EAN 2013
51th conference on experimental stress analysis

High-Pressure Pipelines Repaired by Steel Sleeve and Epoxy Composition

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Keywords: Repairing pipes, Cold sleeve, Stress of welded joint, Cohesive finite element.

Abstract. The aim of this paper is first to determine the state of stress of welded joint repaired by steel sleeve and epoxy composition. Experimental measurements are performed on samples to determine required material properties. The structural analysis by finite element method (FEM) is performed for a pressurized pipe with insufficiently welded root and installed cold sleeve. Simulated is the case of depressurized pipes that could cause a breach of cohesion between filling material and surface of pipe or sleeve with usage of cohesive finite elements. In the end the sleeve dimensions are optimized with respect to maximum integrity to the repaired sleeve.

Introduction

Older metal pipelines have a lot of different types of material failures or defects [1, 2]. Defects are identified during different actions on the pipelines, as are internal inspection methods, or other activities like making a control probes, pipeline rehabilitation, searching gas-escape and similarly. Comparable carrying capacity of repair of the damaged pipe with the pipe without disturbance can be achieved by applying steel sleeves filled welds to pipe with composite epoxy (Fig.1), which could include circumferential (girth) fillet weld [3]. Repairing pipes with cold sleeve we can reduce stresses at failure, and provide sufficient corrosion resistance of pipelines for the next operation.

Fig.1. Installed cold sleeve.

The disadvantages of these methods are a low resistance and low axial tensions the security protection in case of seepage pressure medium and short lifetime repairs. Installation of the proposed sleeve takes place in the full operation of the pipeline. The repaired place of the pipeline is cleaned from the original coating. For maximum adhesion between polymer filler and pipe surface or surface of the sleeve, these surfaces are cleaned. Subsequently, the two halves of the sleeve are mounted on the pipe and the space between the sleeve and the pipeline is defined by distance prisms (Fig. 2). Then the sleeve is welded by the classical ”V” weld and is sealed with a bandimex clamp and shrink wrap (Fig. 3). The tension spring is creating space and conditions for a continuous, integral filling of the space between the sleeve and the repaired pipe. Finally, by using the filler the space between the sleeve and the pipe is filled by polymer. This type of sleeve is used for the repair of insufficiently welded roots too.

Problem formulation

For accurate reproduction of the stress state for all components of the cold sleeve, the procedure of cold sleeve installation has to be simulated. During the cold sleeve installation the pipeline is loaded by internal gas pressure and axial force. The cold sleeve and polymer adhesive are at stress-free state at this time. The cold sleeve and polymer are stressed when we change the value of internal pressure.

Polymer material used in the cold sleeve is based on PROTEGOL polymer. We note that PROTEGOL is polymer successfully used as anticorrosion protection on steel pipes and constructions placed under ground. It is one of the materials with the highest quality which is used for the rehabilitation of transit pipeline.

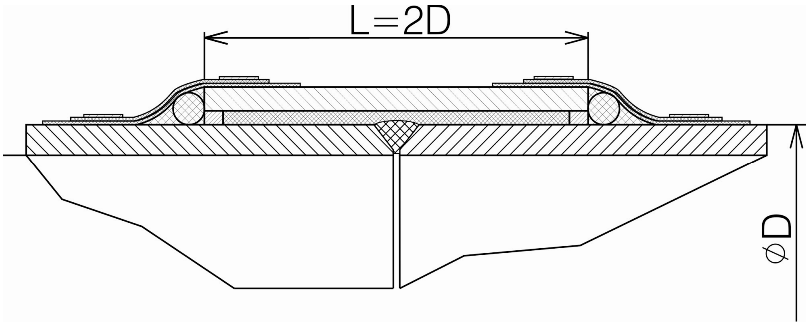

Fig.2. Cut pipe with installed cold sleeve.

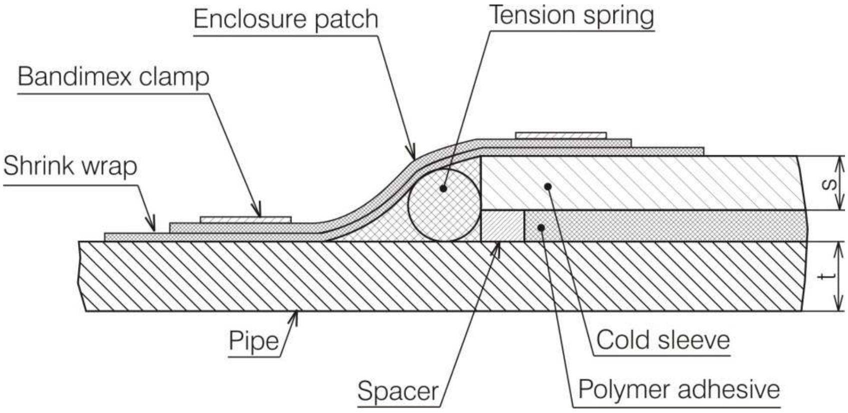

Fig. 3. Cross-section of installed cold sleeve.

The size and shape of the weld is created in compliance with the norm STN 131075 (Slovak technical norm). In Fig. 3 is a cut through the pipe with a cold sleeve installed. For simulation the pipes with diameters 1220 and 1420 mm are considered.
Material properties of PROTEGOL based polymer were experimentally measured. The two-parameter Mooney-Rivlin hyperelastic constitutive model was used [4]. General models for modelling of rubber-like materials are given in [5]. The quality of adhesion between the polymer layer and pipe or sleeve was characterised by DPARAM parameter. The value of this parameter lies between 0 and 1 where 0 or 1 represents total adhesion or total separation of adjacent surfaces. Critical values of DPARAM parameter were obtained when the pipe depressurisation occurs.

Experimental procedure

To get material input data needed to perform the finite element (FE) simulation were made two experimental tests. To determine the material properties of the modified polymer PROTEGOL tensile tests of test samples (Fig. 4) was carried out in accordance with standard norm BS EN 10002-1. The testing machine Zwick 1361 with force measuring range (0.002 – 50) kN for the static tensile test was used (Fig. 5). For measuring of deformation was used system ARAMIS HS [6].

Fig. 4. Test sample.

Fig. 5. Tensile test.

The results of this test are given in Fig. 10 and they show the statistical behaviour of the specimens with a large variance of maximum force. The maximum force required to tear the specimen is in the range < 200, 500 > [N]. In our opinion a large variance of maximum force is mainly due to the chemical composition of polymer, surface and internal inhomogeneity of the material and method production of polymer, because the conditions of carrying out the test were the same.

The next test, which was necessary to obtain input data for the FE simulation by using cohesive FE was the tearing test. For this test cylindrical test specimen were made (Fig. 6). The specimen was attached to the ZWICK tensile machine. Fig. 7 displays the tearing of the specimen in the tensile machine. Fig. 8 shows in the detail experimental results of displacement distribution in the location of the tearing, with the highest displacements localized at the test specimen edges. Fig. 9 shows results of displacement distribution obtained by FE simulation using ANSYS software. The tearing test results showed the similar behavior as the tensile test results. The maximum tearing force is 4150N (Fig. 11).

Fig. 6. Test specimen.

Fig. 7. Tearing of the test specimen.

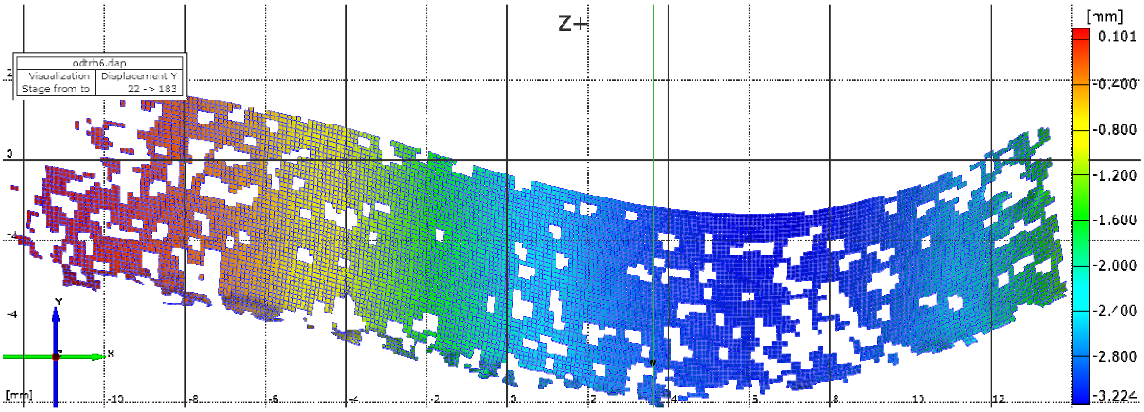

Fig. 8. Detail of tearing of the speciment.

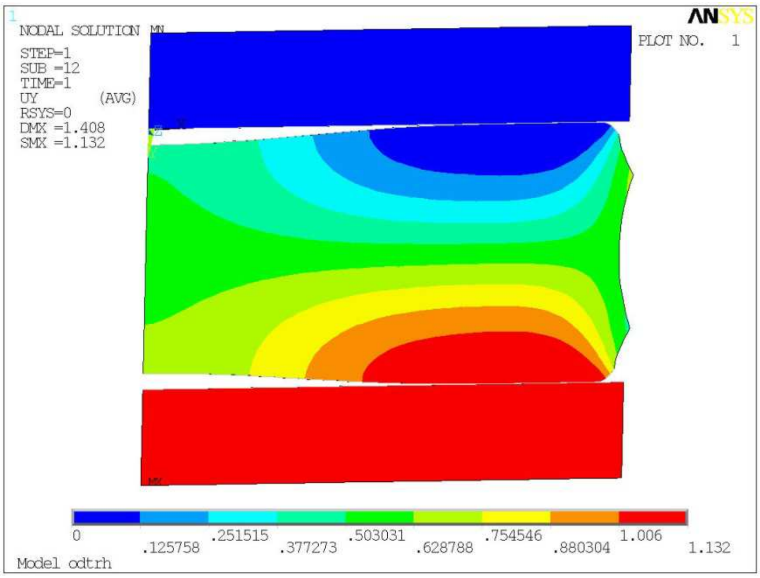

Fig. 9. FEM displacemet results of thearing.

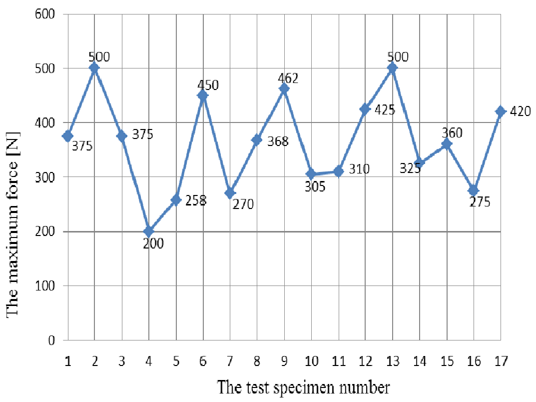

Fig. 10. The results of tensile test.

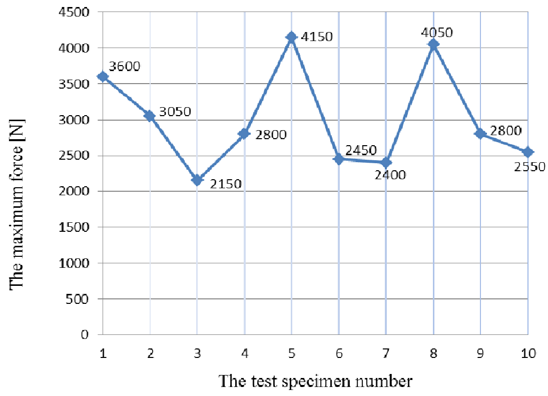

Fig. 11. Tearing force.

FEM simulation

Over the last two decades, a number of finite element simulations of sleeve repairing welding have been conducted to investigate the stress fields. The commercial finite element code ANSYS [7] was used for static nonlinear analysis to obtain stress state of all parts and risk assessment of debonding. Analysis was performed on the pressurized pipe with a subsequent depressurization to atmospheric pressure. Operating pressure was 7.35MPa. Based on above given tests, we decided to use a two-parameter Mooney-Rivlin hyperelastic constitutive model for polymer. To determine the parameters of the Mooney-Rivlin model we broke 10 specimens. Additional three samples were used to tune the attachment to tensile testing machine and 4 specimens for optical tuning of the spray for the system ARAMIS. From the performed FEM calculations we evaluated the separation of polymer from the surface of the pipe and the sleeve using the parameter d_n or DPARM.

The axisymmetric FE model with additional plane symmetry was used. For steel parts PLANE183 element was used [8]. This element has a quadratic displacement behavior. For the polymer part PLANE182 element was used. This element has a linear displacement behavior. The combination of PLANE183 element with the two-parameter Mooney-Rivlin model had convergence problems. Contact elements CONTA171 and TARGE169 with a cohesive zone material (CZM) model were used to simulate debonding of adjacent surfaces. The CZM model consists of a constitutive relation between the traction **T** acting on the interface and the corresponding interfacial separation **δ** (displacement jump across the interface). The mode I dominated bilinear CZM model was used. The Mode I dominated bilinear CZM model assumes that the separation of the material interfaces is dominated by the displacement jump normal to the interface, as shown in Fig. 12.

The simulation consists of two steps. In first step only the pipeline under internal pressure was solved. Radial displacement was stored in parameter and saved to disk. This parameter was used in a second step to modify geometry of the cold sleeve. This is necessary because the gap between the pipe and sleeve shall be defined in the pressurized pipeline. The second step consists of three substeps. In the first substep the complete model was solved (pipe with the installed cold sleeve) with internal pressure and axial force applied. In the second substep element kill/birth technique was used to ensure a stress-free state of the polymer filling and cold sleeve. In the last substep a depressurizing pipeline was simulated.

The simulation was executed for three geometric variants: variant 1 - pipe Ø1220 mm, thickness 15.9 mm, variant 2 - pipe Ø1220 mm, thickness 13.5 mm and variant 3 - pipe Ø1420 mm, thickness 15.6 mm. For all three geometric variants the thickness of cold sleeve was 12 mm and the thickness of a polymer layer was 8 mm. To simulate a worst case scenario for debonding, material properties of the modified polymer was selected in this way: measurement with the highest stiffness for the Mooney-Rivlin model and measurement with the lowest tearing force for the CZM model (2153 N). The applied statically determinate boundary conditions are described in Fig. 13. Gas pressure load is marked by red colour.

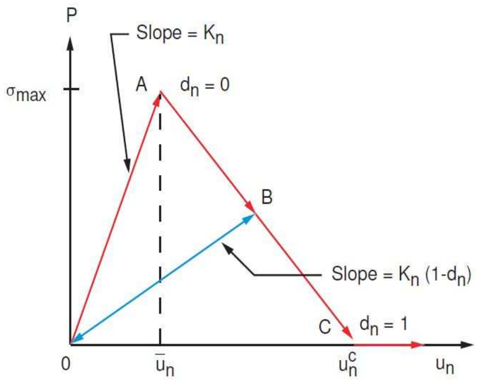

Fig. 12. Normal contact stress and curve of contact gap for bilinear mode I dominated CZM model

Another load that needed to be considered is the axial load due to gas pressure in the closed pipe. This load is calculated as $F_O = p\,.S$, where S is a cross sectional area of the pipe. For the pipe with outer diameter D = 1220 mm and thickness t = 15.9 mm the resulting applied load is F_O = 7.35 x 3.14x 594.1**2 = 8.146.10^6 N. The pipe and sleeve are made from steel 11 523 (S355J0). Elasticity modulus in tension is E= 206.0 GPa and Poisson's number is 0.30. In Fig. 14 is a graph of engineering deformation-stress for polymer PROTEGOL. The maximum deformation is approx. 64 % and maximum stress is approx. 4.5 MPa. The blue curve represents the measurement and pink curve represents the two-parameter Mooney-Rivlin approximation.

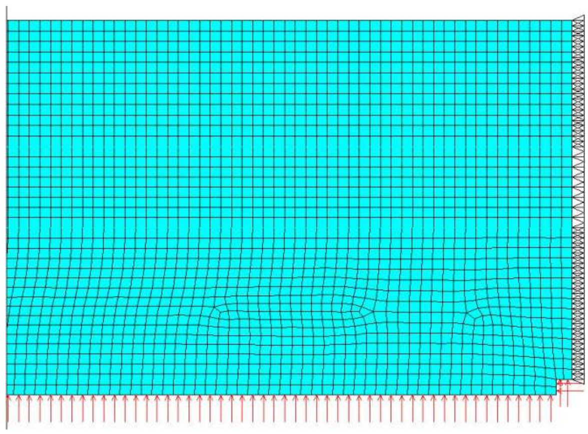

Fig. 13. Boundary conditions.

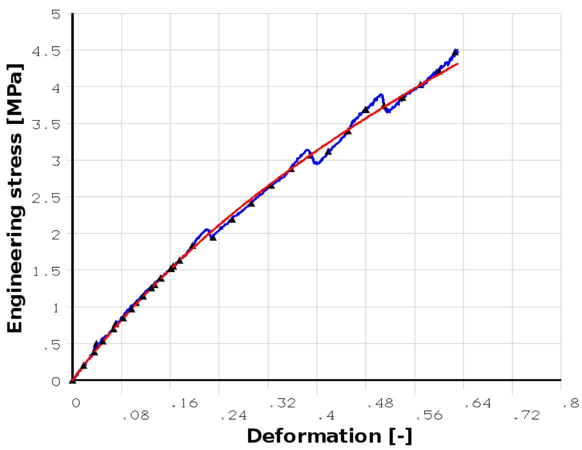

Fig. 14. Engineering stress – deformation curves

The FEM calculation was performed as a geometric nonlinear analysis with elasto-plastic material properties of the pipe and sleeve.

Analysis results

In term of the limit state of the load carrying capacity, vessels or piping are appreciated in terms of the primary stresses which are results of acting a pressure in a piping. Table 1 summarizes the most important results of analyses. It can be seen that the maximum value of the von Mises stress is 392 MPa. This value reaches almost the yield strength and occurs in the tip of the insufficiently welded root. It is a singularity caused by a sharp corner, i.e. transition between the pipe and the insufficiently welded root. Fig. 15 shows the distribution of the contact gap between the polymer layer and the piping and the cold sleeve. The minus sign represents the separation of the adjacent surfaces.

Table 1. Results in MPa for operating pressure p = 7.35 MPa.

		Variant 1	Variant 2	Variant 3
Radial displacement ($\mathbf{u_r}$)		-0.544	-0.641	-0.758
Radial stress ($\boldsymbol{\sigma_r}$)	Depressurized	3.812	5.609	6.04
	Pressurized piping	90.826	112.037	107.729
Circumferential stress ($\boldsymbol{\sigma_t}$)	Depressurized	-121.059	-130.894	-145.38
	Pressurized piping	347.888	414.005	412.931
Axial stress ($\boldsymbol{\sigma_A}$)	Depressurized	- 31.09	-35.957	-37.031
	Pressurized piping	282.299	339.009	339.089
Von Misses stress $(\sigma_{von})_{max}$	Depressurized	123.102	131.233	147.416
	Pressurized piping	329.108	391.191	391.627
Contact gap		-0.060	-0.100	-0.086
D-param		0.418	0.669	0.569

The cohesive failure is needed to reach the value of the contact gap -2.5 mm. Fig. 16 shows the detail of the contact gap at the cold sleeve beginning. From Table 1 it can be seen that the most critical variant of tearing is geometric variant 2. The value of DPARAM = 0.669 and contact gap is – 0.100 mm.

Sensitivity analysis considering changes to the thickness of the polymer layer and thickness of the sleeve was performed. The thickness of the polymer layer was varied in the range 4-8 mm in increments of 0.5 mm. Fig. 17 shows the influence of the thickness of the polymer layer on DPARAM parameter. This dependence is weak for a technologically useful range of the polymer layer thickness.

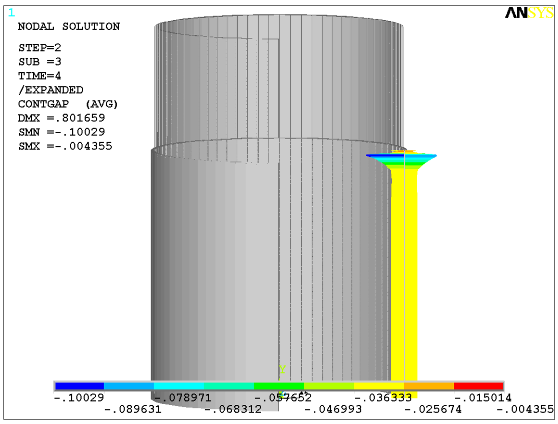

Fig. 15. Distribution of contact gap for variant 2, *p*= 7.35 MPa

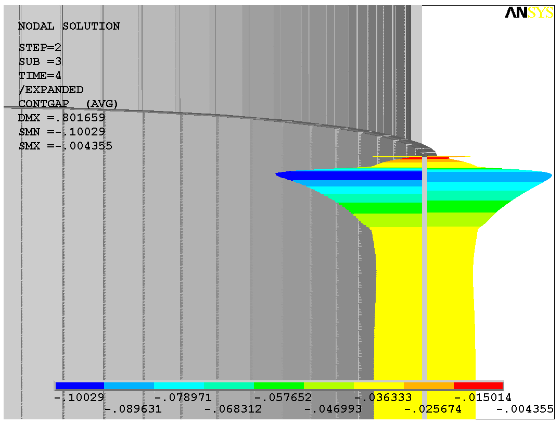

Fig. 16. Detail of distribution of contact gap for variant 2, *p*= 7.35 MPa considering axial force

Other behavior of DPARAM parameter is observed when we change the thickness of the sleeve. In this case, we carried out 15 variants with altered thickness calculation sleeve in the range 5-12 mm in increments of 0.5 mm. Fig. 18 shows the DPARAM parameter dependence of the sleeve thickness. This proportionality is very strong for the range of sleeve thickness from 9 mm to 12 mm.

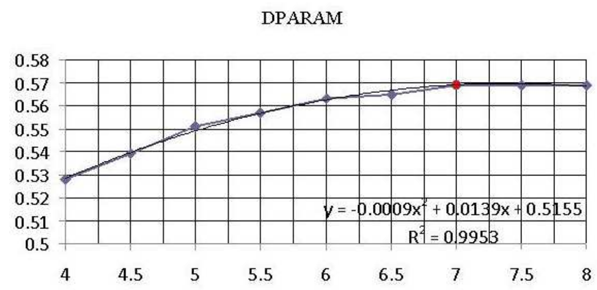

Fig. 17. Graph DPARAM vs. polymer thickness.

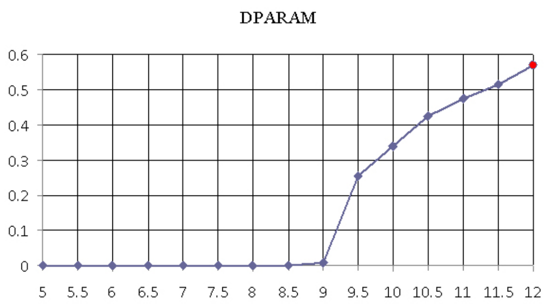

Fig. 18. Graph DPARAM vs. sleeve thickness.

Summary

On the basis of the mentioned results we can state that repairing of anomalous weld by means of the cold sleeve with modified polymer PROTEGOL is safe with respect to tearing polymer. Regard to the limit state, the piping as well as the sleeves are loaded in an elastic domain under the yield strength of the used steels. Since the problem has been solved as a nonlinear problem with elastic-plastic behavior of materials, the results of the numerical simulation proved that plastic strains of the piping nor the sleeve are not reached.

Acknowledgement

The authors gratefully acknowledge for support the Slovak and technology Assistance Agency registered under number APVV-0169-07, Slovak Grant Agency VEGA 1/1226/12.

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