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Strain Distribution in Vicinity of Dent in Tube in the Course of Indentation

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Abstract. Dents are the common mode of damage which can cause failure of pipelines. The paper describes experimental and numerical investigation of the state of stress and strain in the course of the indentation of large thin walled steel tubes. The tubes resting on a V support block were laterally indented by a large spherical steel indenter. Strains in the vicinity of the dent were measured by resistance strain gauges and the elasto-plastic state of stress was evaluated from the experimental data. The results were compared with finite element simulation.

Introduction

Dents are caused by a collision of the tube with an external rigid object during the laying of the pipeline, by the lateral impact of heavy loads or by the shock caused by an excavation equipment. Considerable plastic strains are developed in the course of the formation of dents. The dent size, shape and location can significantly affect the service life of pipeline.

Experimental and numerical investigation of the indentation of tubes was a matter of interest for a number of scientists. The local dent without surface crack in a pressurized pipe was investigated by Ong and all. [1]. They were focused on the experimental gauging test and FE analysis in the elastic strain distribution. Papers of Allouti and all. deal with steel pipelines containing a gouge and dent defect [2,3]. They performed also experimental burst tests and FEA to compare the numerical and experimental results. Experimental and numerical research of Moustabchir [4] presents the stress–strain state of pressurised cylindrical shells with longitudinal external defects which includes the effects of plasticity. A fatigue analysis of dented pipeline subjected to internal pressure which is based on experimental data was presented recently by Garbatov [5]. In this paper, the different failure criteria considering the dent size and applied load are analysed and reliability as a function of number of load cycles is defined. Papers dealing with the analysis of experimentally determined strains in the elasto-plastic domain are sparse. Keil and Benning [6] described the practical procedure of the strain analysis in the elasto-plastic range based on the stress-strain curve of the material and evaluated the 2d state of stresses from the strains measured by resistance gauges. Rao [7] further developed this method. A rigorous approach founded on the flow theory of plasticity for elastic-plastic boundary value problems was presented by Sutton and Deng [8]. They suggested an numerical procedure for the determination of stresses and elastic and plastic strains from the experimental strain data measured on the surface of a structure by the numerical integration of elastic-plastic constitutive equations. The evaluation of strain gauge measurements in the elasto-plastic area was also presented by Dolhof [9].

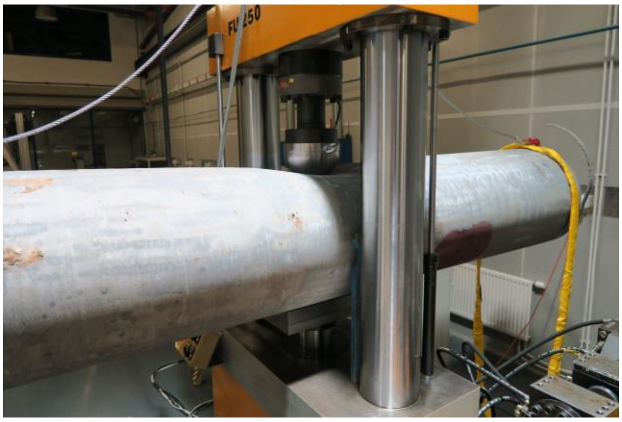

Fig. 1. Experimental setting of the tube indentation

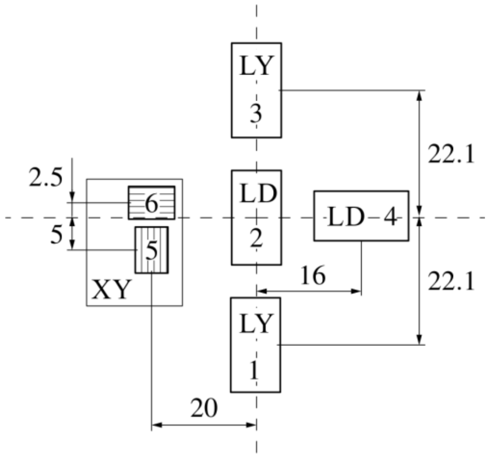

Fig. 2. Placement of the strain gauges

Experimental

The experimental work consisted of the indentation of two large steel specimens cut out of two different thin-walled tubes. The test specimens were 530 mm in diameter, 3360 mm and 2990 mm long, with corresponding D/t ratios of 56 and 66. The pipes were tested on an INOVA FU 250 kN testing machine in Fig. 1. The specimens were simply supported by a V support block at the middle-length and subjected to a concentrated transversal loading by the spherical steel indenter 200 mm in diameter. Load-displacement response and the response of resistance strain gauges as functions of dent depth are recorded for each specimen. The elasto-plastic stresses were evaluated from the records of strain gauges. HBM resistance strain gauges were fixed inside the tube under the indenter. The first experiment was performed on the tube with D/t ratio of 56. We used two linear strain gauges LY with the base 5 mm for strain up to 5%, then two LD 5 mm for large strains up to 10% and one XY rosette of 5 mm for strain up to 5%. The gauges were attached inside the tube under the center of indenter. The strain gauge layout is shown in Fig. 2. The loading process was controlled by the displacement. The indenter was plunged slowly into the tube to a depth of 60 mm then the load was relieved. The residual dent had a depth of 37 mm. The nonlinear loading curve is shown in Fig.3. The response of the strain gauges is shown in Fig.4. The strain gauges LY and the XY rosette were broken when the limit of their strain 5% was exceeded. The data of LD gauges in axial and circumferential directions were evaluated and elasto-plastic principal stresses were calculated.

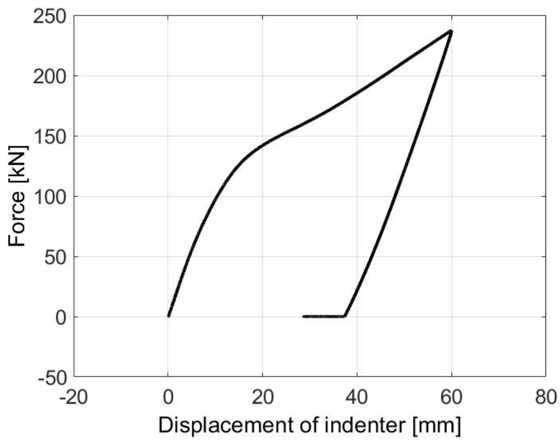

Fig. 3. Loading curve of the tube D/t = 56.

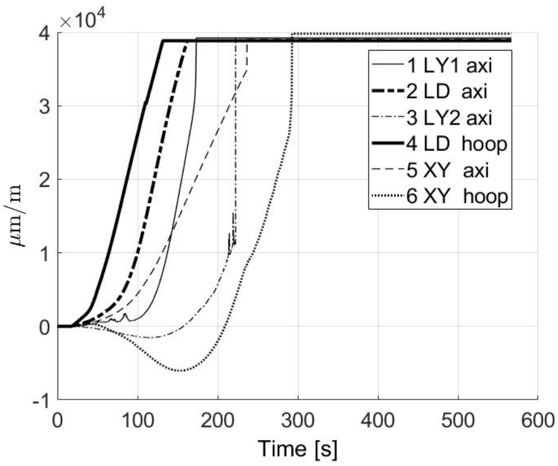

Fig. 4. The response of the strain gauges.

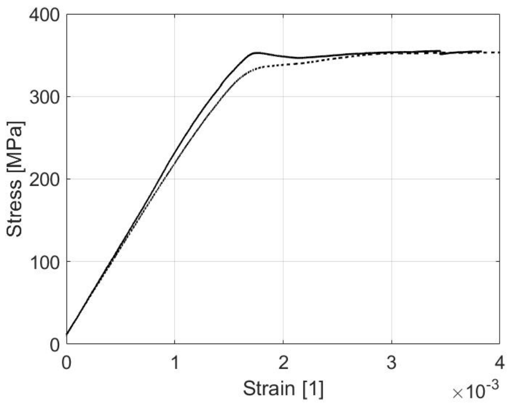

Fig. 5. Tension diagram of tube material

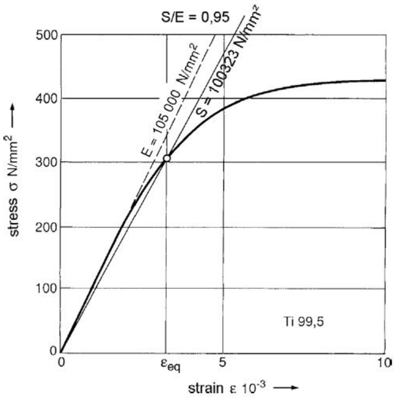

Fig. 6. Example of the evaluation of the secant modulus *S* and the ratio *S/E* from Keil [6]

Evaluation of experimental data

The tensile diagram of the pipe material in Fig.5 shows the ductile steel behavior almost without hardening with the yield stress of about 350 MPa then we can suppose the ideal elasto-plastic material. We use Von Mises yield criterion in principal stresses for 2d state of stress

$$\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2 = \sigma_Y^2. \tag{1}$$

The elasto-plastic stress-strain behavior of 2-d state of stress can be formally described in the same way as the linear elastic ones [6] if the variable secant modulus $S = \sigma_{eq}/\varepsilon_{eq}$ in Fig. 6 and the combined Poisson's ratio ν_g are used instead of the elastic E and ν. The combined Poisson ratio is evaluated by relation

$$\nu_g = 0.5 - (0.5 - \nu)\frac{S}{E}, \tag{2}$$

where *S* is the secant modulus. Apparent Poisson ratio ν_g for our material is in Fig. 6, the value of the ratio lies between elastic ν and the plastic Poisson ratio 0.5. The elasto-plastic 2d stresses will be evaluated from the relations

$$\sigma_t = \frac{S}{1-\nu_g^2}\left(\varepsilon_t + \nu_g\varepsilon_a\right), \quad \sigma_a = \frac{S}{1-\nu_g^2}\left(\varepsilon_a + \nu_g\varepsilon_t\right), \tag{3}$$

where ε_t and ε_a are strains measured by gauges. The equivalent strain is given by relation

$$\varepsilon_{eq} = \sqrt{N_q\left(\varepsilon_1^2 + \varepsilon_2^2\right) + N_g\varepsilon_1\varepsilon_2}, \quad N_q = \frac{1-\nu_g\left(1-\nu_g\right)}{\left(1-\nu_g^2\right)^2}, \quad N_g = \frac{-1+\nu_g\left(4-\nu_g\right)}{\left(1-\nu_g^2\right)^2}. \tag{4}$$

The elasto-plastic axial, hoop and equivalent stresses were determined from LD gauges records. The stresses satisfy the condition of plasticity as shown in the graph in Fig. 7. The evaluation through an iteration process was done in Matlab.

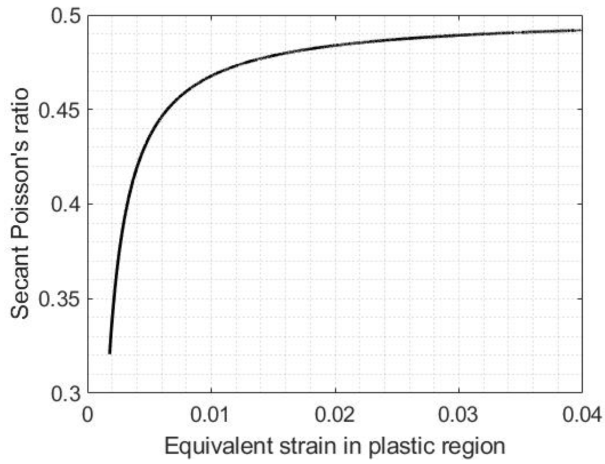

Fig. 6. Apparent Poisson's elasto-plastic ratio

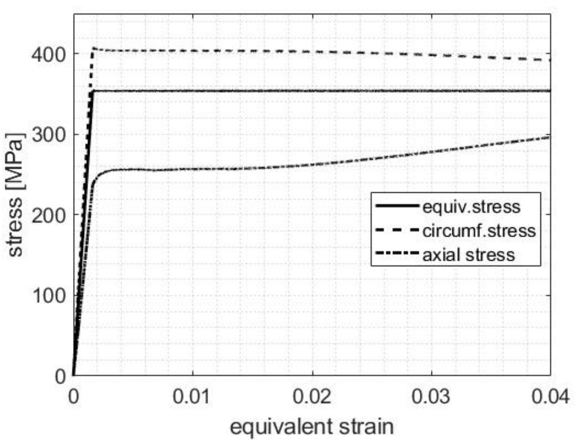

Fig. 7. Stresses calculated from LD gauges data

Conclusion

Elasto-plastic axial and circumferential stresses were determined from the principal strains measured by gauges in the course of tube indentation. The simplified method of the evaluation of strain gauges measurement above the yield limit of material was presented.

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