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ASSESSMENT OF INTEGRITY OF OPERATING GAS PIPELINES

Abstract: Gas pipelines that have been in operation for many years require supervision, taking into account the places and conditions of their usage. The currently applicable normative regulations do not fully determine the scope of the integrity control of such gas pipelines. The standards provide general guidelines for monitoring corrosion phenomena in pipelines, allowing the use of simplified strength patterns based on a flat state of stress; in actuality, real objects usually have complex three-dimensional structures. Such an approach may be a reason for committing significant errors in determining the state of stresses and strains in the construction of pipelines, which is a significant problem in assessing the integrity of pipelines (when combined with the lack of a formulation of the appropriate admission criteria). This paper presents a methodology for assessing the integrity of pipeline structures operating at ambient temperatures based on conducting comprehensive measurements of wall thickness defects (in connection with performing necessary defectoscopy tests). The results of these measurements and non-destructive tests are the basis for the analysis of stress strength and MES deformation based on the verified real geometry as well as the method of supporting the pipelines. The information obtained on this basis regarding the pipeline structure areas of the highest efforts is the basis for selecting the critical areas of pipeline construction for which they should be repaired or modernized, or a monitoring program should be developed using non-destructive tests.

Keywords: gas pipelines, structural integrity, strength, FEM, NDT

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1. INTRODUCTION

All gas production, processing, and distribution plants are obligated to protect their employees and facilities against hazards related to the possibility of explosions and toxic gas interaction. In Poland, the design and execution of pipelines for the gas industry is currently conducted based on the requirements formulated in normative regulations [1–4], among others. However, a significant number of pipelines are still in operation whose working periods exceed 30–40 years and were designed and made based on previous provisions utilizing considerably simplified calculation methods. These documents do not provide recommendations for monitoring the integrity of the pipelines. Also, the necessary scope for monitoring the technical condition of the pipelines is done only in a very general way in consideration of the current normative regulations [1], which often puts those responsible for the safety of their operation in a difficult situation.

In this publication, the current operational requirements formulated in the above-mentioned normative regulations were subjected to a critical analysis. At the same time, the necessary program for monitoring the integrity of gas pipelines operating at ambient temperatures was proposed to test a dozen or more steel overhead gas pipelines operating in the long-term perspective.

2. EQUIPMENT REQUIREMENTS CONFORMING TO PN-EN 14161

The basic minimum requirements for the use and maintenance of pipelines are specified in standard [1]. The document requires corrosion management and the monitoring of the technical conditions, while the structural integrity and serviceability of the pipeline structures can generally be maintained during the design lifetime. If the pipeline is intended to be used in excess of its original design lifetime, carrying out the appropriate engineering tests on the structure is recommended (including an analysis of the conditions and history of the pipeline's operation) to determine its current technical condition, including any restrictions on its further safe usage.

When designing, using the limit state method on the basis of reliability is recommended where limit states are usually identified with the loss of structural integrity; i.e., through the formation of cracks, fractures, material fatigue etc. At the same time, the use of analytical models, empirical models, or combinations of these methods is allowed.

In the basic analytical calculations, the standard allows the use of simple Strength Formula (1) to calculate peripheral stress σ_{hp} caused by the effect of only gas pressure:

$$\sigma_{hp} = (p_{id} - p_{od}) \cdot \frac{(D_0 - t_{\min})}{2t_{\min}} \tag{1}$$

where:

- p_{id} – design pressure,
- p_{od} – minimal external hydrostatic pressure,
- D_o – nominal outside diameter,
- $t_{\min}$ – minimum wall thickness (including corrosion allowance).

In more-accurate analytical calculations, stress components are considered (peripheral, longitudinal, and shear), taking into account all significant functional, environmental, construction, and accidental loads. These calculations should be carried out for the full pipeline design geometry with supports, taking into account the notch and friction areas caused by the guides.

Reduced stresses σ_{eq} should be calculated using the H-M-H hypothesis (Huber–Mises–Hencky), according to Formula (2):

$$\sigma_{eq} = (\sigma_h^2 + \sigma_l^2 - \sigma_h\sigma_l + 3\tau^2)^{1/2} \tag{2}$$

where:

σ_h – circumferential stress,
σ_l – longitudinal stress,
τ – shear stress.

The strength criteria include the occurrence of mechanical damage and excessive deformations caused by the occurrence of buckling, fatigue, plastic yield, excessive deflections (stability), and cross-sectional ovality.

The use of a simplified approach (usually used during a pipeline's operation) allows us to calculate only one component of the stress state from Formula (1) and consider only the flat stress fields from Formula (2), whose components are determined on the basis of simple strength patterns derived for elementary model types (rod, beam, plate, and shell). Such an approach may lead to significant errors in the assessment of the stress levels and strains because, in reality, there is a three-dimensional geometry of the pipelines' structure, fixed and spatially loaded (self-weight, wind, snow, thermal loads and others) for which consideration the geometric notch effect still belongs. Increases in the values of the calculation errors are also influenced by the calculation based on the project's documentation, while the actual geometry and method of supporting the pipelines may significantly differ from the design situation (Fig. 1).

The satisfactory accuracy of the strength calculations can only be obtained by using the appropriate computer programs in which real 3D geometry is modeled with the current method of supporting and loading a pipeline structure.

a) b)

Fig. 1. Changes of support conditions of pipelines found during operation [5]: a) horizontal displacement of pipeline axis; b) no support in bearing

3. MONITORING OF CONSTRUCTION PIPELINE INTEGRITY

Monitoring the integrity of pipeline structures in accordance with the requirements of standard [1] may include the monitoring of corrosion losses together with the performance of inspections and leak detection, which should be determined at the design stage and recorded in the pipeline operation manual.

The monitoring and control of corrosion losses should be based on defined requirements with acceptance criteria based on the appropriate operational experience, taking into account the presence of locally pitting corrosion or slit expansion, microbiologically induced corrosion, stress cracking, hydrogen cracking or gradual cracking, stress hydrogen cracking, erosion and erosion with corrosion, fatigue corrosion, bimetallic/galvanic cells, and the preferential corrosion of welds.

The requirements for corrosion monitoring programs should be determined based on the anticipated mechanisms and corrosion rates. It is recommended to conduct an inspection shortly after a pipeline is commissioned to create a reference point for interpreting future indications. It is possible to install devices such as probes or probes to signal the occurrence of corrosion in the piping system; these should be located in places where it is possible to obtain representative indications of corrosion. Corrosion monitoring on the surfaces of pipelines should be carried out by periodically performing visual examinations.

If defects or damages are found in/on a pipeline, an assessment of the necessity to repair or allow the pipeline to continue to be used should be made, taking into account the possibility of monitoring the possible increase of the defect size and possibly specifying additional requirements such as pressure limitation or other corrective actions.

As can be seen, the extensive requirements set out above regarding the scope of monitoring the integrity of pipeline structures may pose a significant problem for the services responsible for the operation of pipelines in the absence of specifying the necessary actions as well as the failure to define admission criteria whose formulation encounters problems resulting from the quantitative evaluation of the pipeline propagation of fatigue cracks based on fracture mechanics [6].

4. METHODOLOGY OF CONTROL OF PIPELINE CONSTRUCTION INTEGRALITY

Due to the lack of precise provisions in normative documents as well as the lack of operating instructions and determination of admission criteria, the methodology for controlling the integrity of gas pipelines operated at ambient temperatures was applied. This was applied to a dozen or so pipelines used in one of the Polish industrial plants in a perspective time of approx. 40 years [5, 7, 8].

In view of the long period of operation of the pipelines under consideration, the lack of comprehensive measurements of corrosion losses, and the failure to carry out appropriate defectoscopy tests, the following steps were adopted:

- visual inspection of pipelines;
- measurements of corrosion losses using ultrasonic technique at eight points around entire circumference of pipelines on both sides of each weld connection (taking into account knees, bends, tees, and reducers);

– magnetic flux detection of all peripheral joints of welded pipelines along their entire lengths, with adjacent strips of native pipe material that are approx. 40 mm wide on each side of weld;
– strength analysis using finite element method (FEM) carried out for verified current geometry of pipelines with supports;
– determination of pipeline construction areas of highest effort designated as critical areas in aspect of possible occurrence of damage;
– preparation of repair recommendations along with a monitoring program for critical areas, which consists of conducting measurements of corrosion losses in connection with performance of appropriate defectoscopy tests for specified time intervals.

It should be noted that the pipelines operating for many years in the industrial installation were built with technology that complied with contemporary standards, including all acceptance tests, including a radiographic examination of all welds. According to the proposed methodology of integrity control, measurements of corrosion losses, non-destructive tests, and numerical analyses of FEA were performed in relation to 12 gas pipelines operating at ambient temperatures with diameters at different sections of 300 mm, 250 mm, and 200 mm and with different complex geometries. For each of the pipelines, its current geometry was determined along with the method of support, taking into account the existing permanent deformations that sometimes resulted in a change of pipeline support conditions as compared to the design documentation.

The performed defectoscopy showed that there are some surface defects in some cases; examples of those detected in the area of the welded joints are illustrated in Figure 2.

a) b)

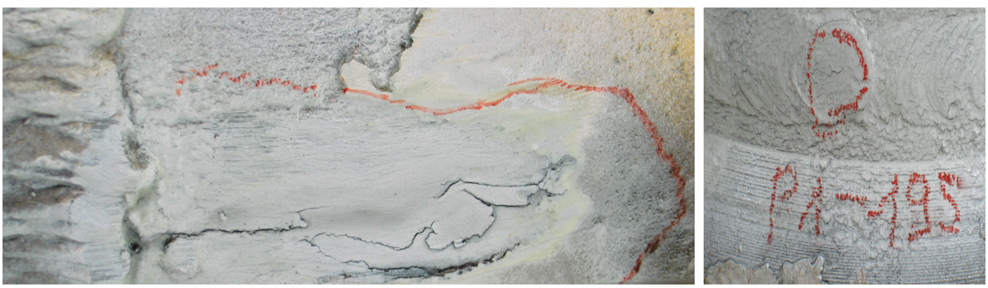


Fig. 2. Cracks detected by magnetic-powder method in area of welded joints of pipelines: a) cracking of native material in direction of pipe axis starting from peripheral weld [7]; b) bursting in perimeter weld [8]

5. FEM STRENGTH ANALYSIS OF PIPELINE CONSTRUCTION

The purpose of the strength analysis performed using the finite element method (FEM) was to obtain information about the state of the stresses and strains in the entire pipeline structure under the influence of operational loads. Knowledge of the constituent values of the stress states was the basis for identifying extremely stressed areas of the pipelines, which was the basis for assessing their strength. The information obtained regarding the value and distribution of the stresses made it possible to select the so-called critical areas of the pipelines that may suffer damage due to the levels of stress.

In connection with the above, an MES strength analysis was carried out for the 12 considered pipelines using numerical methods of structural analysis. The finite element method [9] was applied using FEMAP/NXNastran computer programs based on developed calculation models of the structures in which the pipelines were modeled with surface elements with wall thicknesses corresponding to the average thickness value measured by the ultrasonic method on the pipe length or the averaged thickness value for other elements (e.g., knees, bends, tees, and orifices). The support elements (e.g., poles) were also modeled with the surface elements. The finite element size was adopted within a range of 20–30 mm. In the pipeline models, the valves that are not subject to the thickness measurements are omitted; these are replaced with sections of the pipeline having thicknesses corresponding to the adjacent sections of the pipes. The ends of the pipelines were treated as non-displaceable; i.e., all three displacements were removed from them in the directions of the X, Y, and Z axes, respectively. The geometry as well as the method for supporting the pipelines were assumed to be verified for the real objects.

An example of an analyzed pipeline is shown in Figure 3, the supports of which are marked as the degrees of freedom taken (black pins); i.e., the directions in which the point cannot be displaced. The drawing also shows the locations of the welded joints.

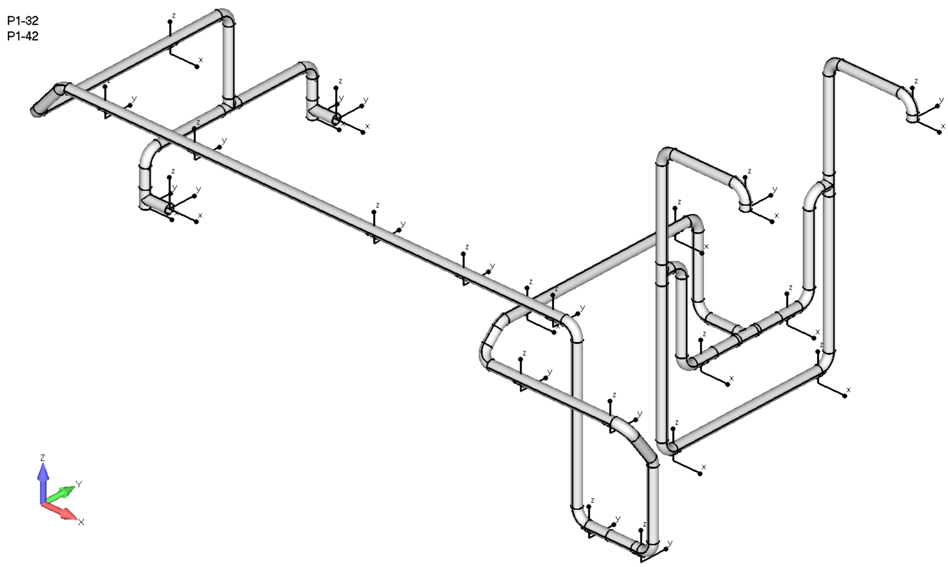


Fig. 3. FEM model of pipeline with marked method of support and welds [5]

On the basis of the analysis of the actual working conditions of the pipelines, the factors constituting the construction load were determined (summarized in Table 1).

Table 1

Load cases of the pipeline

Load case	Value	Comments
Gas pressure [MPa]	$p_{max} = 5.6$	operational data
Self weight [kg/m³]	$\rho_{steel} = 7850$	acc. to [10]
Medium temperature [°C]	$t_{summer} = 18–20$ $t_{winter} = 5$	operational data
Wind (1st zone) [Pa]	$p_{nom} = 250$ $p_{obl} = 750$	acc. to [11]
Snow [N/m²]	$P_{snow} = 980$	acc. to [12]

In the strength calculations, all of the above loads were considered to be occurring jointly. Although the pipelines are not the whole surface exposed to the wind (they are partially covered by other pipeline sections), it has been assumed that the entire pipeline is unprotected and is subjected to wind pressure selected for the most unfavorable load case usually corresponding to the largest windward area. Due to the variability of wind direction, analyses were made for the following directions:

- 0° (axis + X),
- 45°,
- 90° (axis + Y),
- 135°,
- 180° (axis − X),
- 225°,
- 270° (axis − Y),
- 315°.

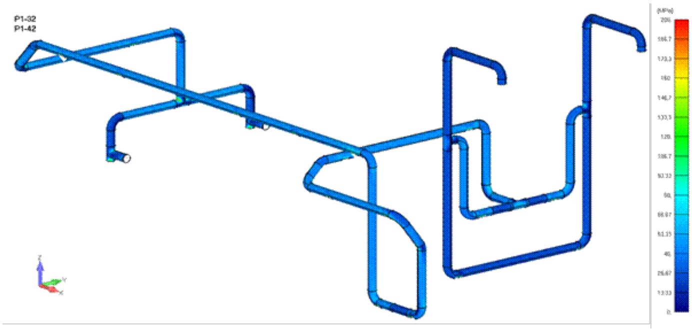
As the pipelines were made of steel grade S235 with thicknesses ranging from 16 mm to 40 mm for the ϕ250–300-mm sections and ≤16 mm for the ϕ200-mm sections, the design resistance of steel f_d in accordance with [10] was adopted as $f_d = 205$ MPa and $f_d = 215$ MPa.

The determined extreme values of reduced stresses σ_{eq} for the individual pipeline models have been referred to the value of f_d according to the following dependence:

$$\frac{\sigma_{eq}}{f_d} \cdot 100\% \tag{3}$$

determining what percentages of the maximum allowable stresses are the resulting stresses reduced in a given area of the pipeline. An exemplary reduced stress distribution obtained for the pipeline from Figure 3 with the area of extreme stresses obtained for the *T*-piece is shown in Figure 4. In the case of the tee of Figure 4b, the value calculated from Formula (3) is 120.4% (i.e., the allowable stresses have been exceeded by more than 20%).

a)



b)

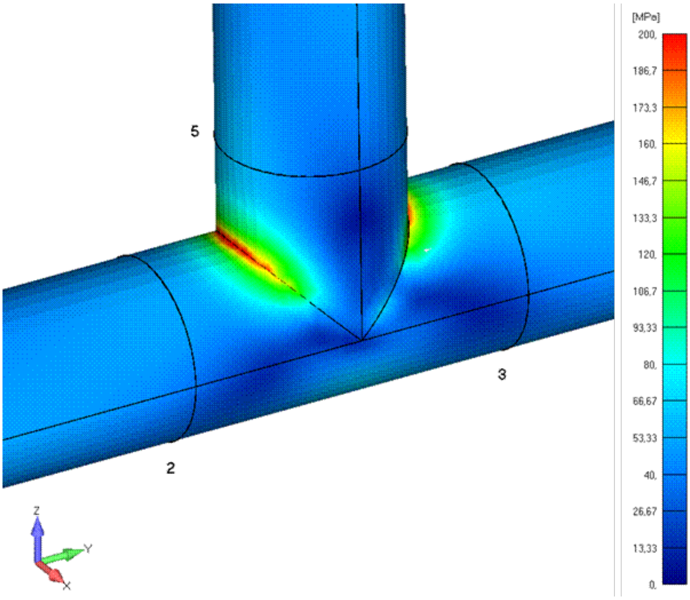


Fig. 4. Distribution of reduced stresses σ_{eq} [MPa] obtained for pipeline from Figure 3: a) view of whole pipeline; b) extreme stresses found in area of vertical tee [5]

6. FEM ANALYSIS RESULTS

The FEM analysis performed for 12 pipelines showed excesses of the permitted stress values in 11 pipeline areas in the case of 5 pipelines, most often in the area of the notches for the tees (Tab. 2). These areas were recognized as critical areas for which exchanges of the excessively strenuous parts of the structure should be carried out. For the five areas of the pipelines listed in Table 2 for which the reduced stresses reached values of greater than 90% of the structural strength of the f_d steel, a monitoring program was developed consisting of regular comprehensive thickness-loss measurements combined with the performance of appropriate defectoscopy tests within a set time period.

Table 2
List of pipelines areas of highest effort

Pipeline no.	Element denotation	Maximum stress σ_{eq} [MPa]	$\frac{\sigma}{f_d} \cdot 100\,[\%]$
P1-1	2-3-10 tee	208.3	101.6
	9-15-14 tee	205.8	100.4
	28-29-31 tee	192.8	94.0
	51-52 knee	189.5	92.4
P1-3	28-30 tee	196.0	95.6
P1-31	39-6-5 tee	185.6	90.5
P1-32	2-3-5 tee	246.9	120.4
P1-43	60-61 tee	245.3	119.7
P1-44	11-12-18 tee	212.7	103.8
	27-28-29 tee	207.5	101.2
	31-32 connector	265.6	129.6
	32-33-34 tee	222.5	108.5
	35-36-39 tee	231.2	112.8
	39-40 connector	264.3	128.9
P1-151	9-11 tee	192.8	94
	22-24 tee	204.2	~100.0

The integrity of the pipeline can be ensured by performing a numerical analysis with the variable operating conditions taken into account [13] (constituting the basis for the implementation of the technical condition monitoring program and repairs) to extend the pipeline's service life, especially in the case of missing output and operational data.

6. CONCLUSIONS

Current regulations do not specify the scope of monitoring the integrity of gas pipelines in a satisfactory manner. The recommendations specified in standard [1] only form general guidelines for monitoring corrosion phenomena in pipelines, allowing for the use of simplified Strength Formulas (1) and (2) based on a flat state of stress; as gas pipelines usually have a complex three-dimensional geometry and are attached and loaded spatially, this may result in significant calculation errors. This is a particular problem in the case of pipelines operating in the long term (often exceeding 30–40 years) with significant thickness losses that were designed on the basis of previous regulations and whose geometry and mounting conditions have changed compared to the design documentation.

In connection with the above, the methodology for controlling the integrity of gas pipeline structures was proposed that is based on the implementation of comprehensive measurements of pipeline thickness losses in combination with defectoscopy tests performed in the areas of welded joints. The results of the performed measurements and non-destructive tests are the basis for carrying out an FEM strength analysis of pipeline construction based on the geometry as well as the method of supporting the pipelines, verified by measurements on the real object.

The information on the pipeline construction areas of highest effort obtained on the basis of the FEA analysis is the basis for selecting the critical areas of pipeline construction that should be repaired or for which a monitoring program should be developed consisting of regular measurements of thickness losses combined with the performance of the appropriate defectoscopy tests.

Strain gauge tests are planned for the selected pipeline construction areas of the highest.

Acknowledgment

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