UDC 622.692.4

# NUMERICAL MODELING OF A STRESS-STRAIN STATE OF A GAS PIPELINE WITH COLD BENDING OFFSETS ACCORDING TO IN-LINE INSPECTION

**Gennady E. KOROBKOV, Anna P. YANCHUSHKA, Mars V. ZAKIRYANOV**
*Ufa State Petroleum Technological University, Ufa, Republic of Bashkortostan, Russia*

Knowledge of the current stress-strain state of any section of the pipeline allows you to make informed decisions on its operation, maintenance and repair, as well as on the prediction of the technical condition. The task of determining the characteristics of the stress-strain state of a gas pipeline section that has cold bend offsets (CBO) according to in-line inspection (ILI) is considered. The bent part of CBO is characterized by the presence of residual stresses and deformations in the wall of the offset, which contribute to the overall level of the stress-strain state of the gas pipeline operating under external and internal loads. Using the results of in-line diagnostics, numerical modeling and a solution, the change in the values of longitudinal stresses, is determined and the need to take into account residual stresses in the zone of elastic-plastic deformations of cold bend offsets is shown.
***Keywords:*** gas pipeline; cold bend offsets; modeling; finite element method; stresses

***How to cite this article***: Korobkov G.E., Yanchushka A.P., Zakiryanov M.V. Numerical Modeling of a Stress-Strain State of a Gas Pipeline with Cold Bending Offsets According to In-Line Inspection. Journal of Mining Institute. 2018. Vol. 234, p. 643-646. DOI: 10.31897/PMI.2018.6.643

**Introduction.** Modern operating experience of the linear sections of main gas pipelines (MGP) indicates little knowledge of the defects of the cross-section stress corrosion cracking (SCC), one of the reasons for which is the high level of bending stresses in the wall of the pipe or fitting [1, 7, 9].

Studies [4, 7, 9] are aimed at assessing the stress-strain state (SST) of potentially hazardous sections (PHS) of gas pipelines on the basis of high bending stresses. The assessment is carried out based on the radius of the sections curvature determined by in-line inspection (ILI) and measurements of the stress level. The SST assessment in [4] is limited to the elastic zone of the metal. On the one hand, this approach is sufficient, since according to the regulations, the stresses in the pipe wall should not exceed the yield strength of the material. On the other hand, in the process of manufacturing of cold bending offsets (CBO), elastic and plastic (residual) deformations occur, the magnitude of which depends on the parameters of bending, geometric and strength characteristics of the pipe. In [9], it was shown the possibility of estimating the SST by the values of the deflections of the opened and covered section of the gas pipeline with CBO according to the results of numerical analysis and geodetic positioning data. Without diminishing the significance of the work [4, 7, 9], we note that additional consideration is needed for residual stresses and strains in the total SST of the PHS, a detailed consideration of the SST of the elastoplastic CBO zone to identify the most possible cracking zones. It is important to take into account the change in the cross-sectional stiffness, the acquired ellipticity and the degree of metal hardening.

**Theoretical results and discussion**. Based on [2, 3], it was determined that plastic deformations and residual stresses in the wall of CBO can be unfavorable factors for the future operational reliability of the MGP section with CBO. The task of determining the stress-strain state of gas pipelines with CBO, taking into account residual stresses and strains, is relevant for the gas transportation industry.

Requirements for CBO and curved inserts for main steel pipelines are established by GOST 24950-81. When determining the SST of a pipeline section made using the curve of an insert – CBO, we assume that the pipeline has a sufficient length on both sides of the bend. In this case, it is assumed that CBO corresponds to the first type according to GOST 24950-81 with an equal length of straight ends of the offset (Fig. 1).

The appearance of plastic deformations in the extreme of height zones of the cross section in pipes occurs with a certain initial curvature. With increasing curvature of the bent pipe, the zone of plastic deformations propagates to the pipe axis. In the general case, when plastic bending (bar model) a volumetric stress state is created, which greatly complicates the process of determining deformations along the height of the cross section. In this regard, in several studies, some simplifications of

DOI: 10.31897/PMI.2018.6.643

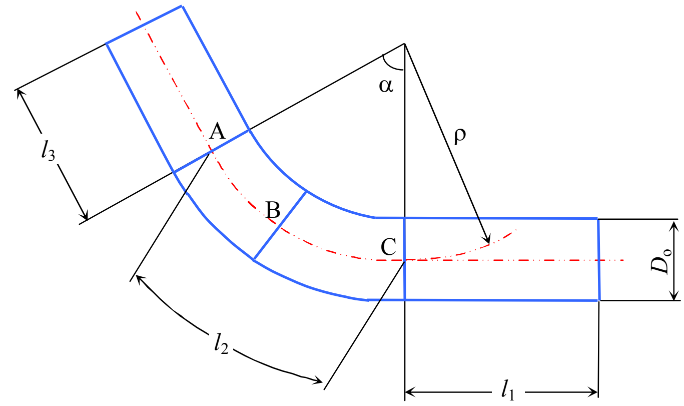


Fig.1. The offset of the first type according to GOST 24950-81
α – bending angle; $D_o$ – offset outer diameter;
ρ – offset curvature radius; $l_1$, $l_3$ – length of straight ends of the offset,
$l_2$ – length of elbow part

calculation schemes are adopted in the mathematical analysis of plastic bending of a bar. In particular, for large relative bending radii of the pipe, only longitudinal stresses and strains can be taken into account in calculations, but the effect of the elastic-deformed zone and the degree of metal hardening are taken into account.

According to GOST 24950-81, the calculated uniform radius for bending (or residual radius) for a pipe with DN 1220-1420 mm should be 60 m. Modern profilers used in in-line diagnostics allow finding the radii of curvature ρ and angles of rotation α of the pipeline. In [6], it was shown that the radii of the elastic-plastic zone of CBO by means of ILI are determined with an accuracy that allows to diagnose the change in the SST of a section. For the most complete picture of the SST CBO and control of its change, reliable data of the technical control of the offset manufacturer, namely the initial geometrical parameters: radius and bending angle, are necessary. As the initial data we will take CBO with $D_o$ = 1220 mm, wall thickness 15.4 mm, length 11.65 m, radius of curvature 60 m, bending angle $\alpha = 3°$. The mechanical characteristics of the CBO material: yield strength $\sigma_y$ = 490 MPa, temporary tensile strength $\sigma_т$ = 640 MPa, Young's modulus $E = 2.06{\cdot}10^5$ MPa, Poisson's ratio $\mu = 0.3$. The plastic model of steel deformation is assumed to be linear with a constant hardening module $G_T$. According to [6], the value of the degree of hardening $m$ for structural metals is within $0 \le m < 0.3$. In turn, the values of $G_T$ and $m$ are interconnected by the following expression:

$$G_T = 0.35mE. \tag{1}$$

The value of hardening degree can be determined by calculation methods based on the mechanical properties of the metal. In the calculations, we take $m = 0.1$, then $G_T = 7210$ MPa.

Researchers widely use the finite element method (FEM) for estimating the SST of the offsets of different radii of curvature and diameter [5, 8-14]. To calculate the SST of the gas pipeline section with CBO, a mathematical FEM model was developed in accordance with [8]. At the first stage of calculating the FEM model, the residual longitudinal stresses of CBO are determined; i.e. the SST of the offset is calculated at the manufacturing stage. Bending occurs under the action of axial bending moments applied to the cross sections of a straight pipe on the longitudinal coordinates of points A and B (Fig.1). At the second stage of calculating the FEM model, the full longitudinal stresses in CBO are determined taking into account axial forces, i.e. CBO SST is calculated at the operation stage. At the same time, it is advisable to solve the problem by the method of successive approximations to the data of the ILI along the radius of curvature and the angle of rotation of the pipeline section.

According to Figure 1, the length of the curve is the bent part of the offset

$$l_2 = \frac{\rho_{resid}\pi\alpha}{180}. \tag{2}$$

The curvature of the offset is acquired in the process of bending, so the length of the curve $l_2$ remains unchanged, and only the radius and angle of the offset change:

$$\rho_1\alpha_1 = \rho_2\alpha_2 = \rho_n\alpha_n, \tag{3}$$

where $\rho_1 \dots \rho_n$ – measured CBO curvature radius during ILI or given after manufacture; $\alpha_1 \dots \alpha_n$ – measured CBO angles during ILI or given after manufacture.

Expression (3) shows that with a decrease in the CBO curvature radius, the angle of offset increases, and vice versa. Any change in the offset angle and curvature radius leads to a change in SST.

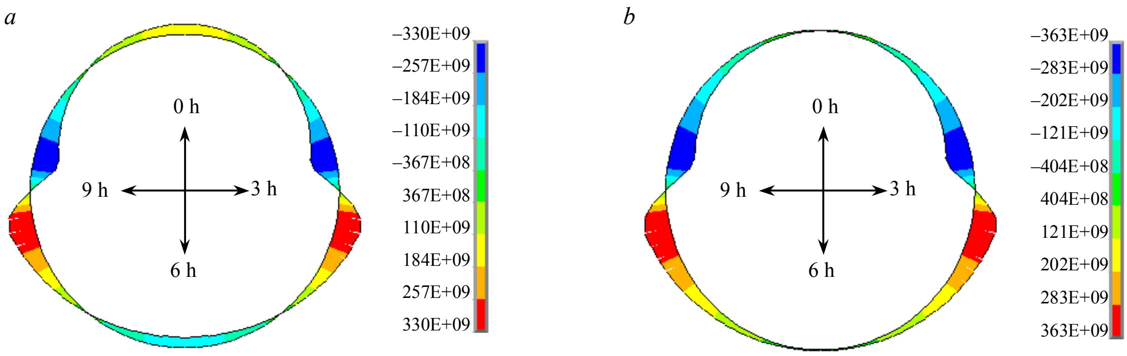


Fig.2. Distribution of longitudinal stresses in the middle cross-section of CBO

Let us consider the CBO SST after its manufacture in the middle cross-section of CBO (in Fig. 1 – the longitudinal coordinate of point B). In the wall of the upper part of the offset (from 11 to 1 h), the residual stresses are tensile, and in the wall of the lower part of the offset (from 5 to 7 h) – compressive (Fig.2, *a*). These data show that an offset tends to «straighten». The residual stresses on the straight sections of CBO are zero. Residual stresses are unevenly distributed around the perimeter of the bent part of the CBO, and the maximum values at the border of the elastic and plastic zones (from –330 to 330 MPa). According to Karman's theory, the cross-sectional CBO is ovalized. It should be noted that the authors of [5, 11] obtained similar results for the values of maximum stresses.

According to the results of the ILI, it is determined that this offset has a curvature of $\rho$ = 56 m, i.e. its curvature increased. It is necessary to find out how much the longitudinal stresses have changed due to the change in the curvature of the CBO. For this, the method of successive approximations determined the axial bending moments at the ends of the bent part of the CBO, the value of which is necessary to change the radius of curvature of the CBO, from 60 to 56 m. The results of the calculation of the longitudinal stresses are given in the table. The elastoplastic area of CBO has extremes of longitudinal stresses (Fig.2); therefore, the table displays detailed calculation results for model units from 2 to 4 hours on a conventional clock face.

**The results of the calculation of the longitudinal stresses in the units of FEM model**

| Position of the unit on the conditional clock face, h | Longitudinal stresses (residual), Pa | Longitudinal stresses (residual + bending), Pa | Change in longitudinal stress, Pa |
|---|---|---|---|
| 0 | 1.327E+08 | –7.935E+06 | 1.407E+08 |
| 1 | 4.398E+07 | –7.595E+07 | 1.199E+08 |
| 2 | –1.969E+08 | –2.608E+08 | 6.385E+07 |
| 2.15 | –2.401E+08 | –2.939E+08 | 5.383E+07 |
| 2.3 | –2.847E+08 | –3.281E+08 | 4.347E+07 |
| 2.45 | –3.305E+08 | –3.633E+08 | 3.283E+07 |
| 2.60 | –3.055E+08 | –3.275E+08 | 2.200E+07 |
| 2.75 | –1.716E+08 | –1.827E+08 | 1.103E+07 |
| 3 | –4.047E-01 | –4.301E-01 | 2.537E-02 |
| 3.15 | 1.716E+08 | 1.827E+08 | –1.103E+07 |
| 3.30 | 3.055E+08 | 3.275E+08 | –2.200E+07 |
| 3.45 | 3.305E+08 | 3.633E+08 | –3.283E+07 |
| 3.60 | 2.847E+08 | 3.281E+08 | –4.347E+07 |
| 3.75 | 2.401E+08 | 2.939E+08 | –5.383E+07 |
| 4 | 1.969E+08 | 2.608E+08 | –6.385E+07 |
| 5 | –4.398E+07 | 7.595E+07 | –1.199E+08 |
| 6 | –1.327E+08 | 7.935E+06 | –1.407E+08 |

**DOI:** 10.31897/PMI.2018.6.643

The maximum change in stress values reaches –140.7 MPa on the upper part of the CBO and +140.7 MPa on the lower one (Fig.2, *b*). Stretching of the lower and compression of the upper components of the offset occurs. Maximum stresses are localized closer to the neutral line of the offset – on the border of the plastic and elastic zones. Flexural stresses caused by changes in the radius of curvature of CBO, summing up with the existing residual stresses, reach 70 % of the yield strength of steel. Studies [1, 15] show that SCC processes proceed more intensively in areas of elevated (tensile) stresses, with a threshold stress range of 70-80 % of the yield strength of pipe steel. These circumstances indicate the need to take into account residual stresses in CBO.

**Conclusion**. On the basis of the studied technical documentation for the gas pipeline section and the data of the ILI, it is possible to carry out numerical modeling and calculation of the SST of sections with CBO, assessment of changes in the level of SST on horizontal, vertical and combined turns of the pipe, assessment of the technical condition of the pipeline. The data of calculation of the FEM-model make it possible to determine the residual stresses and strains; equivalent, longitudinal stresses in the plastic zone CBO taking into account the longitudinal forces and bending moments. Improving the in-line flaw detector shells from the point of view of the accuracy of measuring the geometry of the pipeline will improve the reliability of the results of calculating the SST of gas pipeline sections with CBO.

## REFERENCES

1. Aleksandrov Yu.V. Identification of factors initiating the development of damage to gas pipelines due to SCC. *Praktika protivokorrozionnoi zashchity*. 2011. N 1, p. 22-26 (in Russian).

2. Birger I.A. Residual stress. Moscow: MAShGIZ, 1963, p. 233 (in Russian).

3. Zainullin R.S. Ensuring the efficiency of oil pipelines and pressure vessels. *Sbornik nauchnykh statei*. IPTER, MNTTs «BESTS». Ufa, 1999, p. 110 (in Russian).

4. Tagirov M.B., Mustafin F.M., Askarov R.M., Bakiev T.A. Investigation of the stress-strain state of a potentially dangerous section of the main gas pipeline. *Transport i khranenie nefteproduktov i uglevodorodnogo syr'ya*. 2017. N 2, p. 9-14 (in Russian).

5. Shabalov I.P., Velikodnev V.Ya., Kotova I.S., Kalenskii V.S. Mathematical modeling of forming cold bend offsets, optimization of the technological process, analysis of limit states. Sbornik trudov XXIII mezhdunarodnoi nauchno-tekhnicheskoi konferentsii, 12-18 sentyabrya 2016 g. Sevastopol'skii gosudarstvennyi universitet. Sevastopol', 2016. Vol. 2, p.172-175 (in Russian).

6. Makhutov N.A. Deformation criteria for fracture and calculation of structural elements for strength. Moscow: Mashinostroenie, 1981, p. 272 (in Russian).

7. Usmanov R.R., Chuchkalov M.V., Askarov R.M. Development of technology for identifying and repairing potentially dangerous sections of gas pipelines on the basis of transverse stress corrosion cracking. *Territoriya Neftegaz*. 2014. N 12, p.74-77 (in Russian).

8. Seleznev V.E., Aleshin V.V., Klishin G.S., Fotin S.V. Numerical analysis of the fire hazard of gas pipelines. Moscow: Editorial URSS, 2004, p. 328 (in Russian).

9. Chuchkalov M.V. Development of methods for detecting, inhibiting and preventing stress corrosion cracking on main gas pipelines: Avtoref. dis. … d-ra tekhn. nauk. OOO «Gazprom transgaz Ufa». Ufa, 2015, p. 51 (in Russian).

10. Bathe K.J., Almeida C.A., Ho L.W. A simple and effective pipe elbow element – some nonlinear capabilities. *Computers and Structures*. 1983. Vol. 17 (N 5-6), p. 659-667.

11. Riagusoff I.T., Kenedi P., L.Guimarães de Souza, Pacheco P.L. Modeling of pipe cold bending: a finite element approach. VI National congress of mechanical engineering. 2010. URL: https://www.researchgate.net/publication/282861951 (date of access 31.01.2018).

12. Sözen L., Guler M.A., Görgülüarslan R.M., Kaplan E.M. Prediction of Springback in CNC Tube Bending Process Based on Forming Parameters. 11th International LS-DYNA Users Conference. Deaborm, USA, 2014, p. 7-20.

13. Śloderbach Z. Generalized model of strains during bending of metal tubes in bending machines. *Journal of Theoretical and Applied Mechanics*. 2014. N 52 (4), p. 1093-1106.

14. Xu J., Yang H., Li H., Zhan M. Significance based optimization of processing parameters for thin walled aluminum alloy tube NC bending with small bending radius. *Transactions of Nonferrous Metals Society of China*. 2012. N 22, p.147-156.

***Authors*: Gennady E. Korobkov**, *Doctor of Engineering Sciences, Professor, korobkov45@mail.ru* (*Ufa State Petroleum Technological University, Ufa, Republic of Bashkortostan, Russia)*, **Anna P. Yanchushka**, *Candidate of Economic Sciences, Associate Professor, korobkov45@mail.ru* (*Ufa State Petroleum Technological University, Ufa, Republic of Bashkortostan, Russia*), **Mars V. Zakiryanov**, *Postgraduate Student, mars.zakiryanov.1988@mail.ru* (*Ufa State Petroleum Technological University, Ufa, Republic of Bashkortostan, Russia*).

*The paper was received on 4 April, 2018.*
*The paper was accepted for publication on 10 May, 2018.*