for the 3rd HT.

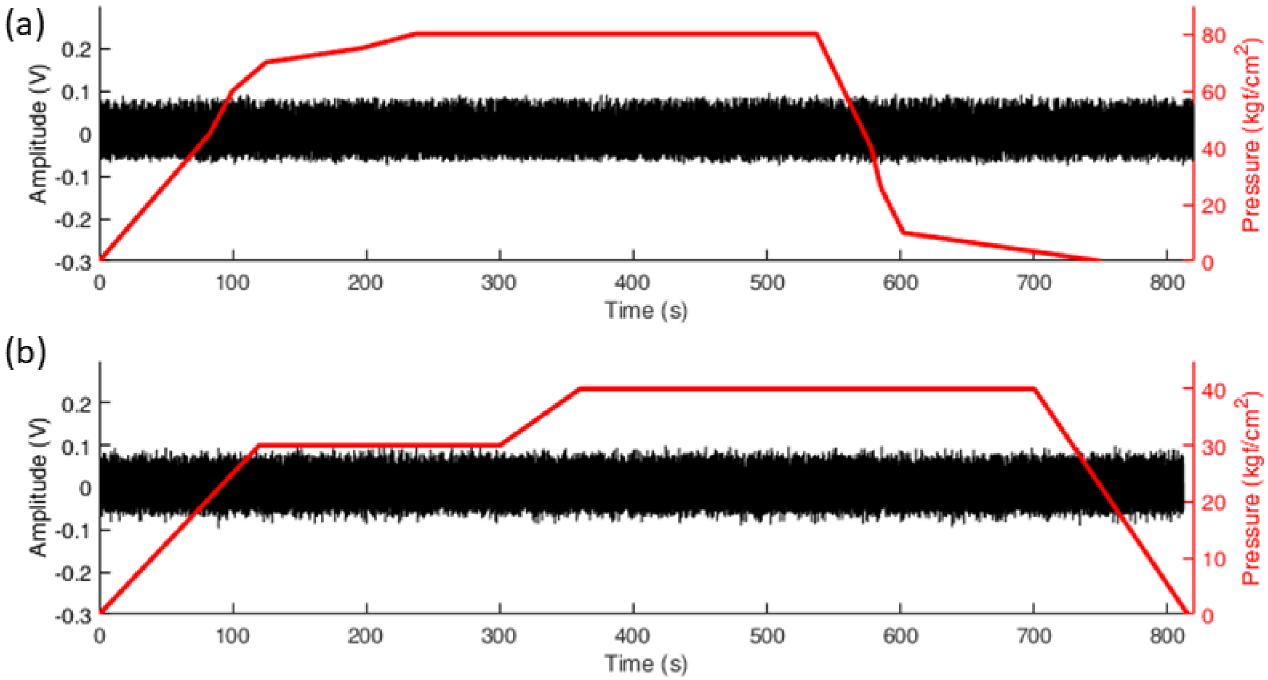

Fig. 4. AE signal at peak testing pressures: (a) 1st HT and (b) 3rd HT.

Even under extreme conditions, the signal response of the specimen, with a repair patch degraded to 75% of its original thickness, showed no significant events. This lack of events indicating internal crack/failure of the patch supports the efficiency of the technique adopted to repair the locally damaged pipe. Furthermore, the patch failure, during 4th HT, and the failure region was only visible after using penetrating fluid.

4. Final Remarks

The repair of locally damaged metallic structures proved effective even under loading scenarios exceeding the design specifications of the tested specimen. The AE results support the high efficiency of the fiber-reinforced patch, i.e., no dissipation events due to internal cracking. Despite the limitations of the tests conducted, which are still part of ongoing research, the results showed that the proposed approach is promising and could lead to a methodology to replace the conventional, and costly, welding repair operations for pipelines such as the one repaired in the present study.

Declaration of Competing Interest

Besides the first author's employment relationship as an Equipment Engineer with the Brazilian company Petróleo Brazileiro S.A., the authors declare no conflict of interest.

CRediT author statement

DL da Silva: Conceptualization; Formal Analysis; Writing – original draft. **L Echer:** Conceptualization; Methodology; Supervision; Writing – review. **BN Rojo Tanzi:** Data curation; Software; Formal analysis; Resources. **RJ Marczak:** Methodology; Formal Analysis; Writing – review. **I Iturrioz:** Conceptualization; Resources; Supervision.

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