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Influence of multiple sleeve repairs on the structural integrity of gas pipelines

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Abstract

This paper addresses the structural integrity of gas pipelines with multiple full-encirclement weld repairs. The scope of the work is to identify and quantify the effects of the number and type of repairs, the distance between them, and the pressurization of the pipe to sleeve gap on the mechanical behaviour of the component. The study includes full-scale experimental testing and finite element modelling. Burst tests were carried out in tracts of pipelines removed from service, including various geometric configurations with and without circumferential girth welds. It is concluded that the reliability of the repairs is strongly influenced by the construction procedures and that interaction effects between successive repairs are not appreciable if the repairs are more than a half pipe diameter apart.

Keywords: Pipeline repairs; Full-encirclement weld repairs; Structural integrity

1. Introduction

Full-encirclement welded sleeves are a common practice for repairing or reinforcing defective gas pipelines, on which localized loss of thickness or gas leakage are detected. Standard designs can be found in Appendix B of API RP 1104 [1]. They consist of two half sleeves welded lengthwise, which could include circumferential (girth) fillet welds to the pipe at their ends (Fig. 1). Repairs which are not welded to the pipe, are used for reinforcement purposes, and they are referred to in this work as clamp reinforcements. On the other hand in the presence of a gas leakage or other severe defects, the repair requires the circumferential weld to prevent gas leakage during the subsequent service. These are referred to here as shell reinforcements.

Sleeve repairs can modify the structural response of the pipeline, increasing its stiffness and originating zones of high stress at the ends of the sleeve. Hence, stress distributions in the area of the sleeve-to-pipe girth welds can be identified as a critical point of the repair. The eventual failure of the repair, typically in the longitudinal or girth welds, depends upon various factors [2]. These are loading, geometry and arrangement of the sleeves, and welding procedure. Applied loads come from internal pressure, gap pressurization due to gas leakage into the sleeve, and longitudinal and bending stresses, which depend on the buried pipe condition and soil settlement.

Present regulations [3] and specialized studies [4,5] consider isolated repairs only. However, it is easy to find pipes with two or three adjacent sleeves in aging systems. The relevance of the present work is defined by the need to optimise the reliability of pipeline repairs and to obtain experimental data describing the influence of multiple repairs on the structural integrity of pipelines. The present work aims to determine the strength of installed repairs, to identify and quantify the interaction between successive sleeves, and to define acceptable limits to the installation of multiple repairs. Six burst tests involving 20 repairs were carried out on ex-service tracts of pipeline. Experimental tests are complemented with numerical FEM models devised to extend the analysis to other geometries and loading conditions.

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Fig. 1. A tract of pipe with multiple sleeve repairs being prepared for hydrostatic burst testing.

2. Experimental procedure

Experimental tests were performed on six tracts of gas pipeline removed from service during the year 2000, (API 5LX52 pipe of 609.6 mm diameter and 7.9 mm wall thickness). The pipe age is about 40 years, and the ages of the repairs range from 5 to 20 years. Due to the wide variations in age, the toughness of pipe and sleeve base materials are between 70 and 100 MPa $m^{1/2}$. As depicted in Fig. 2, experiments include 20 sleeves, six of which are clamp repairs, nine are shell repairs and two are tandem repairs, consisting of multiple reinforcements welded to each other. The tracts were plasma cut and test manifolds welded at their ends, resulting in 16–20 m long vessels with semi-elliptic heads. Lengths of sleeves are 0.60, 1 or 2 m; wall thickness of sleeves is 7.9 mm.

Pressure was monitored by means of a class 0.25 (error%) pressure transducer. High-deformation strain gages were employed to measure strains in the longitudinal and circumferential directions at different positions on the sleeves and the pipes. The noise-to-signal ratio was less than 1%. Maximum measurement error was estimated to be lower than 2%. Pressure and strains were recorded by means of a data logger for pressure increments of 5 bar until failure. Hoop, longitudinal and equivalent von Mises stresses in the sleeves and the pipes were determined, assuming elastic behaviour. Linear response to low pressures allowed an estimate of the 0.2% yield strength, thus limiting non-linear behaviour on pressure versus strain plots.

Results of the burst tests are shown in Fig. 3. Also included in the figure are some representative pressures of pipeline operation: the maximum allowable operating pressure (MAOP), the pressure corresponding to specified minimum yield strength (SMYS), and that corresponding to 110% of the SMYS. This last pressure is used during hydrostatic retesting in order to ensure integrity when stress corrosion cracking damage is expected in the line. All burst pressures are well above the highest possible in-service pressure, which means that none of the replaced repairs would have reduced the pressure capacity of the pipeline.

Earlier work by the authors [3] showed that the causes for failures in welded full-encirclement sleeve repairs are often related to poor manufacturing procedures. Among them: sleeve materials with poor transverse strength, high heat input cellulosic electrodes used for field joints, hydrogen embrittlement in HAZ, high circumferential stresses, and lack of fusion and other weld defects. Although the sleeves tested in this study were more than 10 years old and no epoxy fillers were used during their installation, none of the failures was related to quality problems.

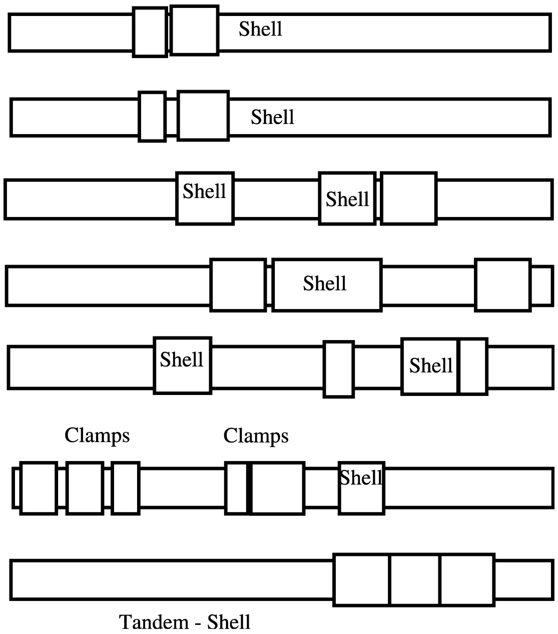

Fig. 2. Geometries of the six tracts tested, from 1 (top) to 6 (bottom), showing size and position of each sleeve reinforcement.

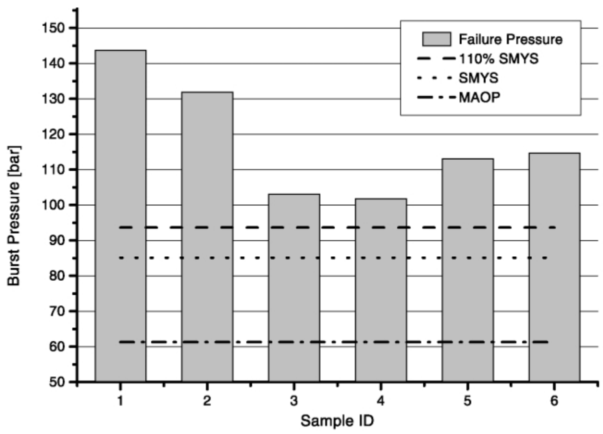

Fig. 3. Burst pressure results of the six instrumented hydrostatic tests, and comparison with representative pressures of pipeline operation.

Plastic collapse was always the origin of the failures. In three of the tests, failure occurred at localized metal loss spots far away from the repairs. In one case, a crack propagated into the HAZ of a girth weld. For the remaining three tests failure took place at the repairs. In every case leaking was detected before plastic deformation. Samples including clamps failed under the repairs. Longitudinal welds were found as the critical points for the shell repairs. Final failures always happened in the HAZ or weld metal of these longitudinal welds, preceded by the failure of the defects under the repair. In every case, fractures were arrested at the girth welds, and never extended to the pipe.

3. Numerical modelling

Eighteen axisymmetric finite element models were analyzed in order to validate experimental results and to extend the analysis to other geometries and loading conditions. The Algor [6] software package was employed. A schematic with model dimensions is depicted in Fig. 4.

Reports by the Pipeline Research Committee of AGA [5] show that in the case of single shell repairs, stress levels at girth welds are almost independent, or have a weak dependence on H/D in the range $1.5 < H/D < 4$, where D is pipe diameter and H is sleeve length. At the same time it is shown that the ratio of the thicknesses of pipe and sleeve, t_1/t_2, is important and that the pipe to sleeve gap mainly affects the stress distribution at the weld root (point C in Fig. 4).

In the spirit of the results referenced above the selected geometry has an external diameter $D = 609$ mm (24 in.) with pipe and repair wall thicknesses $t_1 = t_2 = 8$ mm and a sleeve length $H = 910$ mm. From the inspection of the samples it was found that gap values, g, were in the range between 1 and 3 mm ($0.125 < g/t < 0.35$). The distance L between adjacent reinforcements was studied for values ranging from 7.5 to 910 mm ($0.008 < L/H < 1$). In the case of clamp reinforcements, the condition of perfect adherence between the pipe and the reinforcement was assumed, resulting in a model of a pipe with wall thickness $t_1 = 16$. Material behaviour was set to be linear elastic for all cases.

Applied loads involved internal pressure with and without gas leakage under the repair, under ideal buried pipe conditions (zero longitudinal displacements). The effect of the longitudinal component of the residual stresses due to the pipe-to-sleeve circumferential welds was also

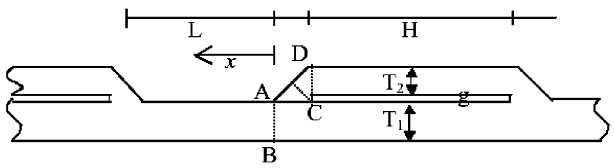

Fig. 4. Schematic with dimensions of axisymmetric finite element models.

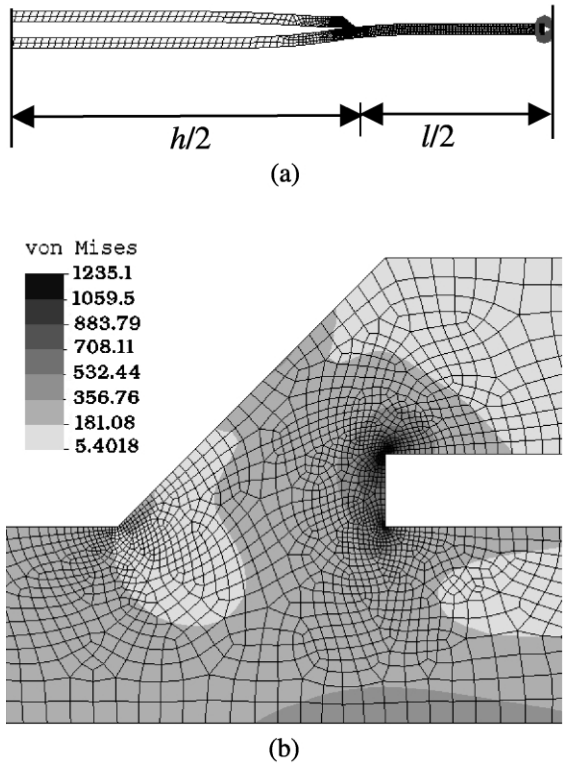

Fig. 5. Example of model discretization (deformed), using bilinear quadratic and triangular elements with symmetry boundary conditions.

assessed for the shell repairs. These stresses were superimposed to those originated by the applied loads. Residual stresses were modelled recurring to a thermo-elastic model in which a fictitious cooling was applied to the sleeve. In this way, a longitudinal traction stress is induced in the reinforcement, which is equilibrated by compression in the pipe.

A sample mesh (deformed) is shown as an example in Fig. 5. Model discretization was made using bilinear quadratic and triangular elements with symmetry boundary conditions (no displacement in the longitudinal direction) in the sections coincident with half the repair length and half the distance between repairs. Fig. 5(a) shows the typical response of the pipe between the sleeves. It could be seen how the pipe 'inflates', being restricted at the ends by the sleeves. This effect is responsible for the stress distribution in the wall thickness, with maximum values at the outer surface. Fig. 5(b) shows in detail the stress distribution in the vicinity of the circumferential weld, with the highest stresses localized at the toe and the root (points A and C in Fig. 4).

4. Discussion of results

4.1. Shell reinforcements

Figs. 6 and 7 show numerical and experimental results for the longitudinal S_L and circumferential S_C components

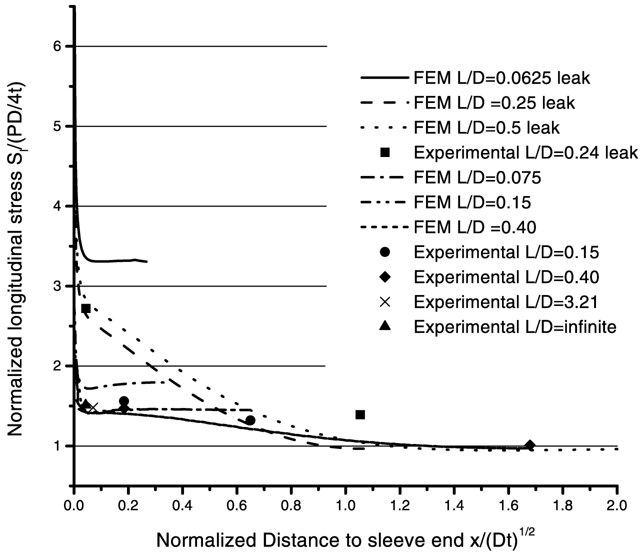

Fig. 6. Numerical and experimental results for the longitudinal S_L component of the stress field in the outer surface of the pipe between two shell reinforcements.

of the stress field with the distance to the weld toe, in the outer surface of the pipe between two shell reinforcements. The results are given for different distances between reinforcements L, normalized with respect to pipe diameter D. According to axisymmetric thin shell theory, the distance to the weld toe is normalized by $\sqrt{(Dt)}$ in the abscissa (Fig. 4). Stresses are also presented in normalized form, in this case with respect to the nominal stress corresponding to a pipe without reinforcement. The figures include results for cases with and without gas leak under the reinforcement. The validation of the numerical curves is given by the experimental results, included as hollow symbols. A reasonable correlation between the numerical and experimental data is observed. Local variations in wall thickness and pipe ovality could account for these discrepancies.

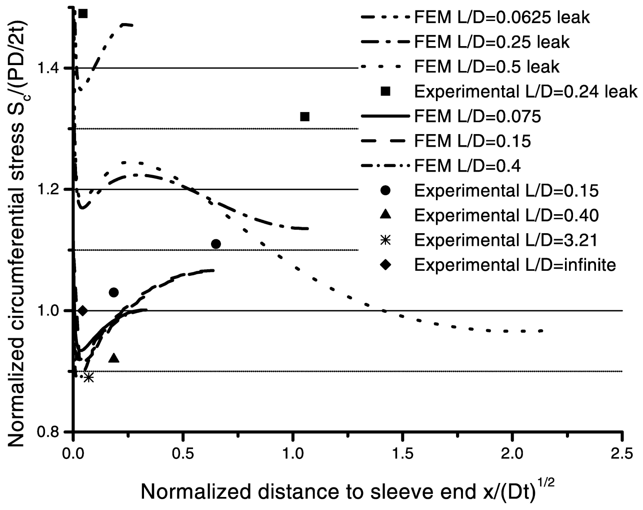

Fig. 7. Numerical and experimental results for the circumferential stress S_C in the outer surface of the pipe between two shell reinforcements.

Figs. 6 and 7 show that the stress levels on the pipe are always higher for the loading cases including gas leaks. These outer surface stress values diminish inside the pipe wall. This stress distribution is due to the effect of the 'inflation' described above. Secondly, it is observed that the position of the weld toe ($x/\sqrt{(Dt)} = 0$) is the area that presents the highest stresses, with values reaching five times the nominal longitudinal stress and 1.5 times the nominal circumferential stress. It is also observed that stresses in the weld show a weak dependence on the pipe to sleeve gap for values in the range $0.125 < g/t < 0.35$. Results in Figs. 6 and 7 enable the minimum distance that should exist between two adjacent reinforcements to be determined to avoid these interference effects. This distance is given by the position at which both stress components (longitudinal and circumferential) on the pipe reach their nominal value (that is, normalized stress equal to 1). This distance corresponds to approximately $L/D = 0.4$, that is 245 mm for a pipe diameter of 609 mm. Similar results were obtained for the load case assessing residual stresses.

As it was already mentioned, the weld zone constitutes the critical section of the repair. This is in agreement with results from the Edison Welding Institute [4] for the AGA PRC Project PR-185-014 for a single reinforcement, where the section A–B (Fig. 4) is reported as the critical one for a defect located at the weld toe. For this reason, the effect of the distance between reinforcements on the longitudinal stress distribution in the section was assessed. Fig. 8 shows the distribution in the wall thickness (where the origin $z/t_1 = 0$ corresponds to the inner surface) of the longitudinal stress component for the load case given by internal pressure. The results obtained in Ref. [4] are also included for comparison. Excellent correlation is observed with the results of this work. These results demonstrate that the effect of the proximity between two reinforcements is significant for distances $L/D < 0.07$ (around 40 mm for pipes diameter of 609 mm). The largest effect appears at the weld toe, which is an important stress raiser. Similar trends were observed for

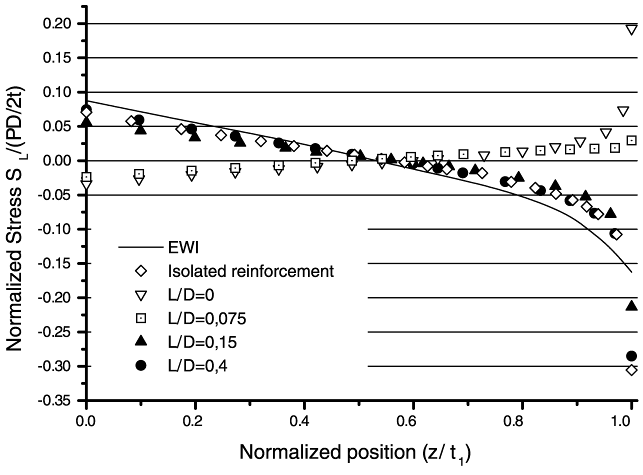

Fig. 8. Distribution in the wall thickness ($z = 0$ is inner surface) of longitudinal stresses due to internal pressure.

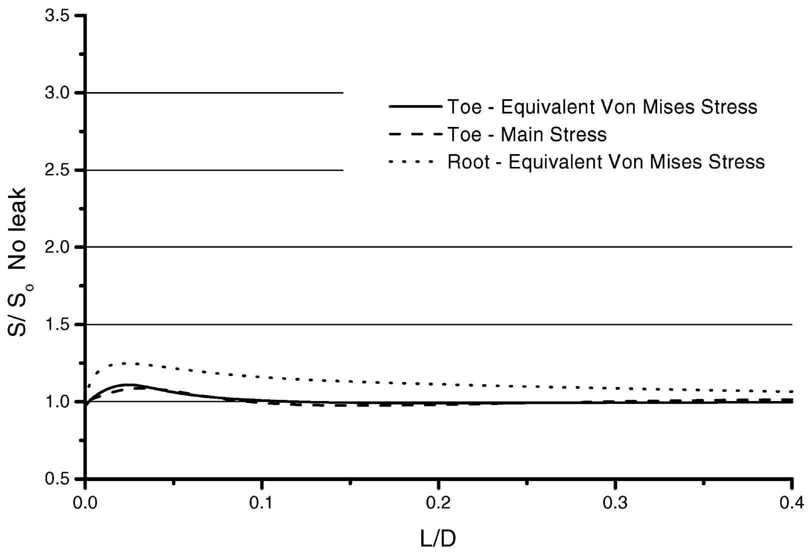

Fig. 9. Effect of distance between reinforcements on maximum principal and von Mises stresses at the toe and root of a girth weld, when subjected to internal pressure and longitudinal traction.

the load cases given by longitudinal traction and internal pressure with gas leak under the reinforcement.

Maximum principal and von Mises equivalent stresses at the toe and the root of the weld are plotted as a function of the distance between reinforcements in Figs. 9 and 10. The load cases include internal pressure and longitudinal traction, with and without gas leak, respectively. Note that the normalizing stress parameters S_0^{leak} and $S_0^{\mathrm{no\ leak}}$ refer to the corresponding stress (von Mises or main) in each location (root or toe) of the girth weld for a single reinforcement. The effect of the distance between repairs is weak when only the effect of the internal pressure is considered, with maximum stress increments of around 25% (Fig. 9). On the other hand, when gas leak is considered the picture changes (Fig. 10). While the stress level in the root of the weld remains almost unaltered, stresses at the toe

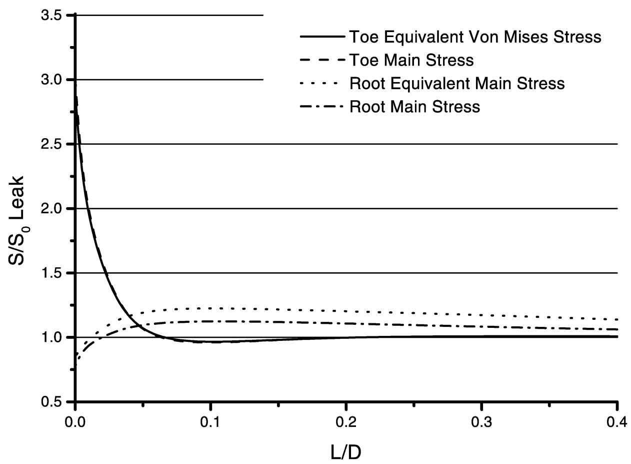

Fig. 10. Effect of distance between reinforcements at the toe and root of a girth weld, when subjected to internal pressure, longitudinal traction and pressurization of gap.

dramatically increase up to 300% of the nominal value for very close reinforcements. It is worth nothing that the locally high stresses at the weld toe are a mesh dependent numerical artefact of the sharp notch, and will not occur in practice. In this way and in order to make the comparison between the different geometries valid, the same discretization was used for all models.

These results compare well with the results of a previous study by the authors, in which the stress states in sleeve materials were assessed [7]. 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. High stresses were found in tests carried out with short sleeves and O'rings, and occurred once the reinforcement was fully welded and the pipeline pressure re-established. Maximum stresses, up to 270 MPa, were generated on tests with artificial gas leaks.

4.2. Clamp reinforcements

The difference between clamp and shell reinforcements is that the former lacks the girth weld. In the case of clamps, the load transfer between the pipe and the reinforcement is given by contact forces. The limiting case corresponds to perfect adherence between pipe and reinforcement, a reasonable hypothesis only for reinforcements with zero gap. At the other extreme, there are reinforcements with a large gap, for which the sleeve does not interfere with the pipe.

Numerical and experimental results for the stress fields in the pipe are shown in Fig. 11. Numerical results correspond to the case of perfect adherence between the pipe and the reinforcement. Results for a large gap would lead to a constant normalized stress value equal to one, and experimental results should lie between these two extreme

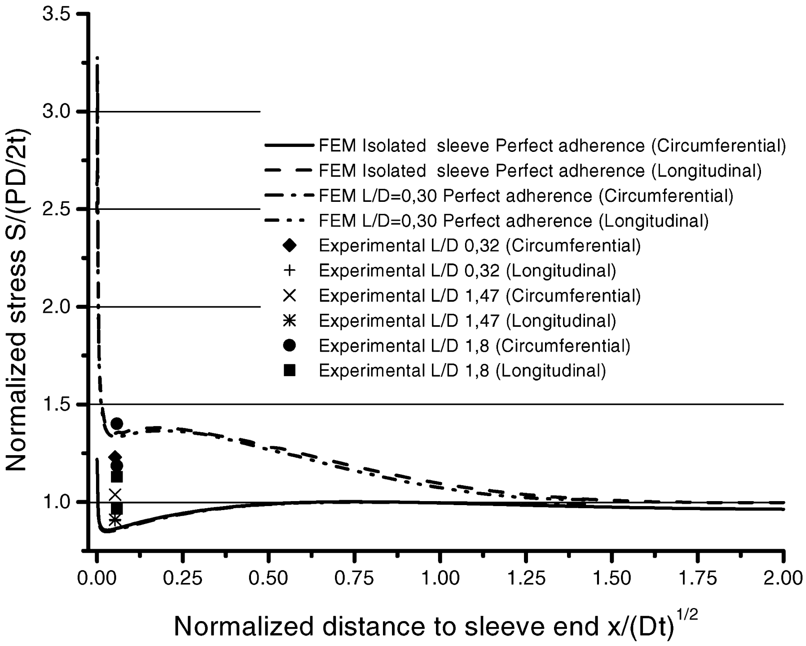

Fig. 11. Numerical and experimental results for the stress fields in pipe material close to a clamp repair.

conditions. However, the experimental results present quite a large dispersion. Local variations in wall thickness and pipe ovality could be the reason for these discrepancies. Note that the stress distribution presents the same general behaviour as that for shell reinforcements (Figs. 6 and 11). Discrepancies arise in regions very close to the reinforcement, due to the differences in local geometry. Experimental and numerical results for stresses in the reinforcement are depicted in Fig. 12. It can be observed that numerical results for stresses at locations far from the ends of the reinforcements are about twice those on the pipe (Fig. 11). This was expected as the model wall thickness in this region is double that of the pipe. At the same time, it is easy to see that results for a large gap would lead to zero stresses on the reinforcement as no load is transferred to the pipe. Consequently with this observation experimental results are lower than the numerical ones. Stress levels in the vicinity of the reinforcement ends do not show significant variations for different sleeve lengths.

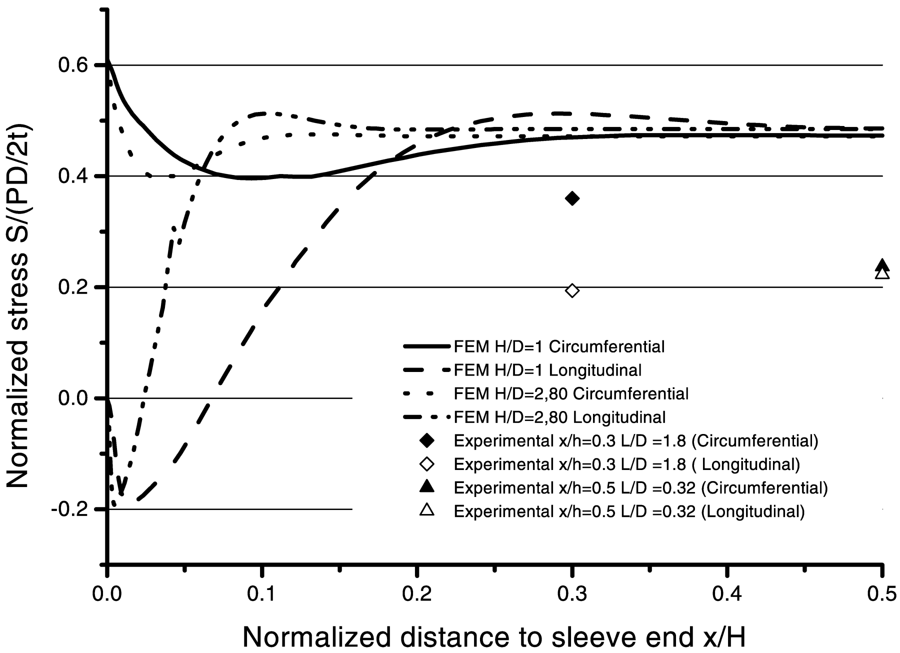

Fig. 12. Numerical and experimental results for the stress fields in sleeve material in a clamp repair.

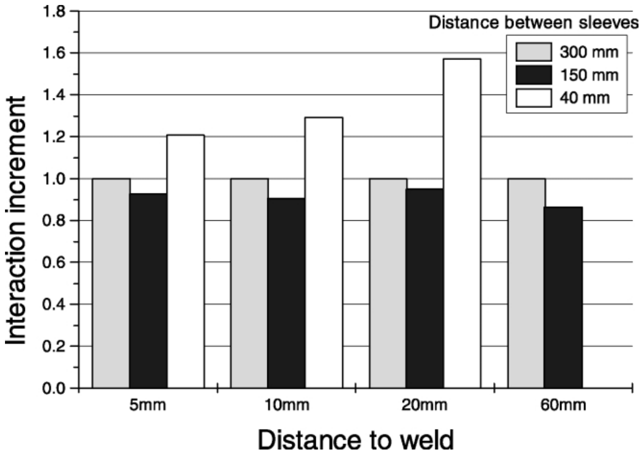

Fig. 13. Interaction between two successive reinforcements, defined as the increase in longitudinal stresses with respect to a single repair.

5. Conclusions

Experimental and numerical (finite element modelling) work is reported in this paper, to identify and quantify the effects of multiple repairs on the structural integrity of gas pipelines. Addressed variables include the number and type of repairs, the distance between them, and the pressurization of the pipe to sleeve gap. Instrumented hydrostatic burst tests were carried out in tracts of pipeline removed from service, representing various geometric configurations with and without circumferential girth welds. Fig. 13 shows the experimental and numerical results on the interaction distances between two successive reinforcements, where the interaction increment is defined as the ratio between longitudinal stresses for various distances between adjacent sleeves with respect to a single repair.

It is worth noting that the present work only covered one t/D pipe ratio. However, we expect our results to be valid over a wide range of t/D based on the results reported by AGA [4] in a study for a single repair. In their work, researchers from AGA found that for the different load cases considered the stress results are 'almost independent' or at most 'relatively insensitive' to t/D for the range $24 < t/D < 48$. Nevertheless new results are needed to confirm our assumption.

According to the experimental and numerical results of the present study, it is concluded that the reliability of the repairs is strongly influenced by the construction procedures, but appreciable interaction does not exist between successive repairs if they are at least a half pipe diameter apart.

Acknowledgments

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