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# Experimental Analyses of Limit States, Stress-Strain Distribution, Defects and Failure Mechanisms of High-Pressure Gas Pipe

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**Abstract.** The paper contains results and discussion of a comprehensive experimental programme aimed at evaluation of limit states, stress-strain distribution, defects and failure mechanisms of a section of high-pressure gas pipeline taken from an actual line of the nominal diameter DN700, made of an L290NB steel (API 5L X42 steel), operated at maximum pressure 6.1 MPa, with the aim to confirm the service safety and reliability. The experiments were performed using both laboratory specimens machined from the pipe and full scale pipe section of the length 3820 mm. During the full-scale pressure test, the pipe destruction occurred at pressure 12.7 MPa, which is considerably higher than theoretical failure considering the biaxial loading. The pipeline in these conditions was therefore evaluated as safe with a safety factor more than 2. It should be, however, pointed out that the final destructive crack was not initiated in the area of minimum wall thickness as expected, but at the dent with an evident assistance of the surface small cracks. Therefore, an attention should be paid to such defects in reality.

## Introduction

Natural-gas pipeline accidents mostly result in major damage to buildings and other constructions located not only nearby but also quite far away and often put a lot of people in danger of injury or death. Therefore, safety and reliability management of high pressure gas pipelines is one of the most important issues for the operators and big effort is being put to various investigation projects with the aim to minimise probability of unexpected pipeline explosions. One of the research fields is risk assessment of high pressure pipeline explosion and planning of safe distances between the pipeline and buildings on the basis of probability methods like Monte Carlo simulations etc. [1]. The most effective method, however, looks to be a comprehensive theoretical and experimental evaluation of existing overall operated pipeline conditions using different available tools like intelligent pigging, regular internal inspections of corrosion occurrence and its growth, pressure cycle induced fatigue crack growth assessment and other tools [2], followed by a dedicated research programme dealing with a specific technical problem of damage to the pipeline, either local or of a fairly global character.

This contribution contains selected aspects and crucial results of a complex experimental programme aimed at evaluation of limit states, stress-strain distribution, defects and failure mechanisms of a section of high-pressure gas pipeline, taken from an actual pipe line of the nominal diameter DN700, made of an L290NB steel (API 5L X42 steel) commonly used in high pressure gas pipelines in Czechoslovakia in the past, operated at maximum pressure 6.1 MPa, with the aim to confirm the service safety and reliability. The NDT internal inspection of the pipeline section did not indicate any actual defects, only fairly reduced pipe wall thickness with 9.5 mm minimum values. During careful and detailed visual inspection of the pipe section, two dents were found, the first one quite inexpressive of the diameter approximately 100 mm and depth less than 5 mm. The second one was even smaller, almost negligible. The experiments were performed using both laboratory specimens machined from the pipe and full scale pipe section of the length 3820 mm.

## Experimental Programme

A comprehensive experimental programme was proposed with the following aims:

- to verify limit states of the pipe integrity, stability of strength and deformation properties and limit pressure values for safe service,
- to evaluate changes of material mechanical properties after loading close to limit states,
- to evaluate effects of dimension irregularities, particularly variable wall thickness, on damage mode and limit states of pipe integrity under biaxial stress,
- to verify whether some creep occurs at stresses corresponding to service loading.

The most important phases of the experimental programme contained:

- evaluation of the material composition, microstructure and mechanical properties, effects of limit loading on changes of mechanical properties,
- visual inspection of all the pipe, detailed non-destructive ultrasonic measurement of pipe wall thickness using mesh 100 x 100 mm,
- experimental stress-strain analysis at numerous important points like minimum and maximum wall thickness, at two inexpressive dents, found during the visual inspection,
- static pressure test to service pressure 6.2 MPa with 100 hours low temperature creep test, when strain values were corrected considering pressure and temperature changes,
- fatigue cycle pressure test to 1000 cycles and final pressure test to destruction,
- fractographical analyses of fracture surface to explain crack initiation mechanisms and failure mode.

Chemical composition was analyzed using optical-emission method, device SPECTROMAXX. Mechanical properties were evaluated using SVÚM a.s. laboratory machines, independently calibrated by the Czech Metrology Institute within the laboratory accreditation. Static tensile tests were performed according to the ČSN EN ISO 6892-1 on the test machine Instron 1185, impact bending tests according to ČSN ISO 148-1 on test hammer PSWO30. Fracture toughness tests were carried out according to ČSN EN ISO 12737 on Instron 1185 machine using three point bend specimens.

Material microstructure was evaluated using optical microscopes. Strain values were measured and recorded using high precision Hottinger Baldwin Messtechnik GmbH device HBM UPM 60 with computer data recording. HBM strain gauges (SG), mostly of 6 mm grid length were used (type 1-LY11-6/120). Fractographical analyses was performed using scanning electron microscope (SEM) Zeiss.

## Results and Discussion

**Evaluation of Wall Thickness.** Thickness of the pipe wall was one of the most important issues as NDT internal inspection indicated areas with reduced thickness. Therefore, this was the primary reason of the experimental programme – to verify, how and whether the reduced thickness affects the limit pressure of the pipe destruction.

As already mentioned, surface network of measurement points with distances 100 x 100 mm was prepared for the ultrasonic measurement. As the pipe section length was 3820 mm and actual circumference almost 2400 mm, there were 38 points in longitudinal direction and 22 points at circumferential direction. Circumferential positions were indicated by alphabetical letters A – W, where position A was on the top line – so called 12 o´clock, longitudinal positions by numerical order 1 – 38. By this method, each position was clearly defined.

According to the literature and codes commonly used for high pressure gas pipelines [3, 4], the minimum wall thickness *t* is given by following formula:

$$t = P\,D_0 / 2\,F\,E\,T\,S_y \qquad (1),$$

where *P* is internal service pressure, $D_0$ is outer pipe diameter, $S_y$ is yield stress and *F, E, T* are safety coefficients expressing pipeline position in relation with buildings and roads, types of welding joints on the pipeline and temperature conditions, respectively. Temperature coefficient for normal temperatures is T = 1, joint factor for the specific method used also E = 1. Basic design factor for areas outside buildings and roads is F = 0.8. Then minimum pipe thickness for the service pressure P = 6.1 MPa made of steel with minimum yield stress 290 MPa is t = 9.5 mm.

Results of the thickness measurement at individual points in the area of reduced thickness are in Table 1. In addition, circumferential average thickness values for individual longitudinal positions and also longitudinal average values for individual circumferential position were evaluated to obtain simplified, clear information about longitudinal and circumferential distribution of wall thickness reduction – Fig. 1

Tab.1 Actual values of wall thickness at individual measurement points in the area of wall thickness reduction, position of the dents indicated by red circles (G29, negligible dent G25)

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **17** | | 9.45 | 9.63 | 10.76 | 10.07 | 9.58 | 9.70 | 9.58 | 9.63 | | | | |
| **18** | 9.72 | 9.56 | 9.58 | 9.16 | 9.28 | 8.94 | 9.09 | 9.28 | 9.34 | 9.68 | 9.89 | 10.03 | 9.77 |
| **19** | 10.13 | 9.34 | 9.15 | 9.31 | 8.90 | 8.53 | 9.25 | 9.01 | 8.92 | 8.53 | 9.12 | 9.13 | 9.28 |
| **20** | 10.68 | 9.53 | 9.03 | 8.41 | 8.81 | 8.46 | 8.97 | 8.93 | 8.69 | 9.01 | 8.78 | 9.24 | 9.58 |
| **21** | 10.55 | 9.61 | 8.96 | 8.54 | 8.62 | 8.48 | 8.94 | 8.78 | 8.73 | 9.09 | 9.53 | 9.84 | 9.36 |
| **22** | 10.12 | 9.37 | 9.08 | 8.75 | 8.91 | 8.92 | 8.99 | 8.81 | 9.09 | 9.09 | 9.41 | 9.40 | 9.32 |
| **23** | 10.27 | 9.48 | 8.88 | 8.64 | 8.97 | 8.59 | 8.67 | 8.97 | 9.26 | 9.40 | 9.31 | 9.86 | 10.08 |
| **24** | 10.33 | 9.71 | 9.56 | 8.75 | 8.71 | 8.63 | 8.92 | 8.92 | 9.31 | 9.25 | 9.35 | 9.57 | 9.34 |
| **25** | 10.34 | 10.03 | 9.35 | 9.04 | 9.07 | 8.93 | 9.33 | 8.98 | 9.19 | 9.21 | 9.72 | 9.50 | 9.62 |
| **26** | 10.35 | 10.09 | 9.46 | 8.85 | 9.16 | 9.01 | 9.28 | 9.05 | 9.38 | 9.60 | 9.42 | 9.45 | 9.56 |
| **27** | | 9.62 | 9.80 | 9.23 | 9.41 | 9.37 | 9.62 | 9.48 | 9.46 | | | | |
| **28** | | 9.97 | 9.86 | 9.57 | 9.62 | 9.58 | 9.86 | 9.58 | 9.38 | | | | |
| **29** | | 9.67 | 9.78 | 9.61 | 9.55 | 9.52 | 10.01 | 9.45 | 9.58 | | | | |
| **30** | | 9.31 | 9.63 | 9.87 | 9.90 | 9.74 | 9.74 | 9.47 | 9.63 | | | | |
| **31** | | 9.28 | 9.89 | 9.88 | 9.62 | 9.25 | 9.60 | 9.64 | 9.49 | | | | |
| **32** | | 10.07 | 9.78 | 9.60 | 9.37 | 9.32 | 9.53 | 9.48 | 9.30 | | | | |
| **33** | | 10.06 | 9.90 | 9.58 | 9.19 | 9.51 | 9.64 | 9.58 | 9.55 | | | | |
| **34** | | 9.94 | 9.90 | 9.82 | 9.56 | 9.09 | 9.16 | 9.37 | 9.28 | | | | |
| **35** | | 9.19 | 9.47 | 9.85 | 9.14 | 9.07 | 9.32 | 9.10 | 9.21 | | | | |
| **36** | 10.09 | 9.42 | 9.28 | 9.08 | 9.14 | 8.69 | 9.23 | 9.64 | 9.44 | 9.36 | 9.75 | 9.87 | 9.71 |
| **37** | 10.07 | 9.02 | 9.32 | 9.30 | 8.78 | 8.69 | 9.26 | 9.18 | 9.03 | 9.35 | 9.30 | 9.40 | 9.59 |
| **38** | 10.37 | 9.68 | 9.20 | 8.94 | 9.14 | 8.76 | 9.25 | 8.45 | 9.13 | 9.37 | 9.31 | 9.45 | 9.56 |

It follows from Table 1 that there was an area of approximately 800 mm in diameter with wall thickness less than 9 mm, namely around 8.5 mm, the minimum value being 8.41 mm. This thickness is almost by 12 % lower than minimum allowed thickness for this type of pipe. Furthermore an angle dependence of wall thickness follows from Fig. 1, where circumferential differences of the thickness are more than 2 mm, which is a considerably high value. The angle position of minimum and maximum wall thickness is 180° which confirms that the thickness inhomogeneity occurred during pipe manufacture – the pipe was seamless and rolled. The average value from all the measured points was 9.74 mm. Though this thickness is just 0.2 mm above the minimum requested value, the average thickness would be acceptable provided that it was uniform, which was not the actual case.

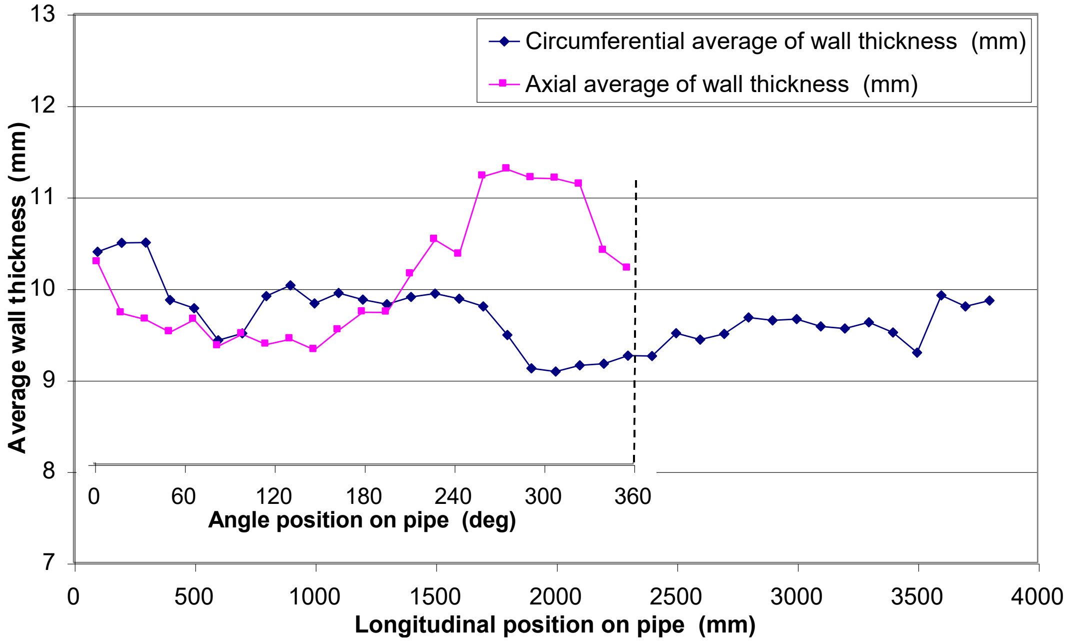


Fig. 1 Longitudinal and wall thickness distribution

**Chemical Composition and Mechanical Properties.** Content of elements in mass % was the following: C 0.15, Si 0.23, Mn 0.96, P 0.024 and S 0.029. The chemical composition was fully in accordance with the X42 (L290NB) standard.

Results of static tensile tests are in Table 2. Three specimen series were tested in both longitudinal and circumferential directions. The first series and second series were taken from the areas of maximum and minimum wall thickness, respectively. The third series was taken from a ring cut after the 100 hours creep test at internal pressure between 6.1 and 6.2 MPa.

Tab.2 Results of static tensile tests

| Specimen direction | Specimen serries | $R_{eH}$ [MPa] | $R_{eL}$ [MPa] | $R_m$ [MPa] | A [%] | Z [%] |
|---|---|---|---|---|---|---|
| longitudinal | 1 | 325 | 321 | 496 | 26.0 | 44.9 |
| | 2 | 332 | - | 485 | 22.7 | 50.0 |
| | 3 | 327 | 321 | 472 | 22.2 | 53.0 |
| **Specimen direction** | **Specimen serries** | **$R_{p0.2}$ [MPa]** | **$R_{t0.5}$ [MPa]** | **$R_m$ [MPa]** | **A [%]** | **Z [%]** |
| circumferential | 1 | 299 | 316 | 494 | 26.1 | 46.5 |
| | 2 | 295 | 303 | 485 | 24.6 | 47.5 |
| | 3 | 297 | 300 | 470 | 22.5 | 42.2 |

It can be concluded that mechanical properties satisfied the minimum requirements with the exception of elongation A, where the minimum value is 23 %. Elongation of the material taken from the area of minimum wall thickness was negligibly lower. Even lower was elongation after the 100 hours creep loading. Proof stress in the circumferential direction was close to the minimum requirements and it was not affected either by the position in the pipe or by the creep loading. Maximum strength fully satisfied the requirements, but it was slightly affected by both position in the pipe and creep loading – material from lower wall thickness area had lower maximum strength and material after the creep loading even more low.

Tab.3 Results of impact bending $KV_2$ and fracture toughness $K_{IC}$ tests

| **Direction** | **Series** | **$KV_2$ [J]** | **Fracture toughness $K_{IC}$ [MPa*m$^{0,5}$]** |
|---|---|---|---|
| longitudinal | 1 | 165.3 | 65.4 |
| | 2 | 45.5 | 62.2 |
| | 3 | 49.7 | 65.3 |
| circumferential | 1 | 29.2 | 61.6 |
| | 2 | 29.8 | 58.3 |
| | 3 | 32.1 | 57.0 |

Results of impact bending and fracture toughness tests are in Table 3. Concerning brittle / ductile properties, the steel is acceptable, but there are distinctly worse results in circumferential direction in terms of both impact bending and fracture toughness. Quite surprising is the very high value of impact bending in longitudinal direction of the material taken from the wall with high thickness – series 1, which is confirmed by fracture toughness, though with much lower difference. In general, fracture toughness in longitudinal direction corresponds quite well to the literature data [5]. Scatter of results, particularly of impact bending indicates that the material homogeneity in macroscopic scale is not optimum.

**Metallographic Analysis.** Microstructure was evaluated using an optical microscope Neophot II. Microstructure was of ferritic-pearlitic type. Residues of casting structure could be randomly found – Fig. 2, which can be considered as microstructure defects. Ferritic grain size evaluated according to ČSN EN ISO 643 corresponded to 6-7. Concerning material purity, oxide content was low unlike content of sulphides evaluated according to ČSN EN ISO 4967, which was at the end of the scale limit, perhaps even above it. Decarbonization to 0.2 mm depth was visible near both outer and inner surfaces – Fig. 3. Quite frequent were inclined cracks of length up to 0.5 mm, which occurred likely during manufacture – rolling.

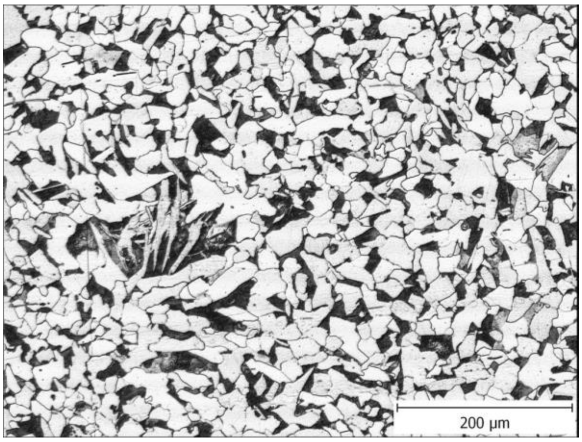


Fig. 2 Ferritc-pearlitic microstructure with residues of casting structure

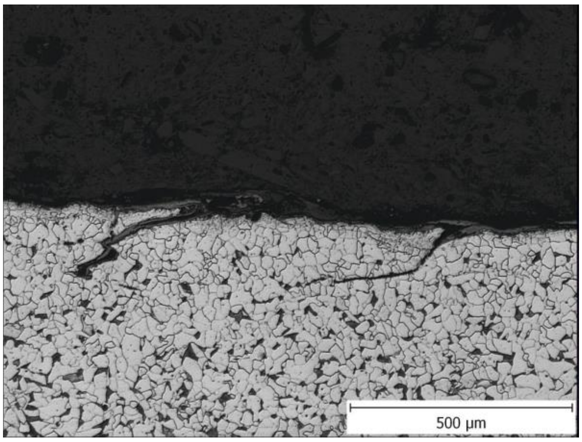


Fig. 3 Decarburized surface with cracks

**Stress-Strain Analysis.** Total amount of 16 couples of strain gauges (SGs) were glued on the pipe surface, one circumferential and one longitudinal SG at each of the 16 positions with the aim to evaluate:

— strains along the pipe length – on the line B, almost along the top line,
— strains along the circumferential line near the pipe centre – position 25,
— strains at areas of maximum, medium and minimum wall thickness,
— strain in the centre of the dents.

Strain values were recorded during the first stage of the pressure test to service pressure 6.2 MPa. In the following diagram, the theoretical stress was not calculated as an average stress using average thickness value, but it was calculated individually for each SG position considering actual wall thickness corresponding to the measured point.

Total survey of stress-strain dependencies with the exception of strains measured in the area of dents is shown in Fig. 4. The diagram contains record of strains along the line B – B12, B25, B33, circumferential strains at longitudinal position 25 – L25, O25, S 25 and strains at points of minimum and medium wall thickness, respectively – D20 and H16. The diagram contains regression lines of all points of circumferential and longitudinal measurements, respectively, and theoretical stress-strain lines calculated for medium wall thickness considering biaxial stress state.

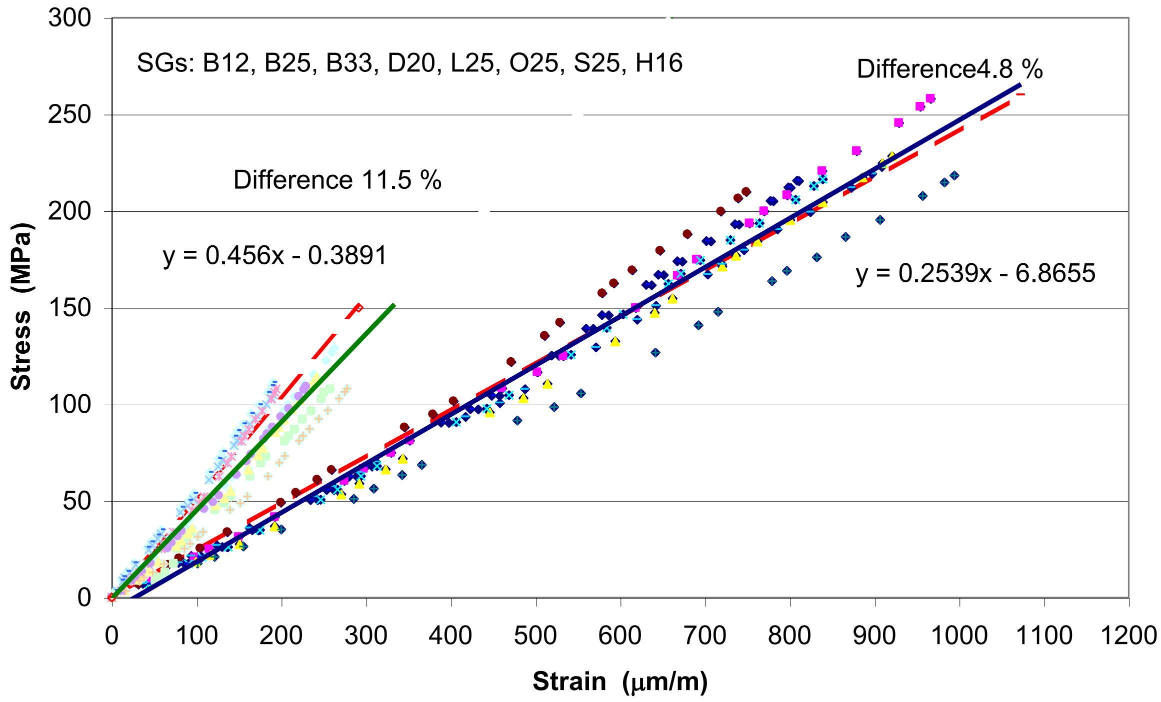


Fig. 4 Total survey of stress-strain dependencies with exclusion of measurement at defects

In Fig. 4, there is quite a good agreement between the regression line corresponding to circumferential measurements, the difference being bellow 5 %. As regards longitudinal measurement, the difference between the regression and theoretical lines is considerably higher, almost 12 %, the actual strains being higher. This fact can be, however, explained. Most of longitudinal measurements were carried out near the line B, i.e. near the top line. The tested pipe was not supported on rollers but just on wooden cross beams near the pipe margins, which partially obstructed free longitudinal motion at the pipe bottom. This eventually resulted in a kind of additional bending, when bottom strains were bellow average and top strains higher than average.

Much bigger differences are those between results measured at individual points and theoretical mean values. The differences are up to ±15% and even up to ±25% for circumferential and longitudinal measurements, respectively. Such differences cannot be explained by different wall thickness only. The likely reason is a more complex stress-strain redistribution in the pipe due to the variable wall thickness.

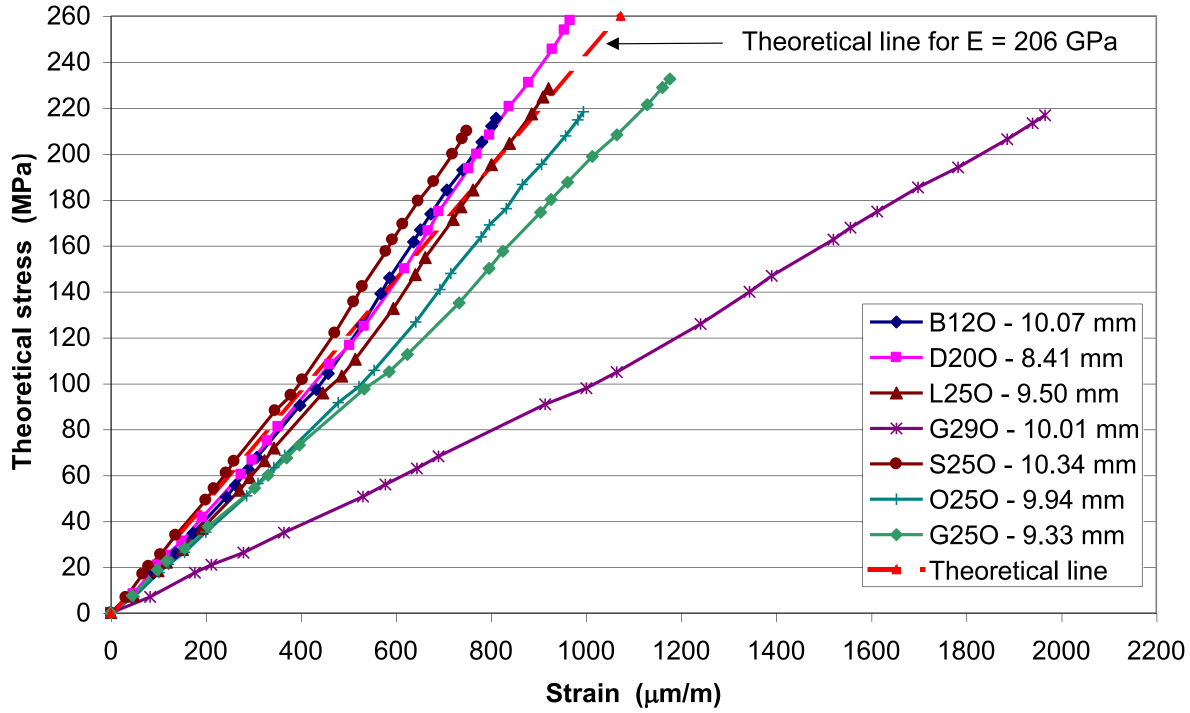


Fig. 5 Stress-strain dependences of selected circumferential measurement points including the two dents

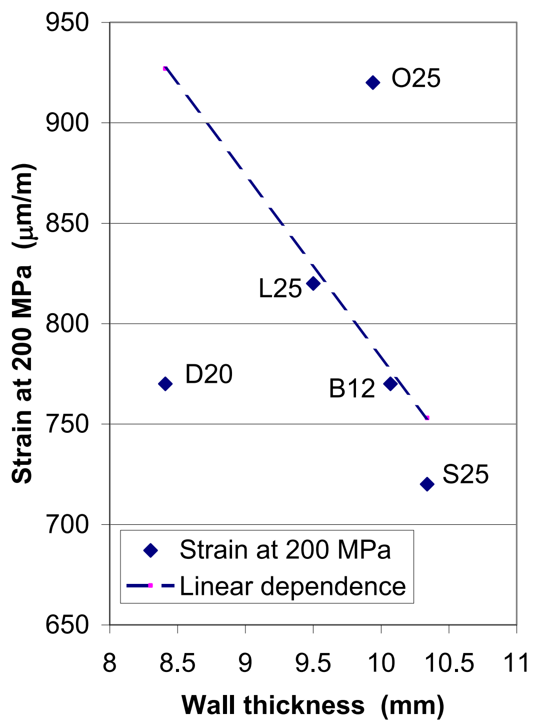


Fig. 6 Strains at 200 MPa at selected measurement points

Stress-strain dependences of selected circumferential measurement points including the two dents are shown in Fig. 5. It is evident that strains at the centre of the larger dent were more than 2.3-times higher in comparison with theoretical values for undamaged wall. Note that the dent actually was shallow, almost invisible, with the depth less than 5 mm and diameter approximately 100 mm. Some increased strains were measured at the centre of the second, quite negligible dent.

Individual values of strains at the stress 200 MPa, except the two dents, are shown in Fig. 6. This figure confirms that actual stress-strain distribution was more complex than it would correspond just to different wall thickness. If the strain only was dependent on the wall thickness at corresponding measurement point, the points would lie at least approximately along the linear line. This concerns only the points L25, S25 and B12. Strain values at points D20 and O25 are fare from this ideal line indicating that the stress-strain distribution is much more complicated.

**Evaluation of Pipe Creep.** Pipeline creep at room temperature and high pressure is a phenomenon recently studied in several literature contributions [6,7]. In this work, possible creep was measured at internal pressure 6.1 – 6.2 MPa, i.e. at maximum service pressure. This loading corresponded to circumferential stress 222 MPa, if mean wall thickness 9.74 mm was considered, which was 86 % of proof stress under biaxial conditions in the pipe. The measurement was performed for the period of 100 hours. The problem complicating an exact evaluation were temperature dilatations. The pipe could not be placed at any air conditioned room, just in a special uncovered basement in a special hall. Though the temperature changes were not so strong in the basement, they significantly affected the results, though the pipe was full of high pressure water. Strain records at all measurement points were carefully corrected considering material dilatations, but the measurement accuracy was not better than 10 – 15 μm/m. Final strain changes after the test were within this interval, even changes at the centre of the dent. It could be therefore concluded that no measurable creep occurred. Nevertheless, a ring was taken from the pipe for evaluation of mechanical properties after the creep test – Tables 2 and 3.

**Pressure Test to Destruction.** Loading by the internal pressure to final pipe failure was performed quasistatically with maximum pressure increments 0.27 MPa / min. Pressure values corresponding to proof stress $R_p0.2$, stress $R_t0.5$ and final pipe failure were 7.9 MPa, 8.3 MPa and 12.7 MPa, respectively. If these values are recalculated to stresses using mean pipe wall thickness 9.74 mm, the corresponding stresses are 284 MPa, 298 MPa and 456 MPa, respectively. Note that the pipe is loaded biaxially with $\sigma_2 = \sigma_1 / 2$, $\sigma_1$ being circumferential and $\sigma_2$ longitudinal stress. Considering this biaxiality and HMH hypothesis, maximum reduced stress should correspond to 0.87 uniaxial stress. In such case the pipe proof stress should be 258 MPa and destruction should occur at approximately at 420 MPa of the circumferential stress. Actual stress values were reduced by the factor 0.95, higher than 0.87 according to the HMH hypothesis. It looks that the HMH hypothesis was slightly too conservative for this case of pipe and the material X42.

**Fractographical Analyses of Failure Initiation Area.** Final pipe failure occurred at area of the dent, near the point of maximum measured strains, i.e. near the dent centre, but not exactly there. The wall thickness at the failure area was 9.58 mm. The failure did not occur in the area of the minimum wall thickness, which was supposed. This is very important fact indicating that even small, almost negligible dents reduce pipe strength at least slightly. Note that in general, dents caused numerous pipeline failures in the past and recently [8]. Fractographical analysis provided further important information. In the fracture initiation area, intergranular surface cracks were observed, likely the same cracks as shown in Fig. 3. It should be, however, pointed out that both the phenomenona supporting the final failure, namely presence of the dent and surface cracks, reduced final pipe strength just negligibly, because final failure occurred at pressure by several percent higher than according to the HMH hypothesis applied to pipe with constant thickness and without any defects.

## Conclusions

The study presented in the paper contains selected aspects and crucial results of a comprehensive experimental programme aimed at evaluation of limit states, stress-strain distribution, defects and failure mechanisms of a section of high-pressure gas pipeline, taken from an actual pipeline line of the nominal diameter DN700, made of an L290NB steel (API 5L X42 steel), operated at maximum pressure 6.1 MPa, Since the NDT internal inspection of the pipeline section indicated reduced pipe wall thickness, the primary aim was to confirm the service safety and reliability. The main results can be summarized as follows:

- Actual wall thickness was even lower than indicated by the NDT method. There was a large area of approximately 800 mm in diameter with wall thickness less than 9 mm, around 8.5 mm, the minimum value was 8.41 mm, almost by 12 % lower than minimum allowed thickness for this type of pipe. Circumferential differences of the thickness were more than 2 mm. The angle position of minimum and maximum wall thickness was 180° which confirmed that the thickness inhomogeneity occurred during rolling of the seamless pipe. The average value from all the measured points was 9.74 mm. Though this thickness was just 0.2 mm above the minimum requested value, it would be acceptable provided that it was uniform, which was not the actual case.
- In general, mechanical properties and material microstructure satisfied the requirements, though in some cases close to limits. Fairly high was content of sulphides, fortunately homogeneously distributed, not in unfavourable chains. Decarbonization was low, up to 0.2 mm near both inner and outer surfaces. The most problematic point was an occurrence of frequent surface inclined cracks of the length up to 0.5 mm, filled with ferrous oxide products.
- Results of the comprehensive experimental stress-strain analyses were in average close to the theoretical values, but individual measurements differed by more than ± 15 % in circumferential direction and even more in longitudinal direction, in the latter case likely affected by fixed wooden supports used. The differences were probably caused by the irregularities in the wall thickness. Strains measured at the dent were more than twice as much higher, though the dent was very small and inexpressive. No creep was observed during 100 hours test at service loading between 6.1 and 6.3 MPa, which corresponded to 86 % of proof stress. No creep occurred even at the dent.
- Final pipe destruction occurred at pressure 12.7 MPa, more than twice as much in comparison with service pressure, at average theoretical stress of 95 % of circumferential material strength, which is considerably higher than theoretical failure considering the biaxial loading. The pipeline in these conditions was therefore evaluated as definitely safe, with a safety factor more than 2. What should be, however, pointed out is that the final destructive crack was not initiated in the area of minimum wall thickness as expected, but at the dent with an evident assistance of the surface small cracks. Therefore, an attention should be definitely paid to such defects in reality.

## Acknowledgement

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