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Local collapse of gas pipelines under sleeve repairs

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Abstract

Local collapse of the pipe wall under full encirclement sleeve reinforcements is associated with breaks and blow outs that cause large gas losses and abrupt depressurisation in gas pipelines. Although these defects do not represent an imminent risk of failure, they should be eliminated because they impede the normal passage of the "instrumented pig" for internal inspection. Four failed repairs were experimentally evaluated, and the effects of different geometric factors were numerically assessed via non-linear numerical modelling of fluid flow and pipe response. All possible causes of the appearance of these defects and measures to minimise their occurrence were evaluated. The position of the repaired portion with respect to the blow out, local geometry of the repair and previous defects, and the amount of gas caught in the interstice between the pipe and the reinforcement, have an important part in the event. The measures for the prevention of this problem involve the use of fillers and improved construction of repair sleeves. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Local collapse; Sleeve reinforcements; Depressurised gas pipelines

1. Introduction

Local loss of thickness and gas leakage are frequently found in underground pipelines, generally due to external corrosion. The most effective way to repair a gas leakage in a gas pipeline is to change the defective portion of the pipe. To do this, however, it is necessary to stop pumping gas and vent the affected portion of the line. Where there are no loops to deviate the gas flow, doing this means stopping the provision of gas to some areas. Therefore, worldwide thousands of full encirclement sleeve repairs are being placed every year, as a temporary or permanent repair.

The sleeve consists of two half shells welded lengthwise, which are also welded circumferentially to the pipe if there is a gas leakage or other severe defects, see Fig. 1. 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. In order to obtain a tight fit on the carrier pipe, the shells are positioned and clamped as illustrated in the figure. When a through-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 (see details in Fig. 1). 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, and the clamps and chains used to assemble the repair sleeve are retired. At this time the gas leaks through the O'ring and pressurises the gap between the pipe and the sleeve. The possibility of repairing gas leaks is probably the most important advantage of welded sleeve repairs over competing techniques, such as clock springs.

In-field welding of these sleeves is normally difficult. Short times and poor soil or weather conditions make cutting, handling and welding the sleeves to the buried pipes require especially trained personnel and equipment. It is no surprise, therefore, that several weld repairs fail in different ways [2]. 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. Local collapse of the pipe wall under full encirclement sleeve reinforcements is mostly associated with breaks and blow outs that cause large gas losses and abrupt depressurisation in gas pipelines [3]. Although these defects do not represent an imminent risk of

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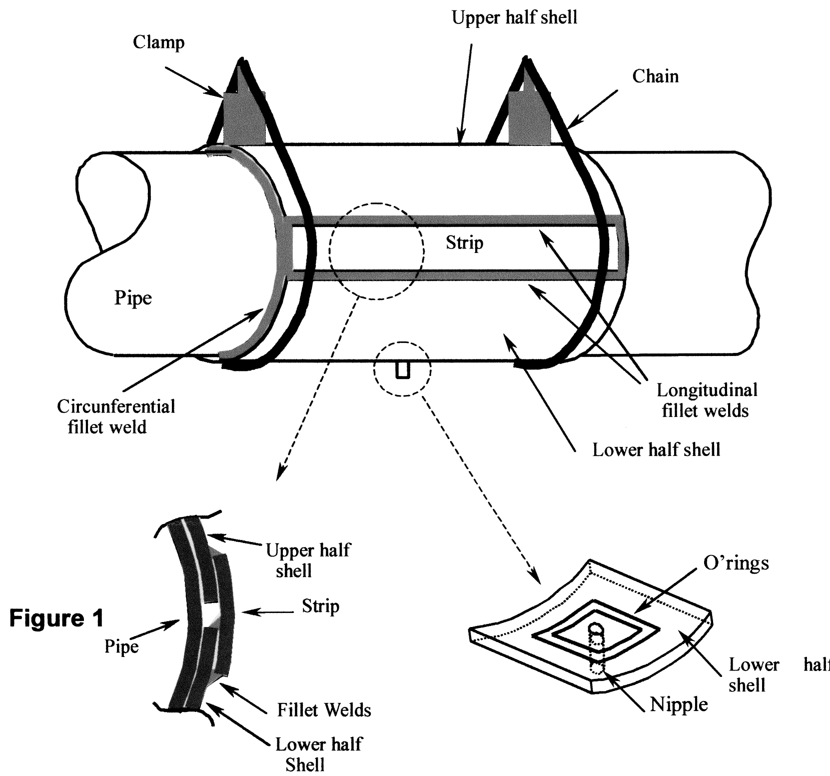

Fig. 1. Schematics of how a full encirclement sleeve repair is placed on a gas pipeline.

failure, they should be eliminated because they impede the normal passage of the smart pig for internal inspection. Given the high derived-cost of the repair of these defects, that includes cutting the pipeline to replace the faulty tract, all possible causes of the appearance of these defects and measures to minimise their occurrence were evaluated.

Blocking valves are placed every 30 km along the gas pipeline, in order to isolate and decompress the tract in case of blow outs, gas leaks or repairs. The closing of two blocking valves in a tract is usually followed by the opening of a venting valve. It is important for the operating companies to understand whether collapse failures under sleeve repairs can also be caused by pressure waves due to the rapid closure of block valves, or rapid venting of a section of the pipeline. The magnitude of pressure variations during the operation of the blocking valves would help in the definition of recommended closing procedures.

The characteristics of three tracts in a gas pipeline were evaluated experimentally, in which defects by the collapse of the pipe wall under full encirclement sleeve repairs were observed. These collapsed regions were found when attempting to run the smart pig, up to about 10 km away from the sites of the previous bursts. The purpose of this study is to analyse the causes that provoked the defects. A fourth repaired region, adjacent to one of the previous but without collapse, was also studied to define possible geometric or operational differences that could justify the absence of collapse. The objectives of this analysis are: identifying the mechanisms of plastic collapse; identifying the causes that made those mechanisms appear; identifying the geometric and operating characteristics that favoured the appearance of the defects; identifying the regions in the gas pipeline susceptible to the repetition of the problem; and defining inspections, studies and/or corrective actions to be considered in future repairs.

2. Experimental procedure

The pipes under study are of the type API 5LX52, and form a part of a 600 mm diameter, 7.1 mm thick gas pipeline, subjected to a maximum operation pressure of 6.05 MPa. Figs. 2(a), (b) and 3 show the three collapsed tracts, defined as 1, 3 and 2. The white lines in Fig. 3 (part of a thickness mesh) give a better idea of the topography of the bump in the pipe wall. The typical gas flow rate and temperature are: $Q = 308.000\ m^3/h$, $T = 30°C$, where Q is the volume transported, referred to normal conditions of temperature and pressure (15°C, 1 atm). T can increase up to 40°C over short distances below the compressor plants. The average physical constants of natural gas were used in this study. Tracts 2 and 4 correspond to two reinforcements placed immediately one besides the other. Collapse was observed in tract 2, while no signs of collapse were found under the reinforcement in tract 4.

The visual evaluation of the main geometric aspects of the defects was carried out in order to identify their shapes and sizes, position relative to the longitudinal weld, the

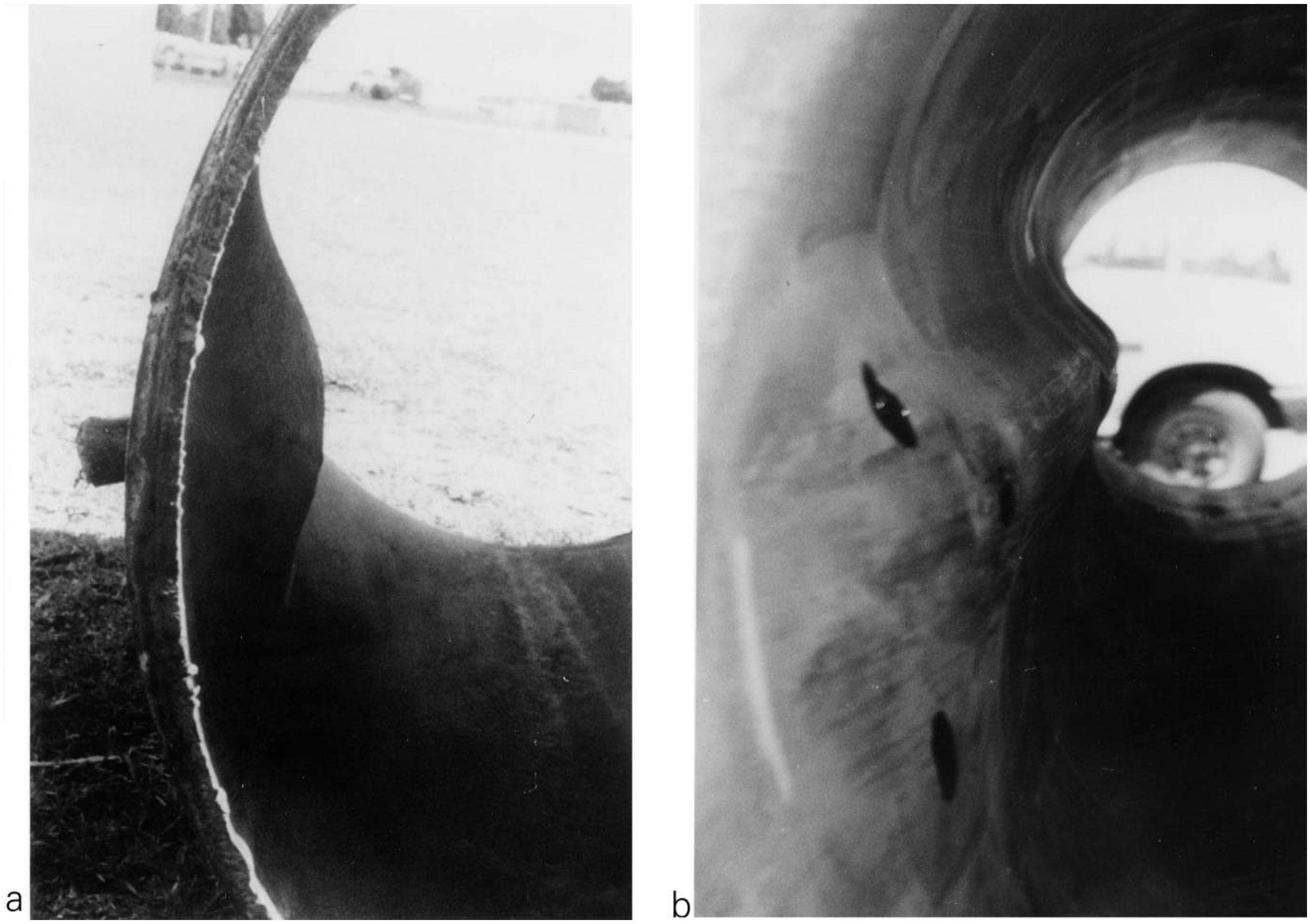

Fig. 2. (a) First and (b) third evaluated tracts showing collapse under the reinforcement, on a 600 mm diameter, 7.1 mm thickness gas pipeline.

Fig. 3. Second of the three evaluated tracts. Note the geometry and position of internal wall collapse.

Fig. 4. (X2) Typical elongated 15 mm long perforation found in a collapsed sample, probably enlarged due to the formation of the plastic hinge during the collapse. The net perforation area is about 1 mm^2.

position of the previous defects that motivated the repair, and the venting valve on the repair sleeve. Figs. 2 and 3 show the profiles of the three pipe wall collapses. There does not appear to be a direct correlation between the positions of the venting nozzle and the collapse. In tract 1, the collapse is located directly behind the nozzle (see Fig. 2(a)), while in tract 3 the collapse is located away from its position. The nozzle is always placed perpendicular to the two longitudinal welds of the reinforcement (Fig. 1), so that a direct correlation cannot be found between the geometry of the reinforcement and the location of the collapsed area. All the collapse failures occurred in a zone very close to the longitudinal weld of the pipe. Although the length of the bumps along the pipe axes varied between 900 and 2500 mm, the bump depths and widths were in all cases around 70 and 300 mm, respectively.

Of particular interest is the morphology and depth of thickness losses. Thickness mappings revealed that the losses of thickness are located in all cases in a very small area around the punctures, not larger than about 1000 mm^2. Therefore, extended loss of thickness can be discarded as a reason for wall collapse. A reasonable hypothesis is that the pressure of the gas caught in the interstice between the pipe and the reinforcement has an important role in the event. Tests were carried out to determine the air tightness of the reinforcement and the condition of the intermediate sealing element (O'ring). In all the cases a previous through wall defect or perforation existed. In the non-collapsed sample two perforations where found, with a total area of 20 mm^2. The perforations observed in the collapsed samples were elongated, probably enlarged due to the formation of the plastic hinge during the collapse. Fig. 4(X2) shows as an example a 15 mm long perforation. The net area of these perforations was less than 1 mm^2.

3. Numerical models

Numerical modelling was used to evaluate the effect of the pressure waves that are generated in the gas pipeline when an abrupt depressurisation occurs, and the effect that these waves have on the loads and stresses generated at different sections of the pipe (especially under the reinforcement) due to a blow out or sudden depressurisation. The situations analysed were: (a) abrupt depressurisation of the pipeline due to a quick break, upstream and downstream of the blow out site; and (b) venting operations on the line, closing of the blocking valves and opening of venting valves. Four types of computational models were carried out, as discussed below.

3.1. Fluid flow

Fluid flow numerical simulation was carried out using a computer code for the simulation of the flow of a compressible, non-linear, time dependent fluid in closed conditions, using the method of characteristics. The code takes into account friction losses (through Darcy's law), convective heat losses to the environment, and gas conductivity [4–6]. The heat transfer coefficient and gas conductivity were provided by the company. The friction factor was obtained employing the Cole Brook formula, i.e. the analytic expression of the Moody chart for pipe flow. Although the gas flow has a very high Pecklet number, it was preferred not to neglect conductivity. Heat transfer through the pipe wall was considered in the model, and therefore the energy

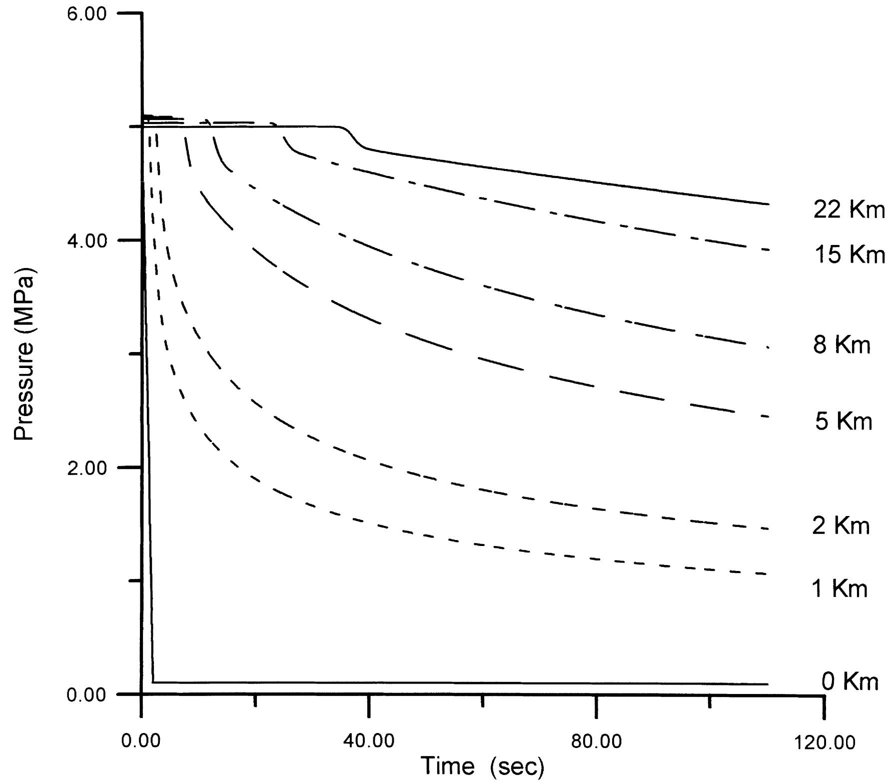

Fig. 5. Line pressure fall with time in the locations affected by the blow out. The different curves correspond to different positions along the 30 km of the analysed pipeline.

equation had to be included in the set of equations to be solved. In this way, temperature could not be eliminated as a variable by using hypotheses such as adiabatic or isentropic flow. When modelling a blow-up, abrupt changes in temperature may be expected, and therefore high temperature gradients may occur. Additionally, including conductivity is another way to perform shock-capturing. Results showed that changes in conductivity were not significant.

Finite element computational modelling was used to assess the pressure waves generated in a gas pipeline when a sudden loss of pressure occurs, due to explosions, closure of blocking valves or opening of venting valves. Non-linearities are manifested by different progradient (in sense of the flow) and regradient (opposite sense) wave propagation speeds, by the dependence of the speed of sound with the local state of the fluid, and by thermal–mechanical coupling due to compressibility effects. The numerical resolution of the problem was carried out on the characteristic lines of the canonic equations, through an implementation of the least-squares finite element method [7–9]. The program solves the one-dimensional mass, impulse and energy equations for a compressible fluid [10]:

$$\frac{\partial m}{\partial t} + \frac{\partial Q}{\partial x} = 0,$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/m)}{\partial x} = -A\frac{\partial P}{\partial x} + f,$$

$$\rho A C_v \frac{\partial T}{\partial t} = -h2\pi \mathrm{R}(T - T_0) + A\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - A\rho\frac{\partial V}{\partial x} + fV,$$

$$P = \rho \mathrm{R} T \qquad \text{(perfect gas law)},$$

$$m = \rho A,$$

$$Q = \rho A V,$$

where ρ is the mass density, A the area, R the pipe radius, V the gas speed, P the gas pressure, T the gas temperature, T_0 the external temperature, C_v the gas heat capacity, k the gas thermal conductivity, f the viscous shear force on the wall and h the coefficient of thermal transfer.

In all three cases (blow out, closure of blocking valves and opening of venting valves), the pressure distribution was analysed as a function of time and position, along 30 km of the pipe. The rapid fracture of the line gives place to an abrupt depressurisation near the broken region. This fall of pressure spreads along the line affecting the pipe wall at distant points. The abrupt depressurisation of the line in the place of the break was modelled using a contour condition that corresponds to a rate of pressure decrease of 2.5 MPa/s.

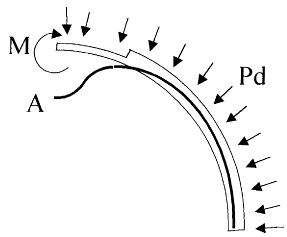

Fig. 6. Original and deformed configurations of the finite element model of local deformations under repairs, with a local 50% reduction of nominal thickness under an external pressure of 4 MPa.

The behaviour of the fluid is computed as pressure versus time, for different positions along the 30 km of the analysed line. Fig. 5 shows the fall with time of the average line pressure in the locations affected by the blow out, starting from the instant of the break. The different curves correspond to different positions along the pipeline. The pressure variations are larger at short distances downstream from the position of the break. The complete fall of pressure is in all cases equal to the operating pressure, taken in this case as 5 MPa. But the time to complete depressurisation varies from a few seconds up to several minutes

3.2. Pipe deformations

The local deformations of the pipe under the sleeve reinforcements due to external pressure were estimated with the finite element technique, using two-dimensional Kirchoff thin beam elements. The mathematical non-linearities introduced by the large displacements and post-buckling plastic deformations of the wall elements were taken into account by using the updated Lagrangian formulation and an iterative non-linear finite element model [11]. The two-dimensional analysis models the case of an infinitely long dent, and tends to overestimate the effect of the external pressure for a longitudinally short dent. Therefore, the results of the model are only qualitative.

The qualitative nature of the model would be difficult to improve, also due to the complexity of the process. The collapse occurs in a pipe under external pressure only if the geometry or the loads are not perfectly axisymmetric. Four possible forms of loss of circular symmetry were evaluated:

1. Lack of roundness of the pipe related to roofing, or deformations during handling. Roofing is a defect produced during the forming of the pipe plate, in which the portions close to the longitudinal welds are straight rather than curved as the rest of the section. Regions with less curvature are not a problem with internal pressure, but secondary stresses generated by external pressure generate a net load towards the inside of the pipe.
2. Reduction of wall thickness (most commonly due to external or internal corrosion) in large areas.
3. Local bending and partially compressive loads due to residual stresses, transverse to the seam [12]. Welding residual stresses are secondary stresses produced by differential thermal contraction during the cooling down of the weld. Cold expansion after seam welding largely reduces the trasnverse residual stresses, so their effect in the collapse conditions is presumably small.
4. Local punching loads and radial displacements applied by the sleeve into the seam weld reinforcement of the pipe, where they are in contact.

Note that the effects of punching, lack of roundness and residual stresses typically occur in areas very close to both sides of the longitudinal weld, where all collapse bumps were observed. Circumferential contraction of the sleeves after longitudinal welding (see Fig. 1) generates compressive hoop stresses on the pipe. This compression contributes to the effect of the external pressure, in promoting local buckling of the pipe wall. Although the punching force on the seam weld would cancel as soon as the two surfaces lose contact, the radial displacement could have a marked influence on the onset of the instability. Were this the main factor, however, the bumps should be more symmetrically located around the seam welds. Therefore, it is concluded that situations 1–3 have an important influence on the observed collapses. These were qualitatively assessed via simplified analytical and numerical models. Only wall reduction (case 2) was found to be sufficient to generate the necessary conditions for collapse acting alone, and is presented in some detail. Experimental and numerical evidence shows that a combination of cases 1, 3 and 4 can also introduce the necessary non-symmetries to initiate the collapse process.

3.3. Pressure variation in the interstice

The analysis of the equalisation of pressures in the line and the interstice was carried out with a model of adiabatic expansion through a hole. To assess the pressure variation with time, the gap was modelled as a container that empties through a circular hole, considering an isentropic and quasi-steady state gas evolution. The resulting equations were solved by finite differences [13,14].

3.4. Conditions for pipe collapse under the reinforcement in case of blow outs

The original and deformed configurations of the model used for the analysis of local deformations in the area of the repairs are shown in Fig. 6. This case was modelled with a local reduction of 50% of the nominal thickness, in a 200 mm wide longitudinal strip on the outer surface of the pipe. This model represents the action of an external pressure of 4 MPa, which corresponds to the depressurisation to which a repair located 1 km away from an eventual break of the line would be subjected. Lower pressure differentials were unable to provoke local buckling.

The effect of welding residual stresses was analysed by

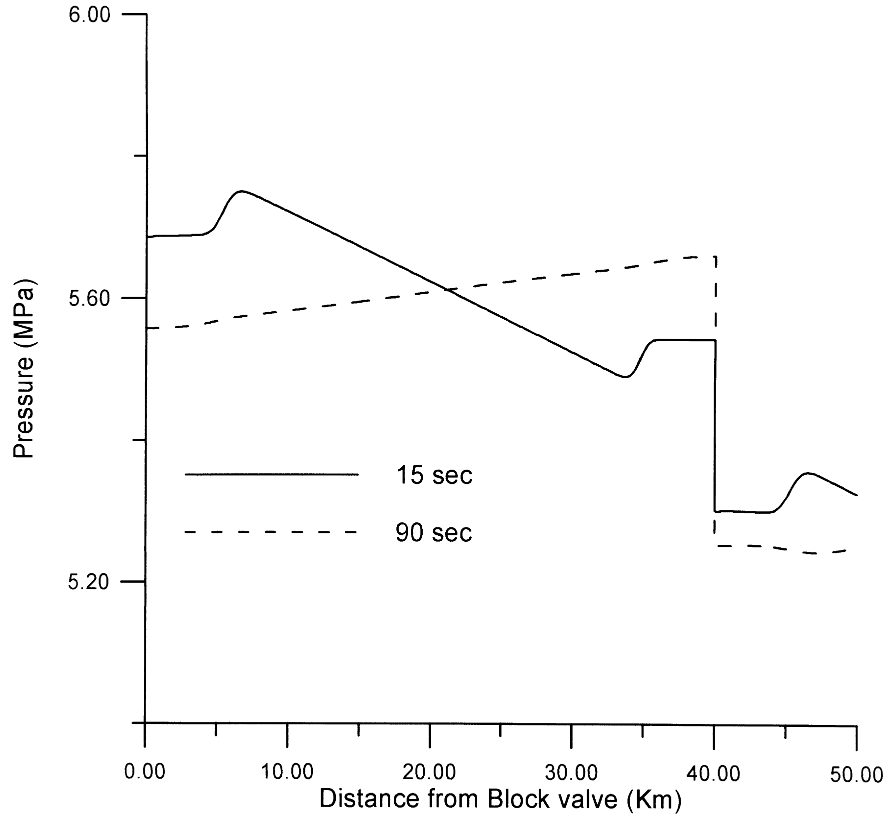

Fig. 7. Evolution along the pipeline of gas pressure, due to closing of the blocking valves, from the start of the closing up to 90 s later.

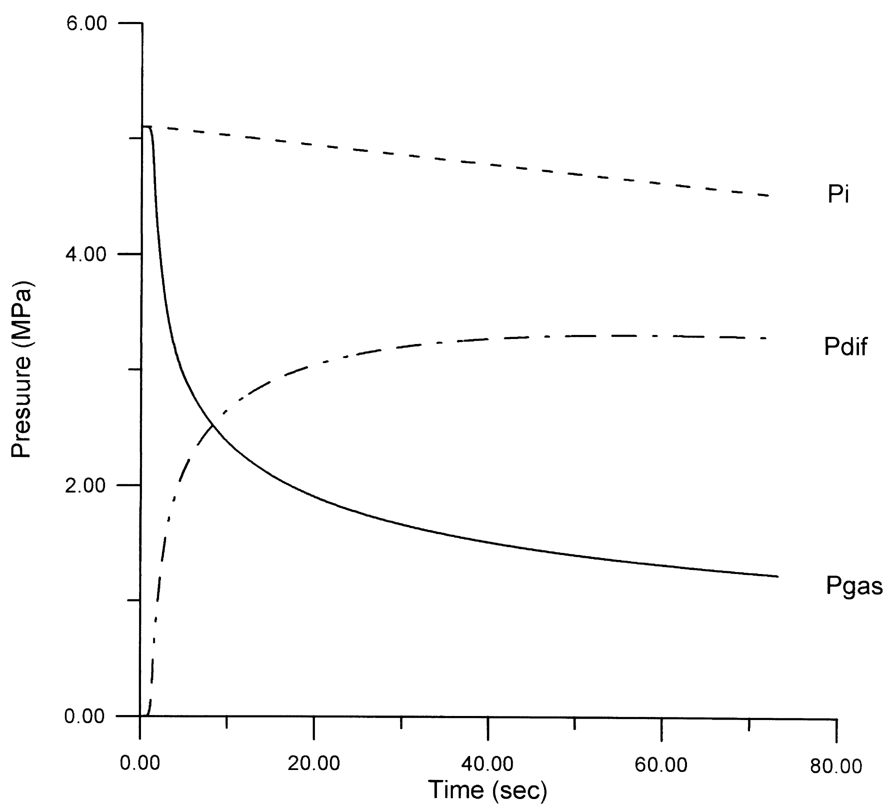

Fig. 8. Variation of pressures inside the pipe (P_{gas}), within the gap (P_i), and differential ($P_{dif} = P_i - P_{gas}$), at 500 m from the site of the blow out, with a 0.25 mm diameter perforation.

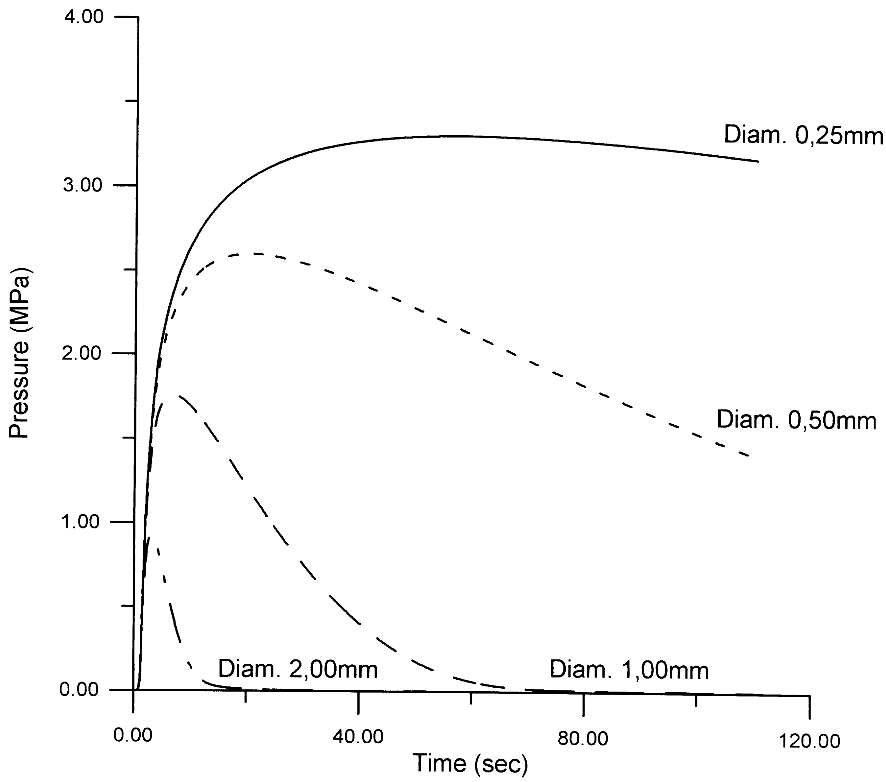

Fig. 9. Evolution with time of differential pressures inside the gap between the reinforcement and the pipe, for different diameters of perforation.

considering a localised bending distribution of circumferential stresses. The maximum stress at either surface of the pipe wall necessary to create a perturbation equivalent to the effects of the previously studied loss of thickness and lack of roundness, was 50% above the yield strength of the pipe material. Consequently, the effect of residual stresses must be combined with other factors for collapse to occur. The standard API 5 L [15] establishes a limit to the pipe out-of-roundness of ±1% diameter. For a 600 mm diameter pipe, this means a maximum variation of 6 mm in diameter along a quarter of the circumference.

Instead of modelling an ellipse, the lack of roundness of the pipe was modelled by a circumference with a 120 mm wide strip of a flat surface, which also gives approximately a maximum radial variation of 6 mm. This geometric perturbation, combined with a maximum bending stress of 25% of the material yield strength, was sufficient to provoke local buckling when the pipe was subjected to an external pressure of 5 MPa. Again, this is a qualitative model that allows justification of the occurrence of collapse, but gives confidence in the order of the pressure differential required to provoke collapse. In all the models, the maximum inward displacement of the pipe wall is predicted to be about 60–65 mm in the vertical sense (descent of point A in Fig. 6). It was expected that all the predictions would lead to a similar displacement, since this is defined by elastic equilibrium after the instability takes place.

3.5. Closing of blocking and venting valves

Blocking valves were modelled using the hypothesis of adiabatic non-isentropic flow. From the quasi-stationary gas flow regime, a blocking operation on a tract of 30 km is simulated by closing both extreme valves simultaneously. The closing of the blocking valves was assumed complete after a time of 2 s. This closing time is a more severe condition than during normal use, to maximise the influence of this operation on the variations of pressure of the line. The opening of venting valves was modelled by imposing steps corresponding to 25% of the total opening every 15 min, which is the normal field procedure [16].

Fig. 7 shows the evolution along the pipeline of gas pressure, due to closing of the blocking valves, in the interval from the beginning of the closing up to 90 s later. When these results are compared with the steady state linear pressure gradient along the pipe, it transpires that even in the area close to the blocking valve no important falls of pressure take place. Note that the maximum pressure drops are less than 1 MPa, an order of magnitude smaller than those produced by the break of the line. Similar results lead to the conclusion that the operation of the venting valves do not impose an extra demand on the integrity of the main line.

3.6. Effect of through thickness defects under the reinforcement

Fig. 8 shows as an example the variations with time of the pressure inside the pipe (P_{gas}) and within the gap (P_i), after a blow out of the pipe about 500 m upstream. These pressure changes generate during a period of several seconds a differential pressure ($P_{dif} = P_i - P_{gas}$), which produces the driving force for the occurrence of collapse of the pipe wall inside the reinforcement. In this example, a 0.25 mm diameter perforation is modelled. The results of the modelling of the differential pressures inside the gap between the reinforcement and the pipe are shown in Fig. 9. This model includes the entire annulus along the sleeve length (1 m). For a diameter of perforation of more than 1 mm, the inner and external pressures equalise quickly, and the maximum P_{dif} is about 1 MPa. This implies that the maximum value of the external pressure acting on the line is a small percentage of the depressurisation. On the other hand, it can be seen that for a 0.25 mm diameter perforation, the P_{dif} reaches about 70% of the operating pressure, and remains near its maximum value for several minutes. This implies that the line is subjected to an external pressure of the same order as the depressurisation, for a time sufficient to give rise to local plasticity and instability processes that lead to the collapse of the pipe wall.

4. Discussion of results

The experimental and numerical results described so far give sufficient information regarding the characteristics of the repaired regions of the gas pipelines where the collapse defects were observed. Visual evaluation of the main geometric aspects of the defects leads to some significant results. The average depth of the protuberances is 70 mm, with an almost constant width of 300 mm in all the cases studied. The total length of the protuberances oscillates between 90 and 250 cm. In all the cases collapse took place in an area close to the longitudinal weld. If we take as 12:00 hours the position of the weld, the collapse is located between 10:00 and 13:00 hours, with its maximum depth approximately at 11:00–11:30 hours (see Fig. 3). Losses of thickness are located in a very small area around the punctures. No loss of thickness was found in areas large enough to justify a significant effect on the formation and localisation of the collapses. Therefore, previous hypotheses that the extended loss of thickness in the pipe could have had an important role in the event should be discarded.

The numerical results conclude that collapse or local buckling occurs due to depressurisation waves generated by blow outs, in the presence of interferences or discontinuities in the pipe beneath the reinforcement that makes the section not perfectly axisymmetric. These interferences can be:

1. *Geometric:* lack of roundness of the pipe (roofing and punching against reinforcement) and reduction of wall thickness.
2. *Mechanical:* welding residual stresses.

Note that the effects of roofing and residual stresses occur in areas very close to both sides of the longitudinal weld, where all collapse bumps were observed. It is then reasonable to conclude that these two discontinuities, inevitable in pipes with longitudinal seam welds, significantly contribute to the occurrence of collapse under the reinforcement.

The numerical predictions are in good agreement with the experimental evidence. Under a sudden loss of pressure (e.g. a blow out), flow perturbations are important in the pipeline up to about 5 km from the site of the fracture (Fig. 5). The pressure fluctuations downstream and upstream from the site of the fracture are very similar, since the speed of the pressure waves is much larger than the speed of the gas flow. On the other hand, closure of blocking valves and opening of venting valves do not generate important pressure fluctuations or stresses in the pipeline. For hole diameters of less than 1 mm, the pipeline is subjected under the sleeve reinforcement to an external pressure of more than 50% of the loss of internal pressure for at least several seconds. This external pressure generates a compressive hoop stress in the pipe wall of up to about 150 MPa, which adds to the compressive hoop stresses transferred by the reinforcement. A recent study [17] showed that for normal field repair procedures, average hoop stresses can be between 50 and 100 MPa, depending on particular geometrical conditions and the gas pressure at which the repair welds are performed. These compressive stresses, along with geometric and mechanical perturbations associated with the longitudinal weld, are sufficient to justify the appearance of instability effects in the pipe wall, in the case of a sudden loss of pressure.

It was experimentally verified that the gas caught between the pipe and the reinforcement has an important role in the event. In all the failures analysed previously through-wall defects were found in the pipe under the reinforcement. Defects in non-collapsed samples have a perforated area of more than 5 mm^2. The perforations in collapsed tracts have in all cases an area smaller than 1 mm^2. The numerical models confirm that for hole diameters of more than 1 mm, the maximum external pressure acting on the pipeline under the sleeve is a small percentage of the loss of internal pressure, see Fig. 9. This suggests a possible way to minimise the recurrence of collapse failures. This is to drill a hole of appropriate size during the assembly of the reinforcing sleeve. This procedure, however, involves machining in an explosive atmosphere, and faces several difficulties when attempted along with the other routine procedures during the placement of the full encirclement repair.

The pressure differentials predicted to provoke local buckling of the pipe wall are affected by the sleeve length, as this affects the volume of gas in the annulus. The fillet welds joining the sleeve to the carrier pipe would restrain the buckle, and so a short sleeve might be expected to be more resistant to buckling than a long sleeve. However, sleeves less than 1 m long are not recommended, in order to avoid too high traction stresses that are generated into the

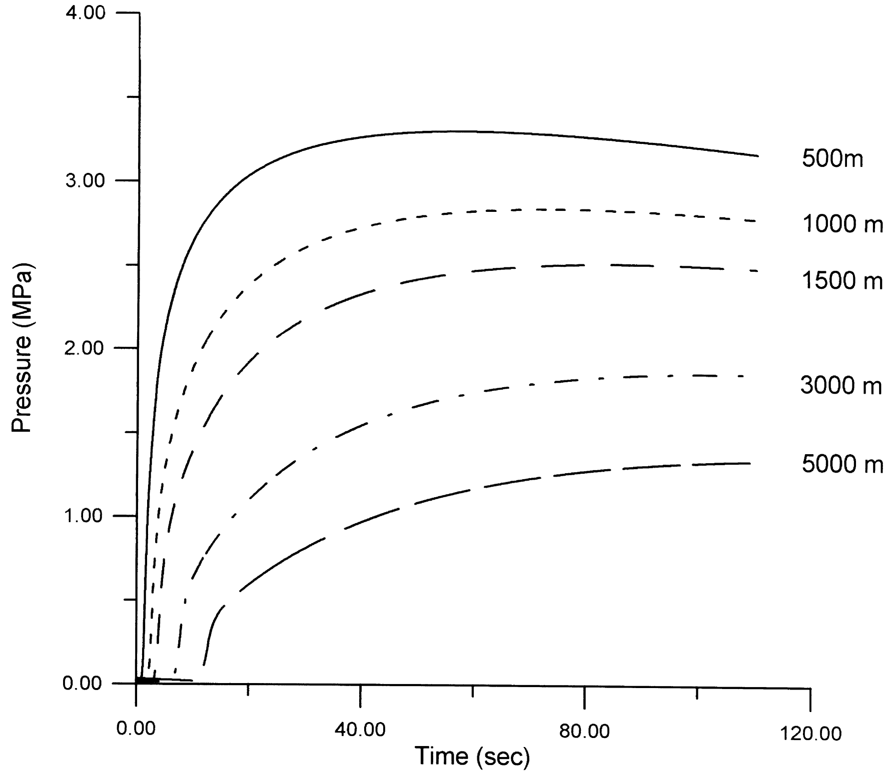

Fig. 10. Evolution with time of differential pressures inside the gap, for a 0.25 mm diameter perforation, as a function of distance from the blow out.

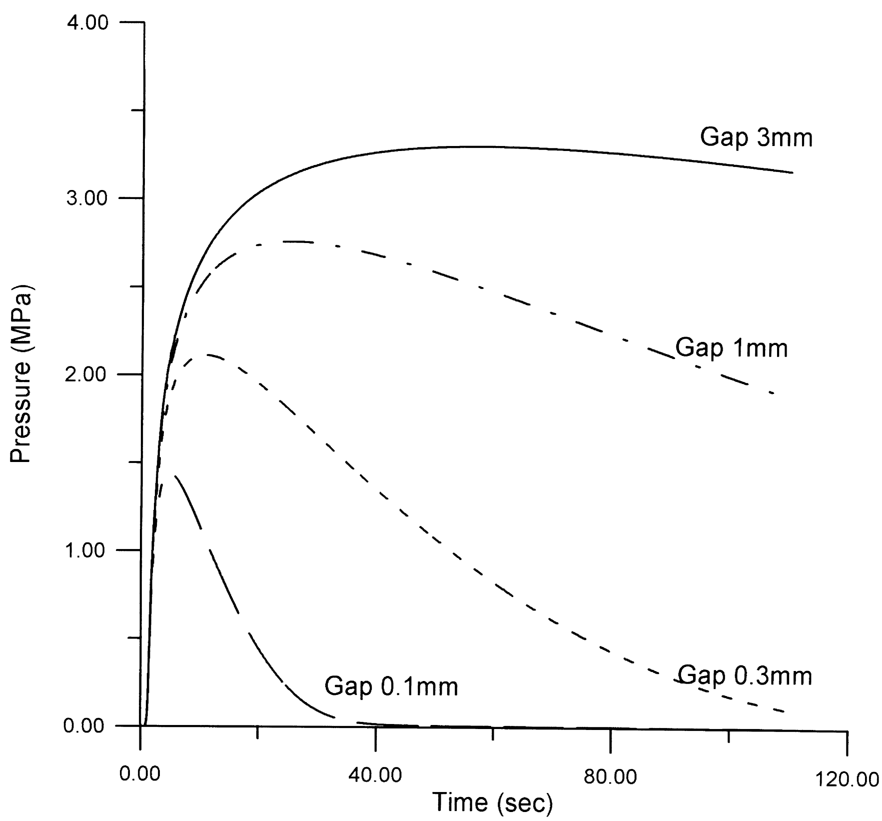

Fig. 11. Evolution with time of differential pressures inside the gap between the reinforcement and the pipe, for a 0.25 mm diameter perforation, as a function of gap thickness.

sleeve and the pipe by the contraction of the circumferential welds [17]. Longer or tandem sleeves are sometimes placed in areas of large corroded surfaces, and the collapse in these cases is more likely to occur under lower pressure differentials.

The risk of collapse is constrained to a few kilometres downstream of the blow out site. Fig. 10 shows the evolution with time of differential pressures inside the gap, for a 0.25 mm diameter perforation, as a function of distance from the blow out. Five kilometres downstream from the blow out site, the pressure variations are less than 50% of those at 500 m. The risk of collapse is also heavily influenced by the average thickness of the gap between the pipe and the reinforcement. Fig. 11 shows the evolution with time of differential pressures inside the gap, for a 0.25 mm diameter perforation, as a function of average gap thickness. Gaps of less than 0.1 mm virtually eliminate the risk of collapse. However, average gaps of less than 1 mm are difficult to obtain in field repairs, mainly due to the lack of roundness of the pipe (ovalisation and reinforcement of the seam weld) and the thickness of O'rings placed to vent gas leakage during repair [17]. Adequate pipe to sleeve welding requires maximum gaps of no more than 3 mm. In order to reduce the amount of gas trapped in the gap, filler materials are required [18].

The most promising methods to minimise the problem of pipe collapse under the reinforcement in the case of a sudden pressure drop in a gas pipeline are:

- ensure roundness and rigidity of the sleeve, to reduce geometric perturbations;
- ensure adequate contact of the sleeve with the pipeline outer surface (that is, minimum volume of gap); and
- during field repair, inject a filler in the pipe-reinforcement gap to reduce the amount of trapped gas [19].

The characteristics of the pressure waves generated by closing blocking valves or opening venting valves, under normal operating conditions, do not induce mechanical loads of relevance in the pipeline. The operation of the closing valves can be carried out quite abruptly, without inconveniences from the point of view of the line. The closing time can be reduced as much as the valve mechanisms allow it, and considering the possible existence of other mechanical effects, such as vibrations in the valve and related pipe systems.

5. Conclusions

Three gas pipeline sections were studied, with local collapse of the pipe wall under full encirclement sleeve reinforcements, and compared with a fourth region that did not collapse. The average size of the bumps was: 70 mm deep, 300 mm wide, 900–2500 mm long, all occurring very close to the longitudinal weld. In all the cases studied, through-wall corrosion holes of different sizes were found in the pipe wall. The loss of depth by corrosion always covered a small area around the holes. Therefore, extended loss of thickness can be discarded as a reason for wall collapse.

The pressure of the gas trapped in the gap between the pipe and the reinforcement significantly affects the collapse process. The numerical predictions are in good agreement with experimental evidence. Under a sudden loss of pressure (e.g. a blow out), flow perturbations are important in a length of about 5 km, both downstream and upstream from the blow out. The closure of the blocking valves and the opening of the venting valves do not generate important pressure fluctuations or stresses in the pipeline.

For hole diameters of less than 1 mm, the gap pressure under the reinforcement is larger than 50% of the loss of internal pressure. This load, along with geometric and mechanical perturbations associated with the longitudinal weld (roofing and residual stresses), is sufficient to justify the appearance of instability effects in the pipe wall. For hole diameters of more than 5 mm, the maximum external pressure acting on the pipeline under the sleeve is a small percentage of the loss of internal pressure. Possible ways to minimise the recurrence of collapse failures include increasing the size of the corrosion hole (if possible), improving roundness and rigidity of the sleeve, and reducing the gap volume by ensuring adequate contact of the sleeve with the pipe surface and/or injecting a filler in the gap to reduce the amount of trapped gas.

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References

[1] American Petroleum Institute. Recommended pipeline maintenance welding practices, API RP 1107, USA.
[2] Otegui JL, Rivas A, Manfredi C, Martins C. Weld failures in sleeve reinforcements of pipelines. Engng Failure Anal 2000 (in press).
[3] GIE Report 3-5/97. Evaluación de las causas de fallas en gasoducto, por colapso interno bajo refuerzo de unión recta. Transportadora de Gas del Norte S.A., 1997.
[4] Dodge RA, Thompson MJ. Fluid mechanics. New York: McGraw-Hill, 1937.
[5] Guyer EC. Handbook of applied thermal design. New York: McGraw-Hill, 1989.
[6] Petukhov BS. Heat transfer and friction in turbulent pipe flow with variable physical properties. Adv Heat Transfer 1970;6:503.

[7] Carey GF, Jiang BN. Least squares finite elements for first order hyperbolic systems. Intl J Numer Meth Engng 1988;26:81–93.
[8] Donea J, Quartapelle L. An introduction to finite element methods for transient advection problems. Comput Meth Appl Mech Engng 1992;95:169–203.
[9] Zienkiewikz OC, Taylor C. Finite Element Meth 1989;2:451–2.
[10] Shapiro AH. The dynamics and thermodynamics of compressible fluid flows, vol. 2. New York: Ronald, 1953.
[11] LUSAS non linear finite element stress analysis and design system. FEA LUSAS Ltd., UK, 1997.
[12] Kiefner JF, Maxey WA. Evaluating pipeline integrity. Flaw behaviour during and following high pressure testing. AGA PRCI Seventh Symp on Line Pipe Research, Houston, paper 15, 1986.
[13] Crane E. Flujo de fluídos en válvulas, accesorios y tuberías. New York: McGraw-Hill, 1988.
[14] Bird RB, Stewart WE, Lightfoot EN. Fenómenos de Transporte. Editor Reverte S.A., 1976.
[15] American Petroleum Institute. Specification for line pipe, API 5L, USA, 1995.
[16] GIE Report 3-9/97. Evaluación del efecto del tiempo de cierre de las válvulas de bloqueo sobre las variaciones de presión en el gasoducto. Transportadora de Gas del Norte S.A., 1997.
[17] Chapetti MD, Otegui JL, Manfredi C, Martins CF. Full scale experimental analysis of stress states in sleeve repairs of gas pipelines. Int J Press Ves Piping 2000 (in press).
[18] GIE Report 4-6/98. Evaluación de fillers intersticiales para refuerzos de unión recta. Transportadora de Gas del Norte S.A., 1998.
[19] Kiefner JF, Bruce WA, Stephens DR. Pipeline repair manual. AGA Cat. No. L51716, American Gas Association, 1994.