Fatigue Tests on Buried or Repaired Dented Steel Pipeline Specimens

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Abstract: This paper presents the results of fatigue tests performed on dented steel pipeline specimens that were tested under different environmental conditions and subjected to cyclic internal pressure. Thirty-three pipe specimens were divided into three groups and tested under three different conditions. A first set of nine dented specimens was tested in air without any restrictions. A second set of eight specimens was tested while buried in the soil. A third set of sixteen specimens was tested in air, after the dents had been repaired by composite material sleeves. Hot-spot cyclic strain amplitudes were measured using two experimental techniques: Digital Image Correlation (DIC) and Fiber Optic Bragg Strain Gauges (FBSG). At first, all thirty-three specimens were tested in air along five full cycles in order to carry out full-field measurements using DIC to identify and quantify strain concentration at sites that were potential locations for fatigue cracks to initiate. Close to these point-locations, measurements of strains using FBSG were also made, and the results were then compared with the DIC results. FBSG were also used during the cyclic pressure loading process while the specimens were being tested, in such a way as to monitor the influence of the environment in the dented areas. The test results demonstrated that a simple uniaxial Manson-Coffin fatigue equation that uses the universal exponents proposed by Manson, together with the circumferential strain amplitude measured at the hot spots can be used to predict the fatigue life of the dented specimens. Moreover, it was determined that the measured strains at the hot-spot locations were not influenced by the soil coverage, although showing a considerable and beneficial decrease in their amplitudes caused by the composite repair reinforcements.

Keywords: digital image correlation; Fiber Bragg Strain Gauges; strain analysis; buried pipelines; composite repair; dents

1. Introduction

Pipelines are important structures for transporting and distributing liquid or gaseous products. In the transportation of oils and gases, structural failure concerns the loss of containment, that is, the release of the product transported through the pipe. Releases of a transported product may affect surrounding populations, properties, and the environment, resulting in injury or death as well as material damage to property and to the environment.

The reliable and safe operation is highly dependent on maintaining the structural integrity of the pipeline. Defects that could compromise the safety, can be introduced into the pipeline at any point throughout its life cycle, including the pipe manufacturing process, construction, and operation.

Among the different types of pipeline damage, dents are dangerous yet frequent forms of mechanical damage that are commonly associated with a loss of integrity. A dent is defined as a gross distortion of the pipe cross-section and may be caused by the impact of
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external elements such as construction equipment during the pipeline construction and operation, resulting in severe plastic deformation of the pipe wall.

The presence of a dent causes a local reduction in the diameter of the pipe, and consequently, strain and stress concentrations are introduced. Dents affect the pipeline’s load-bearing capacity and reduce its operating life [1]. The shape of the dent is a very important factor that influences the fatigue life of the pipeline, since fatigue cracks tend to start at points of strain or stress concentration. Consequently, ascertaining the strain distribution induced by the introduction of a dent plays an important role for determining the structural integrity and safety of the pipeline.

The fatigue behavior of pipeline specimens with dents under cyclic internal pressure loading, with and without restriction constraints to free deformation, have been studied by different researchers (e.g., see [1–9]). Although dent depth criteria are the most frequently used in the industry for their ease of application, the determination of cyclic strains operating on the dent hot spots are needed to enhance the accuracy of fatigue life predictions. Moreover, fatigue test results are related to dented specimens tested under internal cyclic pressure loading where the dent areas have no deformation restrictions, such as those imposed by soil contact for buried specimens or by local repair reinforcements.

The present investigation encompassed the fatigue testing of thirty-three full-scale dented steel pipeline specimens divided into three groups. One group comprised nine dented specimens tested in air (no restrictions to the free dent deformation). A second group comprised eight dented specimens tested while buried in soil. The third group was composed of sixteen dented specimens repaired with composite material reinforcement layers that had been tested in air. The aim of this work is to present the results achieved for the group of buried specimens and the group comprising the repaired dents, briefly mentioning the results of the specimens tested in air for comparison purposes.

More explicitly, the paper has the objectives of:

- presenting the fatigue test results of dented specimens under similar conditions to those in-the-air test, with the difference that those tests were fully completed while the specimens were buried, simulating the same conditions as a real buried pipeline;
- presenting the fatigue test results of dented specimens under similar conditions to those in-the-air test, with the difference that those tests were fully completed after the dent area specimens had been repaired, simulating the same conditions as a real repaired pipeline;
- determining circumferential strains operating at the instrumented hot-spot locations in order to establish the soil or repair influences;
- using two experimental techniques—Fiber Optic Bragg Strain Gauges (FBSG) and Digital Image Correlation (DIC)—to determine strains at the hot spots to be combined to a strain-life approach proposed by Manson-Coffin in order to estimate the fatigue lives of the dented specimens.

2. Experimental Campaign

The results achieved for the nine non-buried specimens tested in air conditions were fully analyzed and presented in previous publications (e.g., [10–12]). They were loaded with hydrostatic internal pressure pulsating at a 1 Hz rate. Six specimens had 15% deep longitudinal smooth dents (ratio between dent depth and outside specimen diameter) and three specimens had complex longitudinal 6% deep-dent shapes. Nominal and hot-spot stresses and strains were determined by experimental techniques (Fiber Optic Bragg Strain Gauges—FBSG, and Digital Image Correlation—DIC) and by a numerical technique (Finite Elements—FE). The stresses and strain fields determined from nominal loading conditions or from experimental measurements and from the finite element analyses were combined with different fatigue assessment methods. The estimated lives were compared with the actual test results. The fatigue assessment methods encompassed those proposed by [1] and by the API 579-1/ASME FFS-1 Level 2 et al. [13] methods described in its parts 12 (Dents) and 14 (Fatigue). Most of the predicted lives using these methods exhibited high
level of conservatism. A Level 3 method that employed experimentally and numerically
determined hot-spot strains in conjunction with a fatigue strain-life equation proposed by
Manson-Coffin predicted fatigue lives very close to the test results \[11,12\]. Eight out of
nine test results are reported in Section 3. Those eight specimens were loaded in fatigue
tests with constant pressure amplitude. It is out of the scope of this paper to present results
for the ninth specimen due to the variable pressure amplitude applied. A separate article
presents the results for this specimen \[10\].

The tests carried out with this second group of buried specimens were divided into
two test phases. The first test phase was performed prior to the dented specimens being
buried. During this phase, the specimens were freely placed (not buried) in the laboratory
and loaded with five hydrostatic internal pressure cycles so that hot-spot cyclic strain
amplitudes in the dent area and at nominal locations could be measured by using DIC and
FBSG. The full-field measurements were taken using DIC to identify strain concentration
sites that could be potential locations or hot spots for fatigue cracks to start to form. Fiber
Optic Strain Gauges were bonded close to these point-locations and the resultant strain
measurements were compared with the DIC results. The second test phase encompassed
long-life fatigue tests. For these tests, the specimens were buried and cyclic pressure-
loaded. The fiber gauges were used to measure the hot-spot strains and to monitor any
possible influence that could be caused by the soil coverage restricting the free deformation
occurring in the dented areas. The results obtained for the buried specimens have also
been analyzed and presented in a previous publication (e.g., \[14\]).

For the third group of specimens, the tests performed in the present investigation
used composite material repairs applied by three different suppliers. The repair systems
were composed by epoxy or polyurethane matrices reinforced with carbon or glass fibers.
The composite repairs are referred here as Supplier 1 and Supplier 2 for fiberglass repairs
and Supplier 3 for carbon fiber repairs.

Similar to the tests of the buried specimens, the tests with the repaired specimens
were performed in two phases. The first phase had been performed prior to repairing the
dents specimens. They consisted of loading the specimens with five hydrostatic internal
pressure cycles so that hot-spot cyclic strain amplitudes in the dent area could be measured
by the DIC and FBSG techniques simultaneously. In the second phase, the specimens were
repaired with the composite material sleeves and then cyclic pressurized. During this test
phase only the optical fiber gauges bonded to the hot-spot sites were used to determine the
strains operating.

All 3 m long pipeline test specimens (324 mm external diameter and 6.35 mm thickness)
were cut from the same batch of 12 m long API-5L grade B ERW carbon steel pipes.
The pipe mechanical material properties such as the specified nominal minimum yield
and the ultimate material strengths were, respectively, equal to SMYS = 245 MPa and
SMUS = 415 MPa. The actual engineering yield and ultimate material strengths were
measured as being \(S_{ye} = 316 \text{ MPa}\) and \(S_{ue} = 420 \text{ MPa}\), respectively. The true ultimate
material strength was determined to be \(S_u = 500 \text{ MPa}\).

The dents were generated using forceful contact by an indenter element on the exter-
nal wall of the pipe in a 500 kN servo-hydraulic test machine, causing a 46% ratio (dent
depth/pipe external diameter) change in diameter after the indenter was removed. Next,
64-mm thick plain head plates were welded to the pipe specimens and these were hydro-
statically pressurized to produce a partial dent recovery. The applied re-round pressure
was calculated to produce a nominal circumferential stress equal to 0.68 SMYS, which is
equivalent to an internal pressure equal to 6.5 MPa. The re-round pressure forced a partial
dent recovery so that the final dent depth ratio became 15%. Details of the indentation tests
and hydrostatic recovery tests are presented in \[12\].

DIC is currently the most popular and effective optical technique used in experimental
mechanics to measure displacement and strain distribution on the surface of stressed
components \[15\]. The DIC technique is a well-established method for measuring in-plane
displacements and strains by using tracking and image registration techniques. DIC
analysis provides full-field strain distributions to characterize the mechanical behavior and to identify any critical points on the structure. In essence, the DIC technique compares (or correlates) digital images of the material’s surface between its non-deformed and deformed state. Generally, the image acquired in the unloaded stage is called the reference image. The specimens’ dented areas were prepared according to DIC standard requirements [16]. To do so, the area of interest was first coated with a thin layer of a black paint, and then white dots were added manually, as shown in Figure 1.

![Figure 1. Speckle pattern on specimen surface as required for DIC analysis.](image)

The DIC experimental test setup consisted of a stereoscopic vision system composed of two 5 megapixel CCD cameras GRAS-50S5M Point Grey (FLIR-Grasshopper, Wilsonville, OR, USA) mounted on a tripod. The cameras were fitted with adjustable focal length lenses A031 AF28-200 mm F/3.8-5.6 (Tamron, Saitama, Japan). A lighting system was used in order to obtain homogeneous illumination in the region of the specimen to be analyzed. Before testing, the stereoscopic system was calibrated to allow for 3D-DIC analysis in order to retrieve three-dimensional strains and displacements on the surface of the dented pipe. The 3D-DIC system used in this study was the commercially available VIC-3D model developed by Correlated Solutions et al. [17]. The experimental tests were carried out in the laboratory prepared for such tests in the facilities of the CTDUT (Center of Technology in Pipelines). The experimental setup is shown in Figure 2.

Fiber Optic Bragg Strain Gauge sensors were bonded to the hot-spot locations at the specimens’ dented external surfaces to collect strain information during testing. Based on findings presented by [9,12], the circumferential strains are considerably higher compared to longitudinal strains, and the circumferential strain range was assumed to be representative of the specimen’s fatigue behavior. Moreover, in most cases the longitudinal strains showed negligible or even small compressive magnitudes when the hot spots were loaded under elastic-plastic conditions, due to the need for constant volume plasticity deformation [12]. Thus, the FBSSGs were placed at the edges of the dents in the circumferential direction, which present the highest tensile strains.

A cyanoacrylate-based adhesive was used. Each fiber DTG-LBL-1550-F Ormocer coating (Fiber Bragg Gauge Sensors FBGS©) contained two Bragg grating sensors (placed 80 mm from each other) with gauge length equal to 8 mm and distinct wavelengths (1514 nm and 1524 nm) allowing for multiplexing the strain signal. The fiber optic conditioning equipment si255-16-ST/160 (Micron Optic, Atlanta, GA, USA) operated with two channels at an acquisition frequency equal to 1000 Hz. Figure 3 depicts two fibers with four gauges mounted along the circumferential direction in the dent region of a tested specimen. The Bragg sensors are highlighted by circles in Figure 3.
The maximum pressure during all the preliminary in-lab cycles applied before the specimens was buried or repaired and, subsequently, the fatigue loading cycles, were limited to 6.2 MPa, generating a maximum nominal circumferential stress equal to 0.65 SMYS. This limited maximum test pressure is lower than the applied re-round internal pressure, which prevents any extra and undesirable dent depth recovery during the cyclic tests. The water-hydrostatic pressure cycles imposed on the test specimens were applied sinusoidally and at a frequency of approximately 1 Hz, using a specially designed cylinder-piston device that was coupled to the hydraulic actuator of a servo-hydraulic 500 kN MTS testing machine [12]. This set-up is depicted in the right image of Figure 2. Each specimen was subjected to a specific pressure ratio: more information is presented in Table 1 (Section 4). For the second group of specimens, after completion of the in-lab (in-air) tests, the pipe specimens were buried in the ground. The specimens were installed in trenches dug in an earth fill. The ditch depth was 1.20 m. The fill was built using residual soil from gneiss that was excavated and transported from a burrowed site nearby. The residual soil is composed mainly of silt and sand fractions with less than 15% of clay, and consists of quartz, feldspar, and kaolinite. The stages of this process, as shown in Figure 4, consisted of digging the ditch, preparing the washed sand cradle, positioning the specimens in the
ditch, and covering them with the selected material. Compacting the soil cover was carried out during the covering in stages of about 200 mm depths.

Figure 4. Stages of burying the specimens in the ground: (a) digging the ditch, (b) positioning the specimens in the ditch, (c) covering them with the selected material, (d) specimen buried in the ground.

As with the buried specimens, the dents of the third group of specimens were first tested in air without any kind of restriction. After completing this phase, the dents’ repair process began. The repair application process for the three different suppliers is similar. They start with surface preparation for the repair application, and then the dent is filled with epoxy resin until the kneaded portion of the pipe is leveled with the other regions. From then on, layer by layer of composite material is added until the thickness previously designed by the supplier is reached.

The estimations of the thickness of the repair and its application process to each dent were carried out by the suppliers, who followed criteria established by their own procedures and by the ISO 24817 and ASME PCC-2 standards, with the dents considered defects that do not go through the pipe wall. The repair process conducted by Supplier 3 is shown in Figure 5.
The first five buried and repaired pressure cyclic tests were carried out with the same pressure range (6.0 MPa) employed during the in-lab tests. In sequence to these preliminary cycles, pressure ranges equal to 2.0, 3.0, 4.0, and 6.0 MPa, as given in Table 1, were applied to the specimens up to their fatigue failures.

3. Results

Two sets of illustrative results are presented in this section. The first set concerns preliminary results for the in-lab tests that were performed with the objective of recording dent deformed shapes and full-field strain distributions using DIC, as well as hot-spot strains, measured using the fiber optic strain gauges. These first-set results entail data gathered during ten pressurization cycles. The second set of results corresponds to the pressurization cycles performed while the specimens were buried or repaired. In this case, although not for all specimens, only the hot-spot circumferential strains were measured using the fiber optic strain gauges. Moreover, blocks of hot-spot strain measurements and the full number of pressurization cycles were acquired throughout the duration of the fatigue tests. The end of each test was indicated when it became impossible to increase the pressure due to a full crack having resulted, plus the consequent loss of containment.

3.1. In-Lab Tests

Performing the 3D-DIC analysis enabled the determination of the shape of the dent area by using the first pair of (stereo) images captured while the dented pipe specimen was unloaded. Figures 6 and 7 show the 3D shape of the dent areas of two specimens here named Specimen #20 (buried) and Specimen #29 (repaired). It is important to note that these actual deformed shape measurements can be exported to the Solid Models and Finite Element software programs to perform numerical elastic or elastoplastic stress analyses in order to assess the static and cyclic integrity of the pipeline with dents, as described in [9–12], for example.
The dented specimens #20 and #29 depicted in this section were subjected to internal pressure cycles with maximum pressure of 6.2 MPa, equivalent to a maximum 0.65 SMYS nominal circumferential strain. The minimum cyclic test pressure was 0.2 MPa. The pressurization ratio is equal to $R(P_{\text{min}}/P_{\text{max}})$, which is equal to approximately 0.03. For the first 10 cycles, while in-lab, the internal pressure was increased and decreased in small increments so that the DIC images could be captured at each load step and analyzed with reference to the images captured during the unloaded state. All the images were analyzed by the VIC-3D software using the normalized-sum-of-squared differences (NSSD) function as the correlation criterion, a subset size of 35 pixels, a step size of 8 pixels, and a strain window of 15 displacement points. In this analysis, the uncertainty in the strain measurement was approximately $\pm 0.014\%$. Figures 8 and 9 show the full distribution of circumferential strain distributions at maximum pressure after 10 cycles were applied to the pipes. One can see that the maximum strains in both specimens occurred on both sides of the rim formed by the indenter while the valley remains in a practically unloaded or lightly loaded state. Although both dented pipes were very similar, small differences in the geometry can be observed, and consequently, in the strain distributions when the pipes were loaded under the same pressure conditions. A more detailed inspection of the geometry of the dents and their most-strained points was performed by using a line inspection (VIC-3D command) along the area of interest, as presented in Figures 10 and 11.

The DIC analysis also indicated the full-field strain behavior during the cyclic pressurization for all points visualized in the area of inspection. Results for the most-strained points given in Figures 8 and 9 above are given herein. Figures 12 and 13 depict the curve pressure vs. the circumferential strain at these points for the two specimens. From the curves, one can clearly see that there is a progressive (but decreasing) plastic deformation accumulating cycle by cycle. For Specimen #20, the critical point was located on the left side of the rim. Strains were slightly higher than the one located on the right side. Thus, a crack is most likely to start at this critical point. For the case of Specimen #29, after 10 cycles...
of observation, both critical points showed similar behavior. This DIC-acquired strain information was also verified by the optical fiber Bragg strain gauge sensor readings, as shown in Figures 12 and 13. These optical strain gauge sensors were bonded to locations close to the anticipated critical points, identified by DIC analysis performed during previous tests carried out to find the critical points on the specimens quickly. One can see that the resultant measurements agreed well with those obtained using the DIC analysis.

Figure 8. Strain distribution in the y-direction (circumferential) at 6.2 MPa obtained with DIC analysis for Specimen #20.

Figure 9. Strain distribution in the y-direction (circumferential) at 6.2 MPa obtained with DIC analysis for Specimen #29.

Figure 10. Specimen #20 data obtained from DIC analysis after the first pressure cycle: (a) shape of the dent; (b) strain distribution along a longitudinal line.
3.2. Buried and Repaired Tests

After the specimens were buried or repaired, they were first loaded during five cycles with the same pressure ranges used in the in-lab tests. Strains at the hot spots operating...
in the case of specimens #20 and #29 are presented in Figures 12 and 13 for the in-lab and buried or repaired tests. Only three cycles were plotted for clarity purposes. One can see that the influence of the soil restraint on the deformation of the dent area is minor by comparing the circumferential strains operating at the hot-spot locations under the in-lab and buried conditions. On the other hand, it is possible to see a clear influence of the repair on the deformation of the dent area, by comparing the circumferential strains at the hot spot before and after the execution of repair. Relief in the circumferential strain levels is evident. Quantitative strain measurements for these conditions are given in Table 1 for these two specimens and for others where those measurements were carried out.

4. Discussion

The test results for the buried and repaired specimens are presented in Table 1, which show that the DIC and FBSG-measured strain ranges agreed satisfactorily if uncertainties of both methods are taken into consideration: (+0.014% DIC and +0.010% FBSG). This observation is also valid for non-buried specimens. Cases not reported in this table refer to specimens where instrumented points with the fiber optic strain gauges did not coincide with the hot-spot locations indicated by the DIC technique.

An important point to notice refers to the influence of the soil cover and its possible restraint effect on the strain ranges induced by the test pressure. Figure 12 and Table 1 show that measured strains by the FBSG gauges before and after burying the pipe specimens present negligible differences helping to draw the conclusion that the soil cover did not restrain the deformation of the dent induced by the pressure variation.

In contrast to the last paragraph observations, the influence of the composite repair on decreasing the strains operating in the same point and measured with the same strain gauge was highly relevant, as shown by Figure 13 and also Table 1. Columns three and four of Table 1 show the ratio between strains measured before and after the application of the composite repairs when the specimens were loaded to the same applied cyclic pressure. The influence of the smaller applied strains on the longer fatigue lives is also noticed by examining the last two columns of Table 1.

Based on the relationship between the results obtained for FBSG in each of the specimens studied (environmental conditions–buried or repaired), it was possible to estimate the potential circumferential strain at the hot spot that would be measured by the DIC technique (Column six of Table 1). A linear extrapolation that considered the effects of test-pressure ranges was used.

Using the strain ranges estimated for the DIC technique at the hot spots for the burial or repair conditions as inputs, fatigue damage calculations were performed using the Manson-Coffin Equation (1) as described in (e.g., [18]) to determine the fatigue life \( N_c \) as a function of the applied (measured) circumferential strain amplitude \( \varepsilon_a = \Delta \varepsilon / 2 \) (results of strains equation given in terms of m/m).

The formula used for calculating the fatigue damage is given in Equation (1), which uses the universal fatigue exponents \(-0.12\) and \(-0.6\), as proposed by Manson [18], and the measured mechanical properties of the employed material (Young Modulus \( E = 182 \) GPa, engineering ultimate strength \( S_u = 420 \) MPa and fatigue strain coefficient \( \varepsilon_f = 0.36 \) m/m). One can see that the calculations did not take into consideration the mean cycle stress \( (\sigma_m = 0) \). One reason for this is that, although the mean stress caused by the pressure operating can be determined, the total mean stress is unknown due to the uncertain previous load history imposed on the pipe material (such as residual stresses caused by the pipe’s fabrication and the indentation processes).

\[
\varepsilon_a = \left( 3.5 \frac{S_u - \sigma_m}{E} (N_c)^{-0.12} + \varepsilon_f (N_c)^{-0.6} \right)^{1/2}
\]

Table 1 (strains given in %) shows the fatigue damage calculations for all tested specimens and the experimental results from the fatigue tests. It is important to compare the results presented in the last two columns. One can see that the fatigue lives (number
of cycles), predicted by the Manson-Coffin Equation (1), and the actual lives, determined via the tests, agree satisfactorily, considering all the uncertainties associated with fatigue calculations and experimental fatigue tests.

Moreover, Table 1 gives fatigue test results for eight out of nine other but similar specimens that were tested in air (not buried specimens and not repaired) and previously published [11,12].

The determined lives for all specimens tested agree well with the curve proposed by Equation (1), this agreement being depicted by the plotted points in Figure 14. One can see that the set of results falls within the given Manson-Coffin fatigue curve without the mean stress presented in Equation (1). This comparison justifies the use of the same curve to represent the fatigue behavior of repaired, buried, and unmodified (unburied and unrepaired) specimens, on the assumption that actual operating strains are used in the plot.

![Figure 14. Comparison between buried and repaired tests results and the in-air specimens tested by [11].](image)

Furthermore, the repair effectiveness on the fatigue life of dented specimens can be verified by comparing the applied cyclic-pressure ranges and the lives obtained for both repaired and unrepaired (both air and buried tested) specimens, Figure 15. The higher dispersion of results is caused by neglecting differences in the dent shapes (although nominally the dents had the same depth relative to the specimens’ diameters) and different reinforcement supplier systems.

![Figure 15. Comparison between repaired and unrepaired tests results.](image)
Table 1. Experimental results.

| Specimen ID and Test Conditions | Cyclic Test Pressure (MPa) | Measured Circumferential Strain Amplitude at Hot-Spot Location, $\varepsilon_a$ (%) | Test Condition Influence Factor (DIC in Air/DIC after Burying or Repairing) | Number of Cycles to Failure Using Equation (1) and Column 6 Strains, $N_{cr}$, $S_{cr} = 420$ MPa, $E = 182$ GPa | Number of Applied Test Cycles until Failure, $N$ |
|---------------------------------|---------------------------|---------------------------------------------------------------------------------|------------------------------------------------------------------|---------------------------------------------------------------------------------|-------------------------------------|
| 1-air                            | 4.0                       | 0.19                                                                            | 1                                                                | 21,543                                                                           | 38,300                              |
| 2-air                            | 6.0                       | 0.25                                                                            | 1                                                                | 9032                                                                             | 7990                                |
| 4-air                            | 4.0                       | 0.50                                                                            | 1                                                                | 1531                                                                             | 2100                                |
| 5-air                            | 3.0                       | 0.16                                                                            | 1                                                                | 40,162                                                                           | 220,000                             |
| 6-air                            | 6.0                       | 0.35                                                                            | 1                                                                | 3606                                                                             | 6500 \(^5\)                        |
| 7-air                            | 4.0                       | 0.22                                                                            | 1                                                                | 13,319                                                                           | 34,400                              |
| 8-air                            | 3.0                       | 0.15                                                                            | 1                                                                | 51,754                                                                           | 53,300                              |
| 9-air                            | 4.0                       | 0.20                                                                            | 1                                                                | 18,121                                                                           | 38,900                              |
| 11-buried                        | 4.0                       | 0.24                                                                            | 0.19 $^{3}$                                                     | $^{1}$ $^{=1.0}$ $^{8691}$                                                     | 26,800                              |
| 12-buried                        | 4.0                       | 0.22                                                                            | 0.17 $^{3}$                                                     | $^{1}$ $^{=1.0}$ $^{15,982}$                                                   | 21,700                              |
| 13-buried                        | 2.0                       | 0.10                                                                            | 0.17 $^{4}$                                                     | $^{0.10}$ $^{=1.0}$ $^{351,085}$                                              | 905,500                             |
| 15-buried                        | 2.0                       | 0.09                                                                            | 0.21 $^{4}$                                                     | $^{0.09}$ $^{=1.0}$ $^{643,306}$                                              | 130,200                             |
| 17-buried                        | 4.0                       | 0.20                                                                            | 0.23 $^{3}$                                                     | $^{1}=1.0$ $^{10,823}$                                                        | 21,900                              |
| 20-buried                        | 6.0                       | 0.33                                                                            | 0.32 $^{3}$                                                     | $^{1}=1.0$ $^{4548}$                                                          | 4610                                |
| 21-buried                        | 6.0                       | 0.33                                                                            | 0.29 $^{3}$                                                     | $^{1}=1.0$ $^{5447}$                                                          | 5970                                |
| 10-repaired (Supplier 1)         | 3.0                       | 0.12                                                                            | 0.06 $^{3}$                                                     | $^{1}=1.0$ $^{172,097}$                                                       | 437,980                             |
| 14-repaired (Supplier 2)         | 6.0                       | 0.27                                                                            | 0.11 $^{3}$                                                     | $^{1}=0.6$ $^{53,896}$                                                        | 123,550                             |
| 16-repaired (Supplier 2)         | 6.0                       | 0.27                                                                            | 0.15 $^{3}$                                                     | $^{1}=0.7$ $^{24,028}$                                                        | 18,050                              |
| 19-repaired (Supplier 1)         | 4.0                       | 0.16                                                                            | 0.09 $^{3}$                                                     | $^{1}=0.6$ $^{634,833}$                                                       | 592,510                             |
| 23-repaired (Supplier 3)         | 4.0                       | 0.16                                                                            | 0.03 $^{3}$                                                     | $^{1}=0.33$ $^{3.46 \times 10^7}$                                             | $^{3}=5970$                         |
| 24-repaired (Supplier 3)         | 6.0                       | 0.30                                                                            | 0.20 $^{3}$                                                     | $^{1}=0.25$ $^{9031}$                                                        | 19,350                              |
| 25-repaired (Supplier 2)         | 6.0                       | 0.29                                                                            | 0.09 $^{3}$                                                     | $^{1}=0.14$ $^{64,998}$                                                       | 141,750                             |
| 26-repaired (Supplier 3)\(^6\)  | 7.0                       | 0.28                                                                            | 0.05 $^{3}$                                                     | $^{1}=0.05$ $^{3.52 \times 10^7}$                                             | 130,030                             |
| 27-repaired (Supplier 2)         | 3.0                       | 0.13                                                                            | 0.04 $^{3}$                                                     | $^{1}=0.07$ $^{2.6 \times 10^6}$                                              | $^{3}=155,000$                      |
| 28-repaired (Supplier 3)         | 6.0                       | 0.27                                                                            | 0.06 $^{3}$                                                     | $^{1}=0.07$ $^{3.3 \times 10^7}$                                              | 155,000                             |
| 29-repaired (Supplier 3)         | 6.0                       | 0.29                                                                            | 0.06 $^{3}$                                                     | $^{1}=0.07$ $^{5.3 \times 10^6}$                                              | 53,910                              |
| 30-repaired (Supplier 2)         | 6.0                       | 0.29                                                                            | 0.03 $^{3}$                                                     | $^{1}=0.04$ $^{3.98 \times 10^6}$                                             | $^{3}=525,240$                      |
| 31-repaired (Supplier 1)         | 6.0                       | 0.30                                                                            | 0.11 $^{3}$                                                     | $^{1}=0.17$ $^{29,556}$                                                       | 62,200                              |
| 32-repaired (Supplier 3)         | 3.0                       | 0.10                                                                            | 0.02 $^{3}$                                                     | $^{1}=0.03$ $^{2.6 \times 10^6}$                                              | $^{3}=35,900$                       |
| 34-repaired (Supplier 2)         | 6.0                       | 0.29                                                                            | 0.12 $^{3}$                                                     | $^{1}=0.07$ $^{35169}$                                                        | 35,900                              |
| 35-repaired (Supplier 1)\(^8\)  | 7.0                       | 0.29                                                                            | 0.03 $^{3}$                                                     | $^{1}=0.03$ $^{9.29 \times 10^5}$                                             | $^{3}=525,240$                      |

\(^1\) Specimen tested only in air (not buried or not repaired). \(^2\) Results of specimen #3 (see reference [10]) and specimen #18 not presented due to tests carried out under different conditions. \(^3\) Not measured at the same site area where DIC showed the maximum strain, see reference [12]. \(^4\) Test not monitored when buried, DIC data for the buried condition as assumed equal to the in-air test based on observations. \(^5\) Test interrupted without leakage after more than 10\(^9\) cycles. \(^6\) Test pressure range of the preliminary in-air test (6.0 MPa) was different from the pressure range of the actual cyclic test (7.0 MPa). \(^7\) The results of DIC for the hot spot after burying or repairing were extrapolated based on the relationship between the results obtained for FBSG in each of the studied conditions. \(^8\) The crack was detected with 4270 cycles, but the specimen leaked with 6500 cycles.
5. Conclusions

The main objective of this research was to analyze the fatigue behavior of steel pipeline specimens containing dent defects under different environmental test conditions. For that, a broad experimental investigation with real scale specimens was conducted. This paper shows that two experimental techniques (Digital Image Correlation (DIC) and Fiber Optic Bragg Strain Gauges (FBSG)) can be successfully applied to accurately determine strain distributions and to locate hot spots in dented pipeline specimens subjected to fatigue damage caused by the application of pressurized cycles.

Based on the obtained results the following conclusions can be made:

• The 3-D DIC technique helped instrumenting the hot-spot sites providing the full-field strain distributions of the dented area. In addition, the DIC technique helped to determine the hot-spot positions near to which fiber optic gauges were bonded;
• The strains measured using the fiber optic gauges showed that the deformations operating in the dented area of buried specimens did not suffer influence from the soil coverage;
• The strains measured using the FBSG after the composite repairs were performed showed a considerable influence of the repairs in decreasing the circumferential strains operating on the same specimen hot spot and at the same applied cyclic pressure, proving the effectiveness of the repair systems used;
• The fatigue life of the dent specimens under different environmental conditions can be accurately predicted with a simple Manson-Coffin equation that uses the actual material mechanical properties and the actual hot-spot measured circumferential strain amplitudes.

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References

1. Cosham, A.; Hopkins, P. The effect of dents in pipelines—Guidance in the pipeline defect assessment manual. Int. J. Press. Vessel. Pip. 2004, 81, 127–139. [CrossRef]
2. Bolton, B.; Semiga, V.; Dinovitzer, A.; Tiku, S.; Alexander, C. Towards a Validated Pipeline Dent Integrity Assessment Model. IPC2008-64621. In Proceedings of the 7th International Pipeline Conference, Calgary, AB, Canada, 29 September–3 October 2008.
3. Bolton, B.; Semiga, V.; Tiku, S.; Dinovitzer Zhou, J. Full Scale Cyclic Fatigue Testing of Dented Pipelines and Development of a Validated Dented Pipe Finite Element Model. IPC2010-31579. In Proceedings of the 8th International Pipeline Conference, Calgary, AB, Canada, 27 September–1 October 2010.
4. Pinheiro, B.C.; Pasqualino, I.P. Fatigue Analysis of Damaged Steel Pipelines under Cyclic Internal Pressure. Int. J. Fatigue 2009, 31, 962–973. [CrossRef]
5. Rosenfeld, M.J.; Pepper, J.W.; Leewis, K. Basis of the New Criteria in ASME B31.8 for Prioritization and Repair of Mechanical Damage. IPC2002-27122. In Proceedings of the 4th International Pipeline Conference, Calgary, AB, Canada, 29 September–3 October 2002.
6. Fowler, J.R. Criteria for dent acceptability in offshore pipeline. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 3 May 1993.
7. Akbaria, R.; Jafari, S.; Hosseinipour, S.J. Load Bearing Capacity of a Dented Aluminum Pipe Subjected to Internal Pressure Considering the Effect of Ductile Damage. Lat. Am. J. Solids Struct. 2015, 12, 355–384. [CrossRef]
8. Garbatov, Y.; Soares, C.G. Fatigue reliability of dented pipeline based on limited experimental data. *Int. J. Press. Vessel. Pip.* 2017, 155, 15–26. [CrossRef]

9. Paiva, V.E.L.; Gonzáles, G.L.G.; Vieira, R.D.; Maneschy, J.E.; Vieira, R.B.; Freire, J.L.F. Fatigue Monitoring of a Dented Piping Specimen Using Infrared Thermography. In Proceedings of the ASME 2018 Pressure Vessels and Piping Conference, American Society of Mechanical Engineers, Prague, Czech Republic, 16–18 July 2018.

10. Freire, J.L.F.; Paiva, V.E.L.; Gonzáles, G.L.G.; Vieira, R.D.; Maneschy, J.E.; D’Almeida, A.L.F.S.; Ribeiro, A.S. Fatigue Assessment and Monitoring of a Dented Pipeline Specimen. In Proceedings of the ASME 2019 Pressure Vessels and Piping Conference, American Society of Mechanical Engineers, San Antonio, TX, USA, 14–19 July 2019.

11. Freire, J.L.F.; Paiva, V.E.L.; Gonzáles, G.L.G.; Vieira, R.D.; Maneschy, J.E.; D’Almeida, A.L.F.S. Fatigue assessment of dented pipeline specimens. In Proceedings of the ASME 2020 Pressure Vessels and Piping Conference, American Society of Mechanical Engineers, On-Line Virtual Conference, 3 August 2020.

12. Paiva, V.E.L. Modern Experimental Techniques with an Emphasis on Infrared Thermography to the Assessment of Fatigue Components with Dents. Ph.D. Thesis, Mechanical Engineering Department, Pontifical Catholic University of Rio de Janeiro, PUC-Rio, Rio de Janeiro, RJ, Brazil, 2020.

13. *API 579-1/ASME FFS-1 Fitness-for-Service*; American Society of Mechanical Engineers: Washington, DC, USA, 2016.

14. Paiva, V.E.L.; Gonzáles, G.L.G.; Vieira, R.D.; Ribeiro, A.S.; D’Almeida, A.L.; Freire, J.L.F. Fatigue of buried dented pipeline specimens. *Procedia Struct. Integr.* 2021, 33, 59–170. [CrossRef]

15. Sutton, M.A.; Orteu, J.J.; Schreier, H. *Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts, Theory and Applications*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2009.

16. Jones, E.; Iadicola, M.A. *Good Practices Guide for Digital Image Correlation*; International Digital Image Correlation Society: Hangzhou, China, 2018.

17. Correlated Solutions Inc. VIC-3D v.8. Available online: [http://www.correlatedsolutions.com/](http://www.correlatedsolutions.com/) (accessed on 11 June 2019).

18. Castro, J.T.P.; Meggiolaro, M.A. *Fatigue Design Techniques, Volume 1: High-Cycle Fatigue*; CreateSpace: Scotts Valley, CA, USA, 2016.