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Full scale experimental analysis of stress states in sleeve repairs of gas pipelines

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Abstract

This study discusses the experimental determination of stress states in sleeve repairs of underground gas pipelines. Work was done to define the effects of the reduction of pressure during welding, the load and place of positioning clamps, the length of the repair sleeve, and the use of O'ring-based devices to prevent gas leakage. Tests were carried out in reinforcements, welded with internal pressure equal to 60, 80 and 100% of the service pressure. High stresses were generated in tests carried out with short sleeves and O'rings, and occurred once the sleeve was fully welded and the pipeline pressure re-established. Maximum stresses, up to 270 MPa, were generated after about 1 min following closing of venting valves, on tests with artificial gas leaks. From the results of these experimental studies, it is concluded that several operative aspects could be optimised, to minimise the stresses in the reinforcements and to reduce the risk of failures. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Stress states; Sleeve repairs; Gas pipelines

1. Introduction

Companies transporting natural gas have thousands of miles of buried pipes, which date back to the 1940s and 1950s. At that time, protection techniques against corrosion (e.g. protective coatings and cathodic protection) were not well-developed, and the companies commonly face defects due to corrosion degradation. Worldwide, the most common way to repair a gas leakage is to change the defective portion of the pipe. To do this, however, it is necessary to pump gas and vent the affected portion of the line. Where there are no loops to deviate the stop gas flow, doing this means stopping provision of gas to some areas, with the consequent losses to the users and the transporting company. One of the alternatives available to minimise service losses and restore serviceability of corroded lines is the use of full encirclement sleeve repairs, with a venting valve.

1.1. Full encirclement sleeves

Full encirclement welded sleeves are used to repair defects in underground gas pipelines, see Figs. 1 and 2. The sleeve consist of two half shells welded lengthwise, which are also welded circumferentially to the pipe if there is a gas leakage or other severe defects. Standard designs are found in API RP 1107 [1]. These reinforcements habitually are carried out in areas where local loss of thickness or gas leakage are detected, generally due to corrosion. When a through-the-thickness defect is detected, full encirclement welded sleeve reinforcements with O'ring and venting valve are used to prevent the gas from reaching the welding operations. One of the shells has a threaded nozzle (typically 25 mm diameter) which is surrounded by an O'ring bonded to its inner surface. This O'ring is placed around the leaking area, and gets compressed against the pipe outer surface once the sleeve is placed. A venting hose is attached to the nozzle, and the leaking gas is vented to the atmosphere, preventing gas from reaching the operations. After installing and welding the sleeve, the venting valve is closed. At this time the gas leaks through the O'ring and pressurises the gap between the pipe and sleeve. The possibility of repairing gas leaks is probably the most important advantage of welded sleeve repairs over competing techniques, such as clock springs.

1.2. Problems with full encirclement sleeves

In-field welding of these sleeves is normally a difficult task. Usually, short times and poor soil or weather conditions

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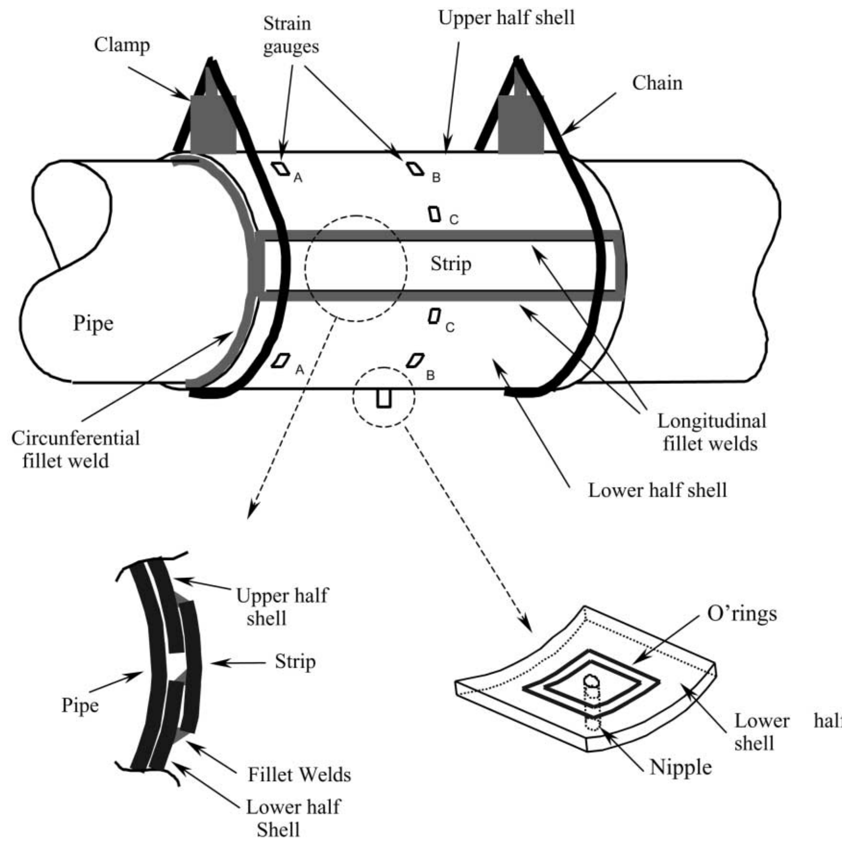


Fig. 1. Full encirclement sleeve repair of a 24″ pipe.

make cutting, handling and welding the sleeves to the buried pipes difficult, even for specially trained personnel and equipment. It is no surprise, therefore, that several weld repairs fail in different ways. Two incidents have been reported involving fillet welds of full encirclement sleeves. In 1985, an incident resulting in a explosion related to a previously installed sleeve was reported [2]. In 1986, a rupture occurred in an oil line following a sleeve installation [3]. These failures have in many cases been the driving force for changes and improvements in the fabrication of the sleeves, field welding procedures and non-destructive testing of the repairs.

Based on fractographic, metallurgical, mechanical and fracture mechanics analyses, the causes of three failures in welded full encirclement sleeve repairs in a 24″ gas pipeline are evaluated in reference [4]. These failures were related to poor manufacturing procedures. The material used to build the sleeves was old and had poor transverse strength. High heat input cellulosic electrodes were used to weld the field joints, which lead to hydrogen embrittlement in HAZ, also helped by relatively high circumferential stresses and defects of lack of fusion.

1.3. Early work on sleeves

Previous work in the field includes evaluations of the strength and integrity of the sleeves by pressurising them to failure, with no attempt to measure the stresses developed during the process [5,6]. Strain gages have been used extensively to monitor stress states in full scale pipeline tests [7,8].

Analytical or numerical estimation of stress distributions in the area of the girth sleeve-to-pipe welds involves a parametric analysis of the influence of each of the geometric and loading variables (thickness of pipe and sleeve, sleeve length, sleeve–pipe gap, pressurisation of the gap, etc.). Analyses of the stresses associated with full encirclement sleeve carried out by Smith and Wilson [9] derived an analytic elastic solution. Their main conclusions were:

- Increasing the thickness of the sleeve above the thickness of the pipe decreases the stresses in the root area of the circumferential fillet weld.
- Reducing the size of the fillet weld increases radial and hoop stresses, but longitudinal stresses remain almost constant.

1.4. Recent work on sleeves

More recently, Gordon and collaborators [10] carried out an extensive programme of numerical modelling to analyse the influence of the different geometric variables involved in the full encirclement (circumferential) welds, and to

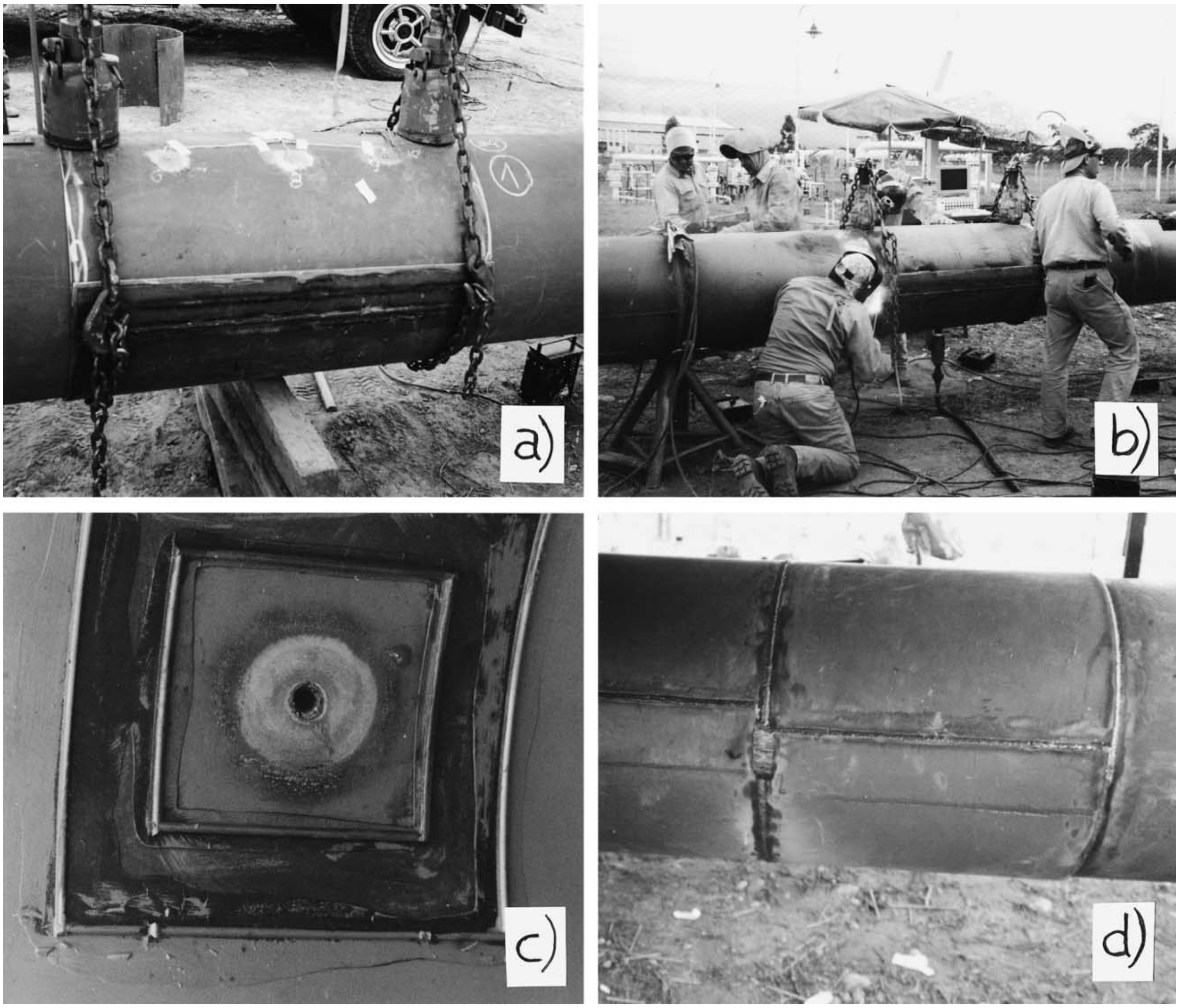
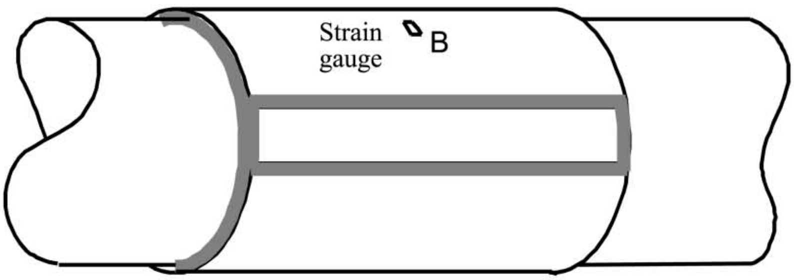


Fig. 2. Stages of the experimental procedure. (a) Clamping method. (b) Welding of tests with gas leakage. (c) Double O'rings used in these tests. (d) Tandem reinforcement, with full penetration intermediate circumferential weld.

develop a procedure to determine their fitness for service. Finite element analyses of sleeve connections were performed to determine how the local stress distributions at the sleeve to pipe circumferential welds are influenced by the pipe diameter to wall thickness ratio, the length and thickness of the sleeve, and the gap between the sleeve and the pipe. Analyses were performed for different applied loading: remote uniform tension, bending of the pipe, internal pressure, and pressure between the sleeve and pipe (simulating a leak in the carrier pipe). Flaw acceptance criteria for the most critical crack locations were developed. This resulted in proposed closed-form stress intensity factor solutions for external circumferentially cracked sleeve assemblies subjected to remotely applied tension and internal pressure plus a leak between the carrier pipe and the sleeve. These solutions are proposed to be used to determine the limiting flaw depth for a sleeve assembly containing an external circumferential crack located at the toe of the full-encirclement fillet weld. Full-scale fracture tests were performed to validate the assessment procedures developed, and residual stress measurements were obtained on a welded sleeve assembly using the neutron diffraction method.

1.5. Present study

The object of the present study is the experimental determination of the states of deformations and stresses in the material of the sleeves, that arise as a result of the assembly and welding operations to the gas pipelines subjected to internal pressure. The experimental measurement of these stresses has the final objective to optimise the assembly and welding conditions of the reinforcements. The results of these experimental studies allowed the effect of the repair procedure to be evaluated, especially the effect of those operations not defined by the involved international entities [1,11]. Such is the case of the loads introduced by the failure



Test	1	2	3	4
Sleeve length (L)	1 m	1 m	0.6 m	1 m
Sleeve thickness	7.9 mm	7.9 mm	7.9 mm	7.9 mm
Repearment Pressure (P_r)	36 bars	48 bars	48 bars	60 bars

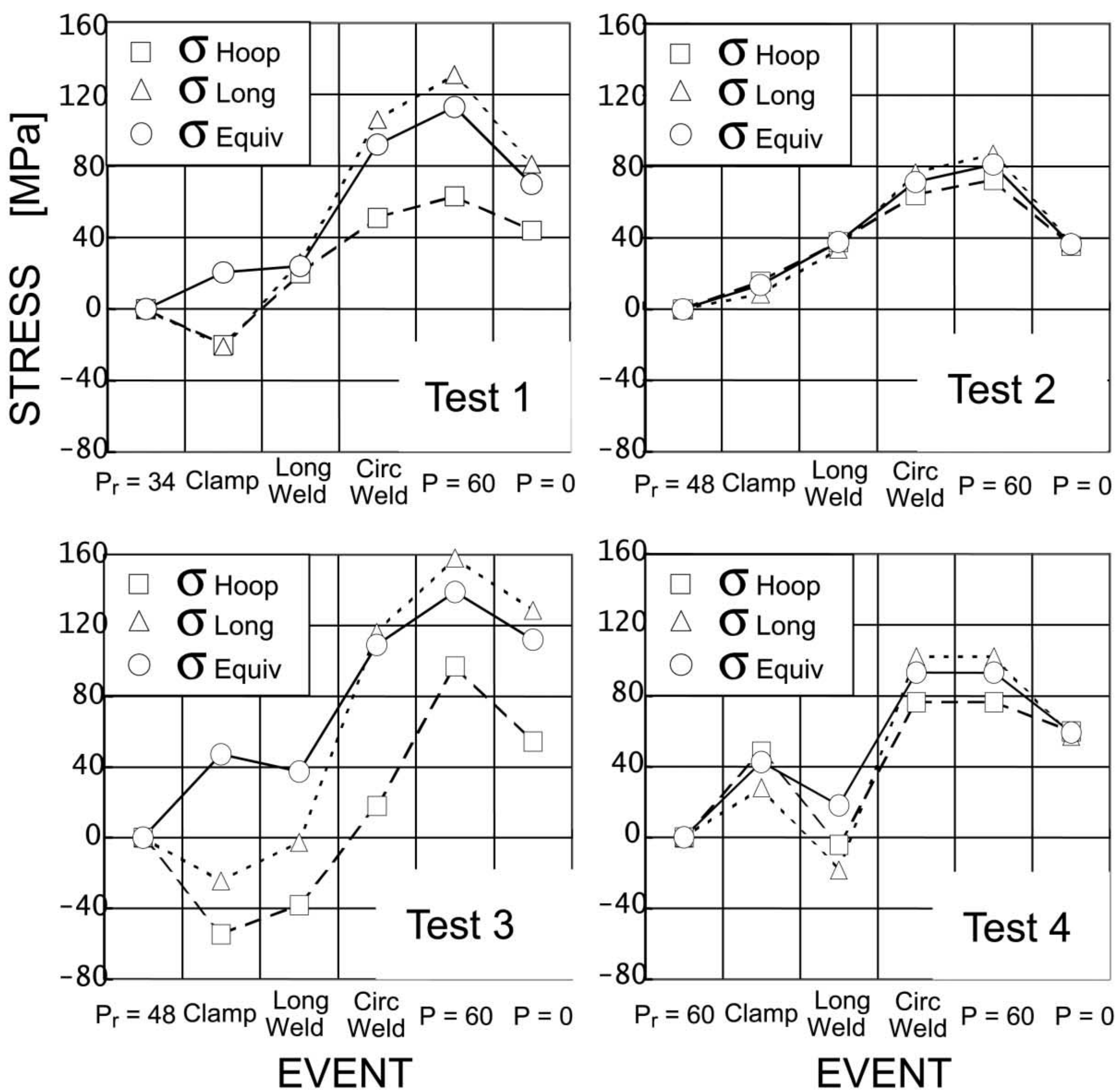


Fig. 3. Hoop, longitudinal and equivalent Von Mises stresses in the sleeve material. Tests 1, 2, 3 and 4. Pressures are in bars.

of the O'ring when closing the venting valve, and the pressurisation of the gap or interstice between tube and sleeve. Other examples constitute the welding of two consecutive reinforcements, with intermediate fillet or butt circumferential weld.

2. Experimental procedure

The experiments were carried out in a loop specially built downstream of a natural gas compression plant. Tests were done on two sections of API 5LX52 pipe, 609.6 mm diameter and 7.9 mm thickness, with semielliptic heads and 25 mm pressurisation and venting nipples. Fig. 2 shows some stages of the procedures. Fig. 2a shows the clamping method prior to welding the sleeve. Fig. 2b shows the beginning of the welding stage in one of the tests with gas leakage, showing the venting valve and hose. To simulate leakage, 2 mm diameter perforations were drilled in each case. Fig. 2c shows the double O'rings used in these tests (see also Fig. 1). Fig. 2d shows a tandem sleeve reinforcement, with full penetration intermediate circumferential weld (see also Fig. 7, test 12).

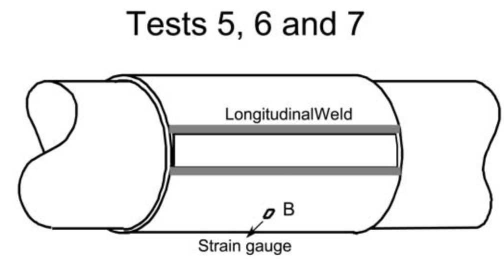
Strain gauges were used: YFCA-5 of TML (Tokyo Sokki Ken Kyjo Co., Ltd.) and EA-06-125RA-120 of Micro-Measurements. Between 6 and 8 strain gages were placed in each test, in circumferential and longitudinal directions on positions A, B, C in the sleeve surfaces, as shown in Fig. 1. Strain gauges were also positioned in links near the ends and in the central area of the chains, in longitudinal and transverse positions to the link.

The data acquisition system involves a multiplexer, a digital–analogical data acquisition card and a program for acquisition and evaluation of data. This system is consolidated in a PC computer. Calibration was by resistances M&M 500 and 1000. Noise in the measurements was reduced to less than 1%. Total estimated maximum error was 3%.

The effects on the stress fields of the following variables were evaluated:

- the amount of pressure reduction during welding,
- the load and place of positioning clamps,
- the length of the repair sleeves,
- the use of O'ring-based devices to prevent gas leakage from reaching the welds,
- dynamic loading on the sleeves after failure of the O'ring, following closure of the venting valve,
- the influence of middle circumferential weld on double (tandem) sleeve repairs.

Twelve tests, involving the welding of 14 sleeves, were carried out: (1) four tests without gas leakage, with circumferential weld (Fig. 3); (2) three tests without gas leakage and without circumferential weld (Fig. 4); (3) three tests with gas leakage and circumferential weld



Test	5	6	7
Sleeve length (L)	1.2 m	1 m	1 m
Sleeve thickness	11.1 mm	7.9 mm	7.9 mm
Repearment Pressure (P_r)	60 Bars	60 Bars	36 Bars

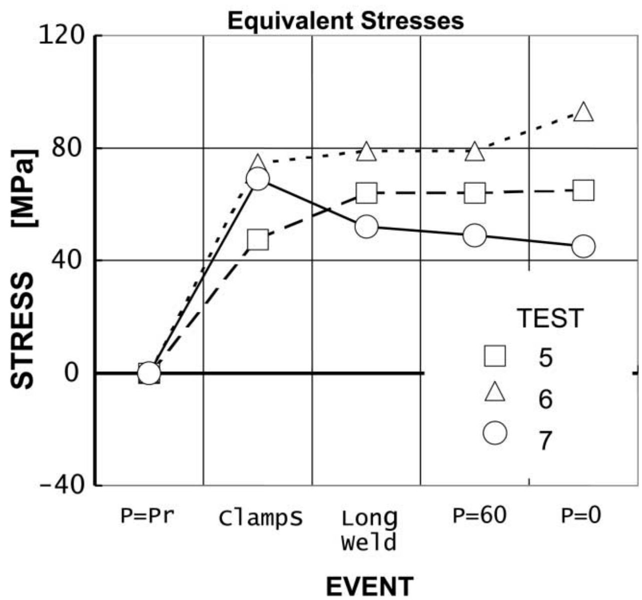
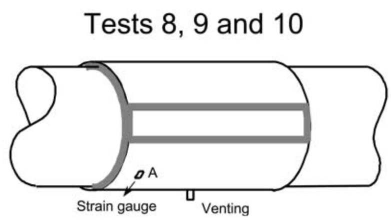


Fig. 4. Equivalent stresses due to the application of clamps and longitudinal welds.

(Fig. 5) and (4) two tests with double or tandem reinforcements, with intermediate weld (Fig. 7). Gas pressure at the compression plant during the tests was 60 bars, which was defined as the nominal pressure. Lengths of sleeves were 0.60, 1.00 or 1.20 m. Thickness of sleeves was 7.9 mm or 11.1 mm. Tandem reinforcements were always 7.9 mm thick.

The repairment pressure (P_r), at which the sleeves were welded to the pipe, were equal to 60 (36 bars), 80 (48 bars) or 100% (60 bars) of the nominal gas pressure ($P = 60$ bars). The stresses developed in the sleeves were measured after each of the following events: application of the clamps, longitudinal welding of the sleeves, circumferential welding of the sleeve to the pipe, pressure rise to nominal gas pressure, and total elimination of the pressure ($P = 0$). Dynamic stress measurements were made when closing the venting valve, during the pressurisation of the gap, in order to verify the existence of possible stress peaks, and the duration of the stress transient. Hoop, longitudinal and equivalent Von Misses stresses in the sleeve material were monitored.



Test	8	9	10
Sleeve length (L)	1 m	1 m	1 m
Sleeve thickness	11.1 mm	7.9 mm	7.9 mm
Repearment Pressure (P_r)	60 Bars	60 Bars	36 Bars

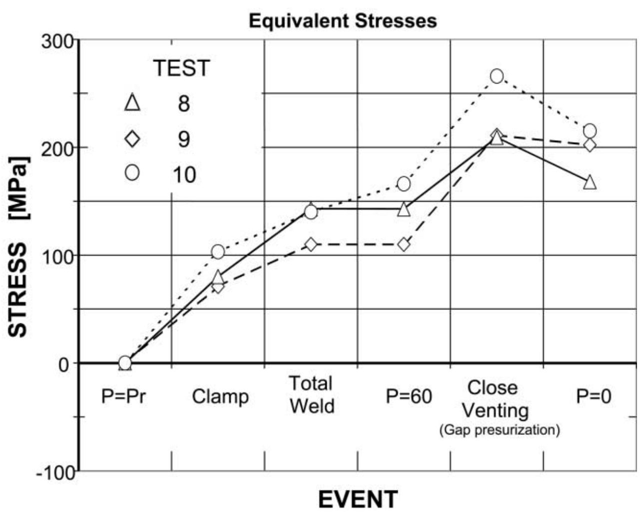


Fig. 5. Maximum equivalent stresses in three tests with artificial gas leaks.

3. Discussion of results

3.1. Tests without gas leak

3.1.1. Tests 1–4

The table in Fig. 3 shows the thickness and length of the sleeves used for test 1, 2, 3 and 4. The pressure at which the repairments were carried out are also shown. The loads on the clamps were maintained in the typical values used in field welding, defined by the operators according to positioning requirements. Loads measured ranged from 10 000 to 27 000 N, for different gap size, O'ring and sleeve thickness conditions. Hoop, longitudinal and equivalent Von Misses stresses on the surface of the upper half shell in position B show similar tendencies in the four tests carried out, see Fig. 3.

Small variations of stresses are observed during the clamping, prestraining with clamps and longitudinal welding. These are tensile or compressive, of up to 50 MPa that is, about 20% the maximum nominal stress in the pipe due to the maximum nominal gas pressure (240 MPa). As a result of the circumferential welds to the pipe, an important increase is observed in the longitudinal stresses in the sleeve, that reach about 100–150 MPa that is, of the order of the longitudinal nominal stress in the pipe at maximum allowable operating pressure (MAOP). This result is due to the longitudinal shrinkage generated by the circumferential welds. An increase in the hoop stresses is also seen, that reach a value between 60 and 100 MPa, due to the longitudinal contractions of the circumferential welds.

Maximum stresses were generated once the sleeve was fully welded and the pipe pressure re-established. The longitudinal stresses in the sleeve are in this case 50% larger than the hoop stresses, reaching values between 80 and 150 MPa. These longitudinal stresses tend to tear the circumferential weld to the pipe, and therefore are important with regard to the evaluation of possible lamination flaws in the heat affected zone (HAZ) of the circumferential welds on the pipeline material. Maximum stresses were recorded for test 3 (80%), carried out with the shorter (0.6 m) sleeve (much shorter than the others) and with the O'ring placed in the lower half shell. In the second place, figures test 1, with the smallest repairment pressure (36 bars). At low repairment pressures the sleeve takes a larger part from the pipe loads due to internal gas pressure. The results of tests 2 (48 bars) and 4 (60 bars) are similar.

3.1.2. Tests 5–7

Tests 5, 6 and 7 were longitudinally welded only. Again, the loads on the clamps were maintained in the typical values used in field welding. Fig. 4 shows equivalent Von Misses stresses in the sleeve material. In all tests they show similar tendencies. It can be also seen that the stresses due to the application of clamps in the ends of the reinforcements are relatively low. In this second experimental set, stresses were measured in the lower half shell. Here the load of the clamps is transmitted through the chains, and local bending is not so important and mostly membrane stresses are generated. This allowed an estimate to be made of the real stresses applied by the clamps.

3.1.3. Discussion

The thickness of the O'ring (about 6 mm) makes it necessary to apply larger clamping loads in order to fulfil the maximum gap specifications (3 mm). The O'ring becomes notably rigid, in spite of being rubber, when compressing to approximately 50% deformation. Longitudinal sleeve welds 'freeze' their relative position and the deformations introduced by the clamps. These welds also add a membrane circumferential tensile load of up to 110 MPa, which is added to the local residual stresses distribution.

The reinforcement to circumferential welds introduce the largest hoop and longitudinal tensile stresses, the maximum stresses obtained in all the tests. The increase of internal pressure until work pressure after welding increases both circumferential and longitudinal stresses. In theory, this increase should be proportional to the difference between the repair and work pressures. After venting to zero gas pressure, longitudinal and hoop tensile stresses remain similar to those obtained after the longitudinal welds.

3.2. Tests with artificial gas leaks

Gordon et al. [10] found that a leak in the carrier pipe can result in a significant increase in the stresses across the weld throat and the HAZ region of the circumferential weld in the sleeve. This is most evident close to the weld root. The difference in stress magnification factors increases as the gap between the sleeve and carrier pipe is increased. In the case of repairs of gas leaks, the experience indicates that when the venting valve is closed, the sudden failure of the O'ring takes place, and pressurisation of the sleeve occurs. In this case, the stresses from the deformations of the sleeve should be added to the stresses generated by gas pressure.

Therefore, a set of three tests in pipes with simulated leaks was carried out, in order to evaluate the effects of some operative variables. The stresses in the sleeve where the O'ring is placed, the load applied by the clamps, and the dynamic effect of the pressurisation after the break of the O'ring were measured. The influence of sleeve length was also evaluated.

Fig. 5 shows the maximum equivalent stresses in three tests, which were obtained in position A. After application of the clamps and welding at gas pressures of 36 bars (60%, test 10) or 60 bars (100%, tests 8 and 9), the stresses developed depend on the load applied by the clamps. After longitudinal welds were completed, the stresses in tests 9 and 10 are similar, because the geometric conditions (dimensions, thickness) and welding conditions (procedure) are similar. In test 8 the sleeve is thicker (11.1 mm) and its stiffness is greater, so lower stresses are generated in the sleeve material.

Stresses in the lower shell before gap pressurisation are smaller than those obtained in test 3 (0.6 m long sleeve with O'ring), as measured in the upper sleeve. This shows the advantage of using sleeves longer than 1 m. The difference of stresses developed after applying the clamps in tests 8 and 10 stays during the whole test. Final elevation of pressure from 36 to 60 bars in tests 8 and 10 generates additional stresses. The failure of the O'ring due to closing of the venting valve produces a significant increase of stresses, product of the pressurisation of the gap, up to a maximum equivalent stresses of 268 MPa. Starting from the elevation of pressure the difference in the stresses is proportional to the differences in the load applied by the clamps and to the difference between repair and normal gas pressures. The pressurisation of the gap in test 8 produces a smaller increase of stresses, than in tests 9 and 10, due to a thicker sleeve (11.1 mm).

3.3. Stress transients due to dynamic pressurisation of the reinforcement-to-pipe gap

Data on the pressurisation of the reinforcement-pipe gap after the failure of the O'ring (when closing the venting pipe) is scarce. Rapid pressurisation was always detected within this program. The O'rings are either vulcanised or bonded to the reinforcement. Although the O'ring did not usually break, it failed after closing the venting pipe, and pressurisation was always very rapid. In test 10, measurements were made every microsecond during 50 s. In this test the internal O'ring was vulcanised and the external one was bonded (see Fig. 2c). Fig. 6 shows equivalent stresses, measured in positions A, B and C. Statically measured stresses before the failure of the O'ring and after venting the tube are also included. It turns out that total pressurisation of the gap is reached in approximately 10 s, and that the stresses reach their maximum values in 4 or 5 s in positions B and C (both near the O'ring). Stress peaks are only found in position B and they are only 5% larger than the final static stresses. Transients in positions farther away from the O'ring (position A) are longer and softer.

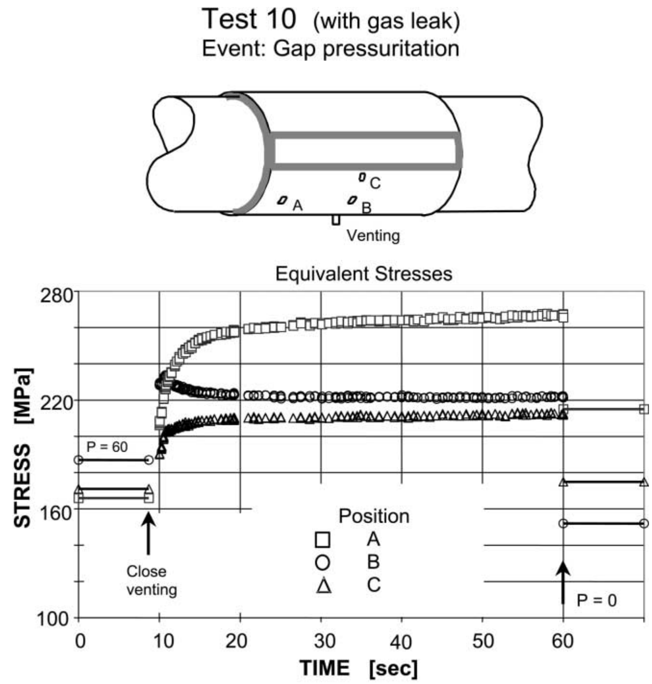
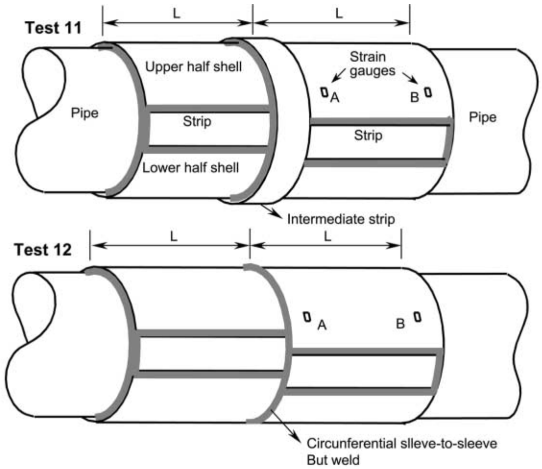


Fig. 6. Stress transients due to dynamic pressurisation of the reinforcement-to-pipe gap.

3.4. Tests of double reinforcements

Numerical results by Gordon et al. [10] showed that increasing the sleeve length from 1.5 pipe diameters to 4 pipe diameters has almost no effect on the local stress distributions, even for the case of pressure between the sleeve and the pipe (simulating a leak in the carrier pipe). Results of tests 11 (sleeves fillet welded to an intermediate strip) and 12 (thick butt circumferential sleeve to sleeve weld) are shown in Fig. 7.

These results show that the stresses developed by the clamps are larger in the extremes of the sleeve which are further from the sleeve to sleeve circumferential weld in both cases. Maximum tensile hoop stresses are 139 MPa in test 12. After the longitudinal welds and retirement of



Test	11	12
Sleeve length (L)	0.6 m	0.6 m
Sleeve thickness	7.9 mm	7.9 mm
Repearment Pressure (P_r)	36 Bars	36 Bars

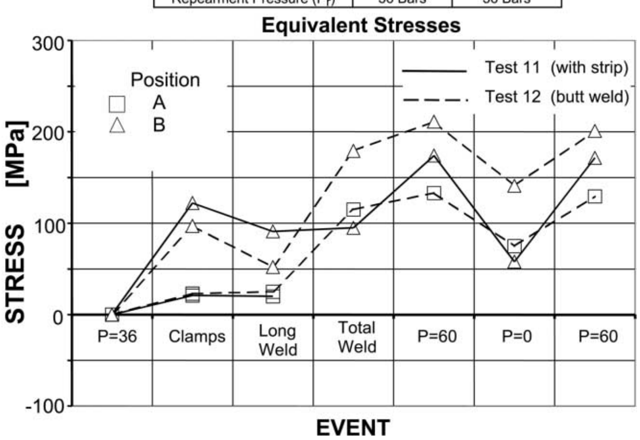


Fig. 7. Tests of double reinforcements: results of tests 11 (sleeves fillet welded to an intermediate strip) and 12 (thick butt circumferential sleeve-to-sleeve weld).

the clamps, the stresses reduce to a value defined by the deformations developed by the clamps (that are 'frozen' by the welds) and the stresses due to the weld shrinkage. Completing the circumferential welds elevates the stresses, which are largest in test 12. This is probably due to shrinkage taken place during welding. Elevating gas pressure to nominal pressure (from 36 to 60 bars) produces stress increments in test 11. This is a partial compensation to the previous effect, giving rise to similar final stresses in both tests (182 MPa in test 11 and 207 MPa in test 12). Releasing gas pressure to zero diminishes the stresses in the sleeves to 57 MPa in test 11 and 146 MPa in test 12. This large difference can be attributed to the differences in restraint conditions and stiffness of both sleeve-to-sleeve circumferential weld procedures. Elevating gas pressure again to 60 bars renders similar stresses as before cycling, confirming no large scale hysteresis effects.

3.5. Implications to field repair procedures

3.5.1. Quality control

The lack of roundness of a buried pipe can not be controlled, and old pipes tend to have more ovalisation defects than newer ones. The use of 300 kN clamps to place and to accommodate the sleeves to the bend conditions and diameter of the pipe generates angular and linear deformations in the sleeves that are translated into stresses after welding. These stresses are added to the contraction effects of the longitudinal welds, and remain 'frozen' definitively in the material of the reinforcement. The value of these stresses can be minimised to some extent, by ensuring an appropriate geometry of the sleeves to be used, and the use of low thickness O'rings. After these tests, new, more stringent quality standards were enforced in the in-plant production of the sleeves, both geometrical and metallurgical. Improvements on the in-plant fabrication of the half sleeves include the use of good quality new pipe material, and reducing geometric errors, in order to avoid poor fit in the field which lead to poor quality side seams. Pipe-to-sleeve gaps more than 3 mm are not allowed. The thickness of the O'ring was specified to a maximum of 5 mm.

Quality standards related with the in-field installation of the repair sleeves into the pipeline were improved by using qualified welding procedures, improving weld procedures (low current, multiple pass-straight bead welds, 45° electrode inclination, etc.), and using low hydrogen electrodes. A quality procedure for pre-repair and post-repair operations was also developed. This procedure includes thickness measurements to verify the minimum weldable wall of the pipe thickness, in order to avoid the occurrence of tube perforation during the circumferential reinforcement-to-pipe weld, and magnetic particles or penetrant ink non-destructive tests.

3.5.2. Repair pressure

It has been shown that keeping the gas pressure in the pipe near the normal operating values leads to lower stresses in the sleeves after they are welded. If the sleeves were welded with zero gas pressure in the pipe, shrinkage stresses of the order of 20–30% yield strength would be introduced into the sleeve material. As soon as the pipe is pressurised again, very high hoop and longitudinal stresses are added to the sleeves, while the pipe material inside the repair remains almost unstressed. If the pipe is repaired at 100% of its working pressure, stresses in the sleeves are created only because of sleeve clamping, weld shrinkage and gap pressurisation (if leaks are present). Although the choice of pressure during repair could be used as a tool to control stresses in pipe and sleeve and to optimise the integrity of the repair, pipe pressure during repair welding must be reduced at present due to safety reasons [11–13].

3.5.3. Circumferential weld

Another issue concerns the circumferential welds to the pipe. Up to now, when a corroded area is so extended that it is not possible to locate sections with at least 85% thickness to lay the girth weld to the pipe, tandem sleeves are used.

This work showed that large stresses develop in tandem sleeves, no matter what weld procedure is used to weld them. That is why thickness requirements for pipe circumferential welds have to be re-evaluated. Modelling the effect of thickness reduction on mechanical and thermal loads introduced by the circumferential weld on the pipe material will allow the conditions of acceptability of corrosion losses in the areas to be welded to be defined. Models to evaluate the risk of burning through the pipe thickness during welding have already been introduced by researchers at Battelle [14].

The maximum measured through thickness axial residual stress at the toe of the full-encirclement fillet weld measured by Gordon et al. [10] was 8.12 ksi (56 MPa), which corresponds to approximately 15% of the pipe yield strength. In general, the maximum measured through thickness residual stresses at each location in the sleeve assembly were in the hoop direction. The maximum measured residual hoop stress in their sleeve assembly was 40.6 ksi (280 MPa), which corresponds to approximately 74% of the pipe yield strength.

Measurements made during failure analyses of some reinforcements that failed shortly after being placed in the field showed that hoop stresses in the sleeve are similar to those measured in the present tests [4]. Most failures have taken place in reinforcements with pressurised gaps, that is, used to repair gas leakages. One of the techniques that can be used to improve the quality of the reinforcement and eventually to replace the circumferential welds is to use a material that fills the gap between the deteriorated pipe and the reinforcement. This filler reduces the quantity of gas caught in the gap, and improves the distribution of loads between the pipe and the sleeve. However, curing of the filler may delay the repair process by several hours. Additionally, it is difficult for the filler to completely occupy the gap, and the filler material can crack and lose adherence during pressure cycles in service.

4. Conclusions

From these experimental studies it is concluded that

1. In order to minimise the stresses in the reinforcements it is required to (i) improve the in-plant production of sleeves to be used in the repairs, (ii) optimise the design of the O'rings, and (iii) always use sleeves longer than 1 m.
2. Welding with higher gas pressures in the pipe gives rise to lower stresses in the sleeves. It has been shown that keeping the gas pressure in the pipe near the normal operating values leads to lower stresses in the sleeves after they are welded.
3. Maximum equivalent stresses in repairs without gas leakage are about 150 MPa.
4. Gas leaks completely pressurise the pipe-to-sleeve gap in a few seconds after closing the venting valve, giving rise to additional equivalent stresses in the repairs of about 100 MPa.
5. Large stresses are generated when welding tandem reinforcements, regardless of the type of sleeve-to-sleeve circumferential weld. In order to reduce failures, this kind of configuration should be avoided.

Acknowledgements

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