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Influence of old rectangular repair patches on the burst pressure of a gas pipeline

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Abstract

Seven full scale hydrostatic burst tests were carried out on pipes extracted from an API 5LX52 gas pipeline that contained rectangular and elliptical fillet welded patches and other repairs of different geometries. All breaks took place after widespread yielding. This analysis shows that the patches that generate greater risks are those that: (1) were attached to the pipeline at very low pressure, (2) were placed to repair large defects, (3) are rectangular, long in the direction of the pipe, and narrow, (4) the quality of the weld is doubtful. Based on data reported by In Line Inspection (ILI), of the four conditions mentioned above, only the third can be assessed in order to quantify risks and to schedule replacements.
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Keywords: Pipelines; Repair patches; Reliability; Burst pressure tests

1. Introduction

The burst of a 24 in. gas pipeline, which occurred at the beginning of 2002, was initiated by a fillet welded rectangular repair patch, see Fig. 1(a) [1]. The burst was caused by the propagation of two consecutive longitudinal fractures, with a total length of 12 m, separated by two sleeve reinforcements that did not fracture. Crack initiation was related to lamellar tearing at the toe of the longitudinal weld, as shown in the cross-sections of Fig. 1(b) (×10) and Fig. 2 (×100). The patch was covering a large microbiologically induced corrosion defect, with a depth of 81% of the wall thickness, located in the bottom part of the pipe. The installation date of the repair is not known. Failure occurred at a pressure of 5.6 MPa, 6% less than the maximum allowable pressure for this line (6.0 MPa).

This failure was clearly related to inadequate design and installation of the repair, the fillet weld was of very poor quality, with severe undercuts. This is not the only patch welded to this particular gas pipeline. Fillet welded patches were widely used in gas and oil pipelines for many years, and several have been found responsible for pipeline failures [2–5]. The most common problems associated with these failures are:

- Very poor through the thickness strength of the old pipe materials, due to severe microstructural banding, high impurity levels and sometimes also lamination defects from aligned non-metallic inclusions (Fig. 2)
- High through-thickness stresses at the toes of the longitudinal patch to pipe fillet welds.
- Welding defects, mostly undercuts and lacks of fusion.

The poor reliability of these repair patches has long been realized, and new repair procedures have been developed [6–8]. Modern repair procedures rely on good control of welding variables, and on avoiding the creation of longitudinal discontinuities in the pipe surface. Although not completely eliminated, failures due to incorrect repairs have been markedly reduced. The mechanical interactions between pipe and repair materials are now better known, and new methodologies are continuously been introduced to ensure reliability of the repairs [9–11].

However, pipeline operators still have to deal with many repairs of which little are known. In Line Inspection (ILI) techniques are used to detect and rank the criticality of defects and previous repairs. In assessing the reliability of old pipelines it is necessary to evaluate whether the condition of these repair patches is critical, to define the probability of failures, and when the probability is high, to define and schedule future preventive and corrective actions.

The objective of this study is to determine the effect that rectangular or elliptical fillet welded patches and other repairs have on the pressure capacity of a gas pipeline and the

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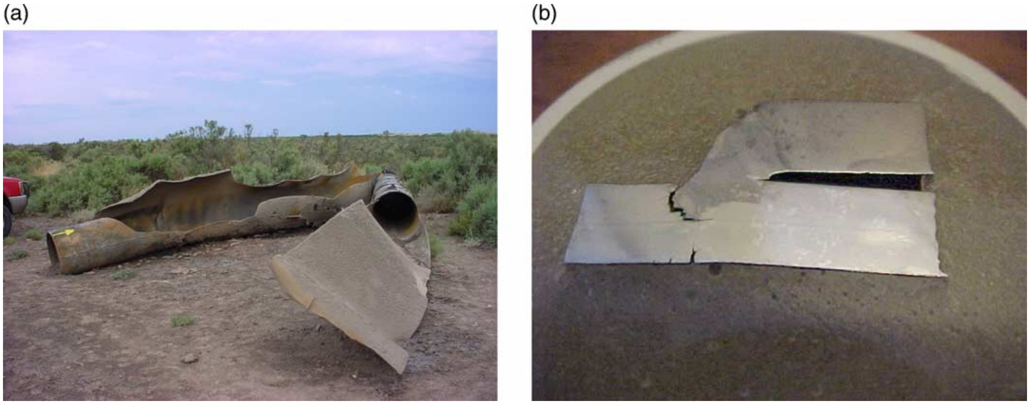

Fig. 1. (a) Burst of a 24 in. gas pipeline, started by a rectangular repair patch. (b) (×10) Secondary crack initiated at the weld toe of the failed repair patch.

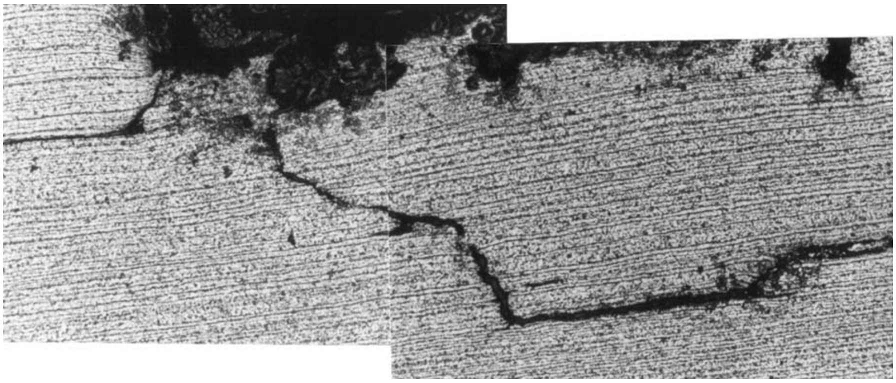

Fig. 2. (×100) Stepped cracks at weld toes follow microstructural banding.

reliability of the affected sections, with the objective of collaborating in the definition of criteria for admissibility and repair of surface volumetric defects. Field and evaluation activities were carried out with the objective of defining critical levels of discontinuities that could be associated with fillet welded patch repairs. These repairs involve welds that are longitudinal to the pipe, for which they generate high stress concentrations in the circumferential direction, which is the highest stressed direction under normal operation.

2. Burst tests by hydrostatic pressure

Seven full scale tests were carried out on ex-service tracts removed from a buried API 5LX52, 24 in. diameter, 7.15 mm thick, double submerged arc (DSAW) seam welded gas pipeline. These tracts dated from the early 1960s, and contained patches of different shapes [12,13]. These tracts were between 4 and 12 m long, and were all removed from a pipe section following an In Line Inspection program. All tracts in the section with indications of repair patches were removed and hydrostatic burst tested. The highest historical service pressure of the pipes tested was around 6 MPa.

Table 1 summarizes geometrical and operational data of the seven tests. Defined in the table are the characteristics of the analyzed repairs, burst pressures, and the type and place of initiation of the fractures. API 5LX52 pipes tested have a yield stress of 393 MPa, an ultimate tensile strength (UTS) of 569 MPa, and a ductility (elongation to fracture) of 28%.

The pipes identified as 3, 5, 6 and 7 had rectangular repair patches. Pipes 1, 2, and 4 had circular repair patches. In six cases, the testing led to fracture of the pipe and a consequent pressure fall, see Table 1. In the remaining case the test was interrupted when a pressure of almost 14 MPa was reached, and the pipe was enduring large plastic deformations.

Three more repairs were present in the tested tracts. Two of them are type B full scale sleeve reinforcements, that is, repairs made with two semi-circular sleeves fillet welded longitudinally to an intermediate strip, and circumferentially to the pipe at each end. These repairs were less than 500 mm long, about half the minimum recommended to maintain the longitudinal stress due to shrinkage of the circumferential welds below an acceptable limit [10].

The third repair was done during the tests. It consisted of gouging a volumetric artificial 4 mm deep, 100 mm long and 80 mm wide defect, that was then weld filled using a manual AWS E8018, 3.2 mm electrode. Straight weld beads were made, to reduce the negative effects of excessive heat input and large stresses due to weld metal shrinkage. The welded area was then ground flat to the pipe surface level.

The pipes were instrumented with strain gauges. Between 3 and 4 strain gauges were placed in each test, in places inside or close to the repairs, according to the characteristics of the repair and the estimated place of fracture initiation. Fig. 3

Table 1
Geometry of repair patches and results of hydrostatic burst tests

Pipe	Length (m)	Repair dimensions (mm): Φ=diameter, L=length, C=width, E=thickness	Rupture pressure (kg/cm^2)	Type and place of rupture initiation
1	12	Two separate repairs: A: type B sleeve repair, $L=400$; B: round patch, $\Phi=310$	121	Short 25 mm crack, from indentation by steel wire
2	10.5	Two separate repairs: A: round patch, $\Phi=400$ mm; B: weld repaired artificial defect, depth=4, $L=105$, $C=80$	139	Ended by safety due to high pressure and pipe length, after large plastic deformations
3	7.5	Square patch, $L=120$, $C=140$	118	Fracture from corrosion defect, near the extreme of the patch
4	11	Two separate repairs: A: round patch, $\Phi=270$; B: type B sleeve repair, $L=490$	132	Fracture from small corrosion defect, 500 mm from the patch
5	4.5	Two rectangular patches: A: $L=750$, $C=465$; B: $L=200$, $C=200$	124	Fracture from small corrosion defect, 180° from the patches
6	7.5	Rectangular patch, 40 mm from seam weld, $L=590$, $C=200$	125	Fracture at toe of patch weld, initiations at corner and centre, 2 m long fracture
7	10	Square patch, $L=150$, $C=150$	121	Fracture at header of same thickness as pipe

shows as an example of the two repairs located in pipe 1: a circular patch (repair 1A) and a very short full encirclement sleeve reinforcement (repair 1B), separated by 45 cm. Fig. 3 also shows the location of the strain gauges in both repairs, before being wired and instrumented. Fig. 4 shows as an example the results of the test of pipe 5. Plots of pressure versus strain at measurement points are shown.

Residual stresses were measured in the rectangular patch placed in pipe 6. Due to its geometry, this patch is the most similar to the one that produced the in-service fracture in 2002. After a longitudinal 2 mm deep groove was cut on the patch surface, a relaxation of 69 microstrain (10^{-6} m/m) was measured. When the groove depth was 3 mm, a relaxation of 97 microstrain was measured. If we consider similar longitudinal and circumferential components of the residual stress field in the patch material, we obtain a residual circumferential stress of 28 MPa. These residual stresses are unexpectedly low, less than 10% of the yield stress of the pipe material.

The test on pipe1, that contained two repairs (Fig. 3), ended after the propagation of a 25 mm long longitudinal crack, initiated at the indentation apparently originated by the friction of a steel wire during the construction or repair of the pipe. Fig. 5 shows a circular patch and the weld repair in pipe 2. The test was stopped when the pressure was almost 13.72 MPa. The square patch in pipe 3, although of poor geometry, did not fail. Final fracture started in a small corrosion defect, located close to the patch but not within the stress field of the fillet welds. Fig. 6 shows the circular patch in pipe 4 (repair 4A), and the fracture that ended the test. Again, initiation of this fracture was not related to the repair.

Two patches were tested in pipe 5. One of them was rectangular, 750 mm long, and the other one was square, 200 mm long, separated by 400 mm. Fracture was initiated at a pressure larger than 12 MPa, from a small corrosion defect situated 180° from the patches. Burst fracture was driven by ductile shear. Fig. 7 shows the rectangular patch in pipe 6 and its instrumentation. Fig. 8 shows the fracture by which the test ended. Crack initiation occurred at the corner of the patch, contiguous to the weld toe. Fig. 9 (×5) shows a detail of the fracture.

All surfaces of the defective areas purportedly covered by the patches were ultrasonically tested, and the criticality of all covered defects was assessed according to API RP 579 [14]. Table 2 shows thicknesses of pipes and patches, and dimensions of the pre-existing defects in the pipe surface under the repairs. A Factor of Safety is also defined in Table 2 as the relationship between the burst pressure [P_{burst}] assessed

Fig. 3. Repairs installed in pipe 1: a circular patch and a sleeve reinforcement.

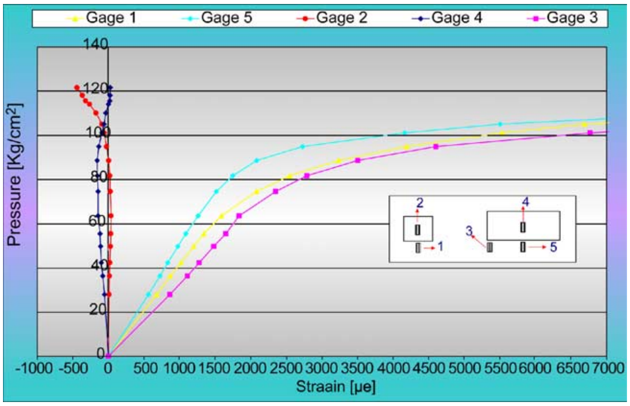

Fig. 4. Example of test results in pipe 5.

Fig. 5. Circular patch and weld repair of artificial defect in pipe 2.

Fig. 7. Rectangular patch in pipe 6 and its instrumentation.

using the Rstreng method [15], and the maximum allowable operating pressure (MAOP) of the pipeline (6 MPa). The last column of Table 2 shows that the repaired defects are in all cases of little importance. The safety factor is always above 1.4, a value that nowadays is considered an upper limit for justifying repair [14,16].

3. Discussion of results

The variation of the longitudinal and circumferential strains and stresses in pipe and patch materials during the application of pressure in the hydrostatic tests was recorded. These variables are considered of importance:

- stress concentrations due to geometry of the reinforcements
- relationship between elastic and plastic deformations and applied internal pressure
- first occurrence of plasticity
- rupture pressure and type (plastic collapse or brittle fracture).

All ruptures occurred at pressures higher than 12 MPa, nearly 200% of the MAOP for the pipeline. Generalized yielding of the pipe wall, identified by an increased intake of water flow, occurred in all tests at a pressure of 10 MPa. This is the yield pressure that corresponds to the yield stress of the material when calculated using the von Mises criterion, so it is called now P_{yield}. Pressure vs circumferential strain curves in pipe material adjacent to the welds of the patches show the elastic to plastic change in slope at pressures between 6 and 8 MPa. Lowest yield pressures occurred near the welds of the rectangular and circular patches.

Average longitudinal strains in the pipe are one-third of the circumferential strains, and reveal yielding only when pressure reaches P_{yield} and generalized yielding in the pipe material occurs (10 MPa). Strains in repair material are relatively small, in both circular and rectangular patches, until the pressure reaches pipe yield (10 MPa).

Further increase in internal pressure provokes a reduction of strains in the outer surfaces of the patches, which can also become compressive. The patches suffer distortions both in longitudinal and circumferential directions. These are due to bending stresses that tend to curve the patches in the opposite direction to the pipe curvature. Only a small fraction of the pipe stresses are transferred to the patches, so the patches undergo small elastic strains even after the pipe material yields. After the pipe yields, the patches start to be compressed in their outer surface. The compressive stresses in the outer surface of the patches transform into traction in its inner surface, but of course this is not experimentally verifiable. The maximum stress in the patch keeps rising after the pipe yields in the surface of the patch that is in contact with the pipe surface.

Fig. 6. Circular patch in pipe 4 (repair 4A).

Fig. 8. Final fracture in test of pipe 6.

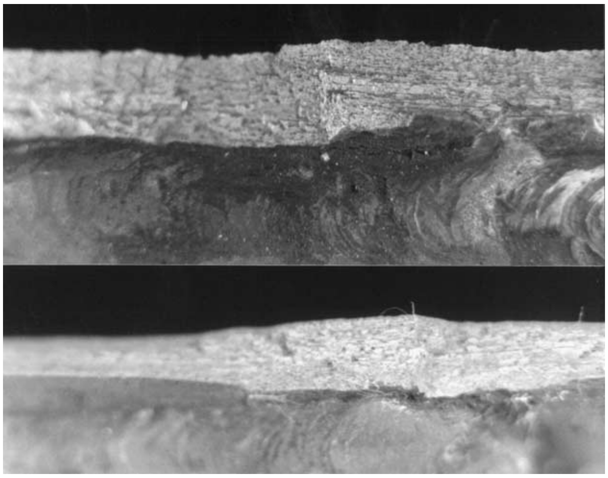

Fig. 9. (×5) Detail of the fracture in pipe 6.

The longitudinal and circumferential stresses, S_l and S_c, are obtained from the values of circumferential, $\varepsilon_{circ,}$ and longitudinal, ε_{long}, strains, using Hooke's law for plane stress. Figs. 10 and 11 show as an example the variations of S_l and S_c with test pressure, for the strain gauges in pipes 4 and 5. In the inset of the figures, sketches of the repairs present in the pipe are shown with the position and orientation of the strain gauges. Linear elastic behaviour is considered, therefore, the curves are valid only up to P_{yield}. When these two strain components are not available at a determined point, the criteria for sites far from stress raisers is used. Considering $S_l=S_c/2$, the von Mises equivalent stress is $S_{vm}=0.87S_c$.

A yield pressure of 10 MPa is defined by the departure from linearity of the strain gages. From Barlow's formula and plane stress Von Mises equation, a yield stress of 365 MPa is calculated, this is 7% less than the yield strength of the pipe material. The difference is due to manufacturing residual stresses in the pipe, due to rolling and seam welding. Cold expanded DSAW pipes typically are left with a through-thickness bending distribution of circumferential residual stresses, with a maximum at the pipe surface of about 10% yield [10].

It is worth noting that the only patch that was directly influencing fracture initiation is the one on pipe 6, this is a long and thin rectangular patch, similar to the one that originated the 2002 failure. All other patches, whether rectangular or circular, did not represent a discontinuity severe enough, and the failures initiated in other defects. Figs. 8 and 9 show the initiation of the fracture in the corner of the patch in pipe 6, adjacent to the weld toe (site 1). Here we can see a faceted fracture surface, normal to the pipe surface, indicating brittle fast fracture. Later the fracture surface becomes less wrinkled and slants at 45° from the pipe surface, indicating typical ductile crack propagation. As the crack grows it moves away from the weld toe. Near the centre of the longitudinal weld a second initiation is produced. Crack arrest is produced, as in all the tested pipes, following the rapid depressurization due to the loss of water through the fractured area.

Residual stresses acting on the patch material are produced during the installation and welding of the patch. These stresses arise from shrinkage of the molten weld pools upon cooling. Its first component is the welding residual stress σ_{res}. This can have very high values, both longitudinal and circumferential, but the stresses are very localized near the weld toes. Its through-thickness distribution is self-equilibrating (e.g. bending). The second component is the constraint stress, σ_{emb}, that only appears when welding in highly constrained conditions, when the patch material is not free to deform or move to accommodate weld shrinkage. If the patch is elastic enough, weld shrinkage produces smaller stresses. So the narrower and thicker the patch is, the greater will be σ_{emb}.

Residual stresses measured in this patch of pipe 6, the most critical in terms of geometry, are unexpectedly low. The other main factor influencing σ_{emb} is the internal pressure of the pipe at the moment the patch was welded. If the patch is installed with the pipe subjected to a pressure sufficiently near MAOP, a large part of the stresses taken by the patch material is relaxed due to the contraction of the pipe that contains it. If installation pressure is low (less than half MAOP), then the patch is kept strained (and therefore stressed) even after complete pipe depressurization.

Failure pressures in all hydrostatic tests are much higher than the pressure in the patch in the 2002 failure. This result is the case for patches of different shapes and sizes (ranging between 150 and 750 mm). On the other hand, all of these repairs have some common characteristics:

- Constraint residual stresses in the patches are low.
- The patches take only a fraction of the stresses in the pipe material.
- Even though the surface aspect of some of the welds is poor, no defects were found in the welds that could have contributed as crack initiation sites.

Table 2
Dimensions of pre-existing defects repaired with patches, and their Rstreng rating

2	Pipe thickness (mm)	Patch thickness (mm)	Maximum defect depth (%)	Effective defect length	Rupture pressure Rstreng (kg/cm^2)	Safety factor Rstreng
1B	7.50	7.29	27	110	99.98	1.67
2A	7.81	7.22	6	150	110.96	1.85
3	7.90	7.11	18	110	110.80	1.85
4A	7.43	7.02	17	200	103.00	1.72
5A	7.90	8.10	41	280	101.30	1.69
5B	7.90	7.69	37	130	104.80	1.75
6	7.80	7.80	38	140	96.01	1.6
7	7.85	7.09	41	110	102.90	1.71

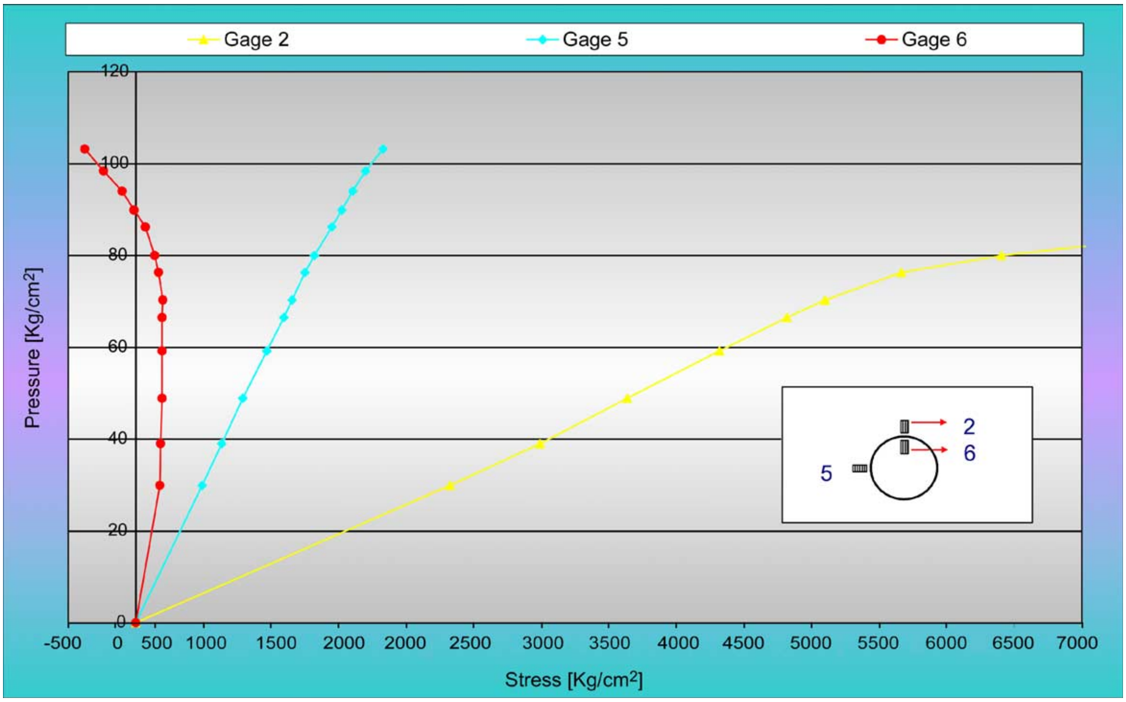

Fig. 10. Circumferential and longitudinal stresses versus pressure, during test of pipe 4.

The reasons for the low residual and operational stresses in the patches, and the high burst pressures, can be found in the combination of the following characteristics:

- The defects originally repaired with the patches were of small dimensions, nowadays their failure pressures (higher than 1.4 MAOP) would not demand their repair.
- The patches were probably placed with the pipe under significant pressure (larger than around 0.5 MAOP). Recent experimental and numerical results show that the stresses in a repair are proportional to the difference between the pressure during repair and the following operating pressure [17].
- Welding electrodes and procedures used in the collocation of the patches were adequate.

The results of the tests show that if the patches are properly welded and are used for repairing defects of little importance, there is a good probability that they will not fail at pressures

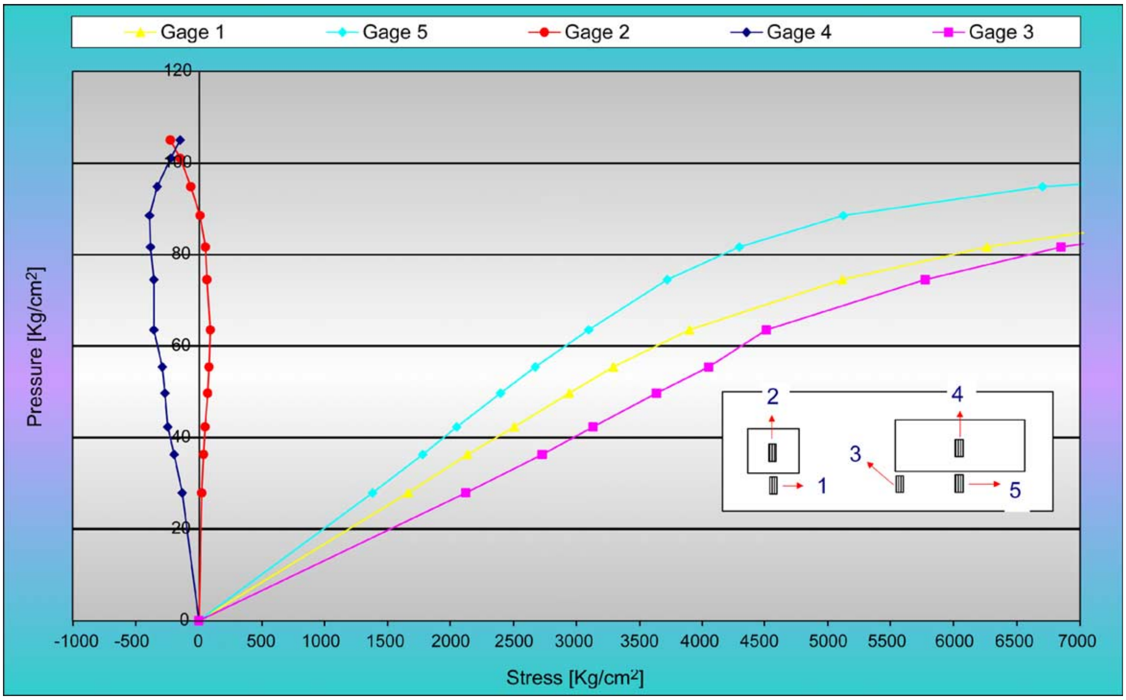

Fig. 11. Circumferential and longitudinal stresses versus pressure, during test of pipe 5.

Table 3
Linear summation of criticality factors for old repair patches: 0, minimum; 5, maximum

Patch geometry	A		B		C		Criticality = A + B + C
	Installation pressure		Size of patch or repaired defect		Qualified procedure		
	High	Low	Small	Large	Yes	No	
Round or elliptical (longer along perimeter)	0	1	0	1	0	1	
Rectangular, wide and short	1	1.5	0	1	0	1	
Square or elliptical lengthwise	1	2	0	1	0	1	
Rectangular, long and narrow	2	3	0	1	0	1	

lower than MAOP. Note that the patches that failed in 2002 and in these tests are long and narrow (a shape factor of 3). It follows that it is necessary to pay particular attention to all pre-existing patches of similar geometric characteristics.

A reasonable geometric parameter is to ensure that any patch remaining in the line has the largest dimension in the circumferential direction. This would ensure enough flexibility in the direction where the stresses in the pipe are larger. It is also desirable to eliminate all patches with sharp corners and notches, which would generate strong geometric stress concentrators. Again, these factors have long being recognized, and present repair procedures involving patches recommend the application of elliptical patches, with the longest side in the circumferential direction.

A patch welded at high pressure will be scarcely effective in taking a large part of the load due to the internal pressure, in which case way the reinforcement is not useful, since it does not significantly reduce the stresses in the pipe material in the area of the defect. If the defect under the patch is deep enough, a gas leakage could occur, with the corresponding pressurization of the gap between patch and pipe. In this instance, the stress level in the patch and in the pipe near the patch welds will markedly increase, and therefore the risk of failure will increase considerably. This was not the case in the 2002 failure, because the defect, although much deeper than the defects studied now, was not able to produce a gas leakage.

4. Ranking repair patches in an operating pipeline

As a result of the previous discussions, it is concluded that the patches that would potentially generate a higher risk for the integrity of the pipeline are those that have the following characteristics:

1. They were placed with the pipeline at a pressure less than half MAOP.
2. They were placed to repair a defect of large dimensions and deeper than around 40% nominal pipe thickness.
3. They are rectangular, roughly two times longer than wide.
4. The quality of the welds is poor or doubtful, for example, no procedures or NDT records available.

The information from the In Line Inspection (ILI) tool does not allow an evaluation of the quality of the weld used in the repair, nor does it establish the pressure at which the repair was made. In general, the ILI information does not allow definition of the actual size of the defect that motivated the collocation of the patch. Therefore, relying on the data reported by the ILI, of the four criticality conditions above-mentioned the third one is the only one possible to be evaluated.

Normally the pipeline operator cannot proceed to immediate replacement of all the patches detected in a pipeline. Therefore, a priority criterion can be established. Table 3 shows a summary of the factors that affect the reliability of the patches welded to a gas pipeline. If reliable data for every condition can be obtained, the sum of every row in the table would allow definition of a risk index for each patch, from a minimum of 0 to a maximum of 5.

5. Conclusions

Seven full scale hydrostatic burst tests were carried out on pipes with old repair patches. Two rectangular, two square and three round patches, of size between 150 and 170 mm, two very short type B full encirclement sleeve reinforcements, and a weld repair of an artificial defect were evaluated. Most highly stressed regions inside and in the perimeter of the patches were instrumented with strain gauges. The dimensions and characteristics of the pre-existing defects under the patches were analyzed after the tests.

All ruptures occurred after generalized pipe yielding, at pressures twice the maximum allowable operating pressure. The only patch that initiated a fracture was rectangular, long and narrow, similar to the patch that originated a failure in a gas pipeline in 2002. The defects that were originally repaired by the patches were in all cases not critical, present standards would not recommend their repair.

The low criticality of the repairs analyzed is due to the combination of the following characteristics:

1. The defects repaired were of small dimensions.
2. The patches were probably installed with the pipe under pressure.
3. Correct weld procedures were used.

The analysis shows that the most dangerous patches are those that:

1. Were installed with the gas pipeline depressurized or at a very low pressure.
2. Were installed to repair a large and deep defect.

3. Are rectangular, long and narrow.
4. Were not welded using reliable procedures.

Of the four conditions above, relying upon the data reported by the ILI it is only possible to evaluate the third.

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