Arch. Metall. Mater. **62** (2017), 3, 1597-1601

DOI: 10.1515/amm-2017-0244

A. SLÁDEK*[#], M. PATEK**, M. MIČIAN*

BEHAVIOR OF STEEL BRANCH CONNECTIONS DURING FATIGUE LOADING

Fatigue behavior of the branch connection made of low-alloyed steel with yield stress of 355 MPa during low-cycle bending test is investigated in the article. Numerical prediction of the stress and strain distribution are described and experimentally verified by fatigue test of the branch connection sample. Experimental verification is based on low-cycle bending testing of the steel pipes welded by manual metal arc process and loaded by external force in the appropriate distance. Stresses and displacement of the samples induced by bending moment were measured by unidirectional strain gauges and displacement transducers. Samples were loaded in different testing levels according to required stress for 2.10^6 cycles. Increase of the stress value was applied until the crack formation and growth was observed. Results showed a high agreement of numerical and experimental results of stress and displacement.

Keywords: branch connection, stress analysis, fatigue bending test

1. Introduction

Metal structures are in many practical applications subjected to cyclic loads, which occasionally may be strong enough to induce repeated yielding of the material [1-2]. Gas transmission pipelines are often loaded by internal pressure fluctuations and external loading can be also present due to insufficient soil concretion, ground movement or presence of frequent road near the pipeline. Similar problems might be present in case of pressure vessels with character of external loading strongly depends upon final construction solution and operational conditions. Branch connections of the pipes can also maintain additional loads caused by the armatures placed on the branch pipe near the connection leading to bending of the branch pipe. Such loading leads to severe stress cycles that may induce low-cycle fatigue damage, the degree of which is influenced by stress concentrations (due to geometrical and material discontinuities, surface roughness, macro and micro inclusions and defects), the type of loading (strain- or stress-controlled and degree of non-proportionality) and the presence of residual stresses (from manufacturing processes, prior large deformations and welding) [3].

Several authors performed low fatigue tests of the pipeline materials, including austenitic steels or Ti and Nb stabilized steels [4-5]. Such material tests are mostly preformed on the cyclically loaded samples from the material, which do not always represents real operational conditions. Rahman et al. [3] evaluated influence of cyclic bending and steady internal pressure influence to straight pipes with proposal of an appropriate plasticity model to describe material behavior. Low-cycle fatigue of the elbows with different thickness (representing wall thinning by corrosion) was studied by Takahashi et al. [6]. Authors showed that local wall thinning influence low-fatigue life mainly if decrease of thickness is at the intrados of the elbow. Fatigue testing of the branch connections is still rather infrequent, although they belong to the most sensitive piping components of nuclear power plants and pipelines [7]. Xue et al. [8] proposed theoretical stress analysis models for connection subjected to external loads transmitted through branch pipes. Stresses indices in branch connections with different angles between header pipe and branch pipe were analyzed by Mkrtchyan et al. [7] and Sajish et al. [9]. However, authors used only numerical solutions and appropriate design codes but no experimental verification were present.

Presented article describes behavior of low-alloyed steel branch connection during fatigue bending test. Experimentally obtained results are compared with numerical solution of cyclic loading by finite element method.

2. Experimental methods and materials

Cyclic bending test was performed on the branch connection made of S355J2H steel pipes. Chemical composition of the pipes is shown in Table 1. Branch connection sample consisted of header pipe with outer diameter of Ø159.0 mm and branch

---

* UNIVERSITY OF ŽILINA, FACULTY OF MECHANICAL ENGINEERING, DEPARTMENT OF TECHNOLOGICAL ENGINEERING, ŽILINA, SLOVAKIA
** MONT IRP S.R.O., ŽILINA, SLOVAKIA

[#] Corresponding author: augustin.sladek@fstroj.uniza.sk

TABLE 1

Chemical composition of S355J2H steel pipes (in wt.%)

	C	Mn	Si	P	S	Al	Cu	Ni	Cr	Mo
Header pipe	0.16	1.15	0.201	0.012	0.009	0.027	0.10	0.04	0.04	0.008
Branch pipe	0.09	1.18	0.217	0.011	0.003	0.024	0.05	0.03	0.04	0.007

pipe with diameter of Ø60.3 mm. Wall thickness was 4.5 mm and 4.0 mm for header pipe and branch pipe, respectively. Angle between the pipes was 60°. Manual metal arc welding technology was used to joining the pipes by circumferential fillet weld with weld throat dimension of 7.1 mm.

Arrangement of the experimental test is shown in Fig. 1. Bending force was applied by electro-hydraulic machine RSVH with force detector LC-IE-20kN-EK acting in a distance of l = 1,000 mm from the weld joint between header pipe and branch pipe. Free end of the branch pipe was supported by the spring (Fig. 2) due to high deformation of the pipe at the end resulting to very low frequency of force during test. Specimens were fixed by the 8 bolts at the ends of the header pipe, 4 bolts at each end. For this purpose, experimental sample was equipped by the steel plates welded to the header through four ribs (Fig. 1).

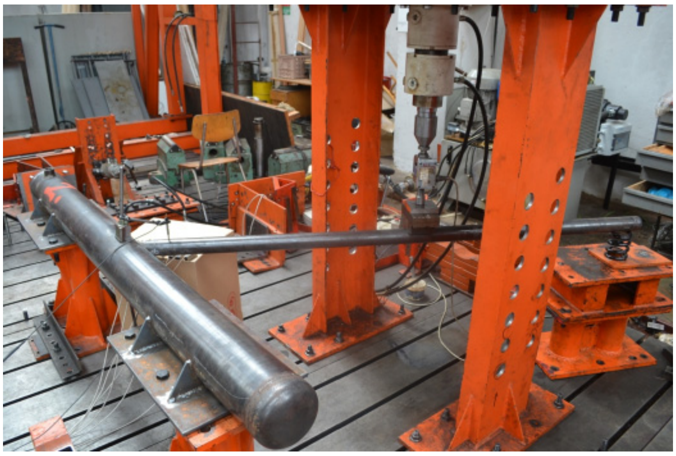
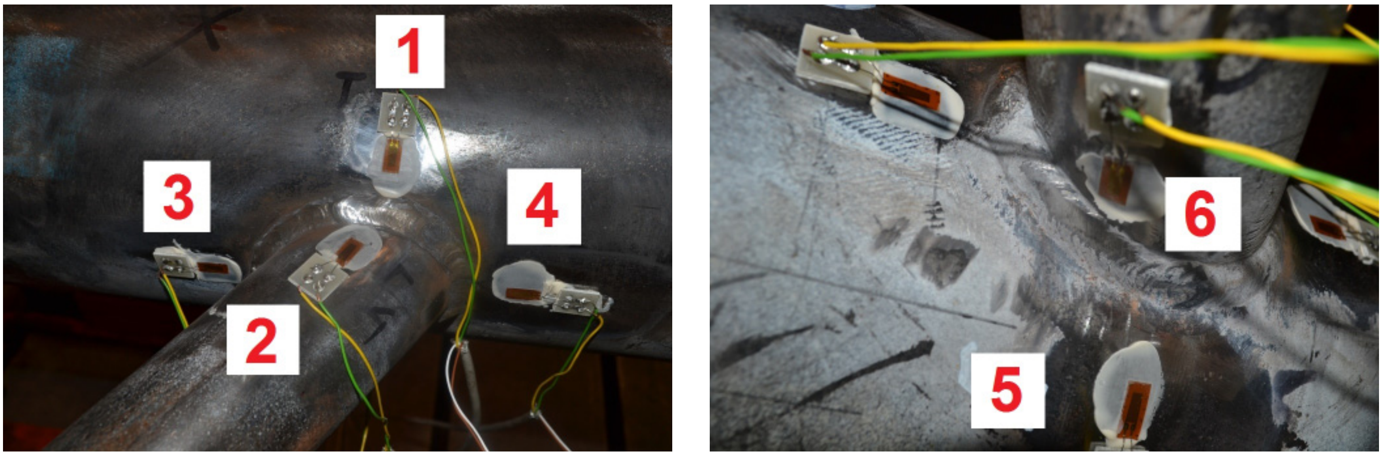


Fig. 1. Experimental bending test arrangement for branch connection

Fig. 2. Reinforcement of the free end of branch pipe by spring

Stresses were measured by 6 unidirectional strain gauges (SG) type 6/120 LY11 placed in the area of fillet weld during testing process (Fig. 3). Unconventional fatigue testing process was used with applied force adjusted to maintain required stress level in at least one of the strain gauges and cycled from the minimal to maximal stress value (force range of 2 kN). Stress level value was chosen from the material Yield stress in such way that stress should be in the range of allowable static stresses for S355J2H steel. Required value of the stress (Table 2) was increased after the sample maintain loading during the $N = 2.10^5$ cycles. Increasing of the force was applied until formation of the crack in the sample was observed. Deformation of the sample was measured by the displacement transducers (HBM WI-10-T) placed on the top and bottom of the branch pipe in distance of 100 mm from the fillet weld.



a) b)

Fig. 3. Position of strain gauges on the branch connection sample in the upper (a) and lower (b) part

TABLE 2

Required stress level and number of testing cycles during testing

Testing level	Required stress σ_r [MPa]	Required number of cycles N
1	140	2.10^5
2	180	2.10^5
3	220	2.10^5
4	260	2.10^5

Finite element (FE) stress analysis of branch connection was performed in to propose the suitable tool for stress prediction. Dimensions and fixing of the model corresponded with experimental sample. Material properties of the branch connection parts was used from material database of the low-alloyed S355 steel. Due to stress levels of the sample under the material Yield stress, only linear stress-strain behavior was considered. FE analysis included stress concentration evoked by weld joint during cyclic loading process. Bending moment to the model was computed by application of the loading force acting in the distance of 1,000 mm from the fillet weld in accordance to experimental measures (maximal and minimal loading force together with frequency was the same as for experiment). Another force was applied at the end of the branch pipe representing the spring used during the bending test at the end of the sample. Force of the spring was obtained by static loading test of the spring with force measuring in dependence of spring deformation.

3. Results and discussion

3.1. Fatigue bending test

Results of the force necessary to obtain required stress value are shown in Table 3 and displacement measured by the upper and lower displacement transducer (DT) are in Table 4. Required stress was in every stress levels measured by the strain gauge placed over the fillet weld on the header pipe (SG 1). In the final testing level of the sample, force had to be increased to sustain constant stress value due to initiation and growth of the fatigue crack from the initial maximal force of 6.4 kN up to more than twice of this value (13.5 kN). Distortion of the branch pipe was in each stress level higher on the upper side (on the side of force acting) than on the lower side of the pipe. Pipe subjected to bend moment thus not only distorted from the longitudinal axis of the pipe but also in the cross-section leading to elliptical shape of the pipe.

TABLE 3

Maximal and minimal loading force during fatigue bend test

Testing level	Required stress σ_r [MPa]	Maximal force $F_{\max}$ [kN]	Minimal force $F_{\min}$ [kN]
1	140	3.0	1.0
2	180	3.8	1.8
3	220	4.7	2.7
4	260	6.4 – 13.5	4.4 – 11.5

TABLE 4

Maximal and minimal displacement measured by upper and lower displacement transducer during cyclic bending tests of branch connection samples

Testing level	Required stress σ_r [MPa]	Upper displacement transducer		Lower displacement transducer	
		Maximal displacement $x_{\max}$ [mm]	Minimal displacement $x_{\min}$ [mm]	Maximal displacement $x_{\max}$ [mm]	Minimal displacement $x_{\min}$ [mm]
1	140	1.20	0.58	0.69	0.32
2	180	2.23	1.61	0.88	0.50
3	220	2.53	1.92	1.05	0.69
4	260	3.08	2.48	1.40	1.03

Fig. 4 shows position of the fatigue crack in the heat affected zone of the fillet weld on the header pipe. Initiation and growth of the fatigue crack was observed in the stress level of 260 MPa after 647,000 loading cycles. Position of the fatigue crack in heat affected zone might be influenced by several factors. First is behavior of weld joint between header and branch pipe as a place where a fatigue crack can emanate [10]. Heat affected zone (HAZ) has also higher hardness and coarser grains as parent metal leading to higher rate of fatigue crack propagation. Rading [11] also include micro-mechanism of fatigue crack growth and hydrogen embrittlement as a reason for presence of crack in HAZ.

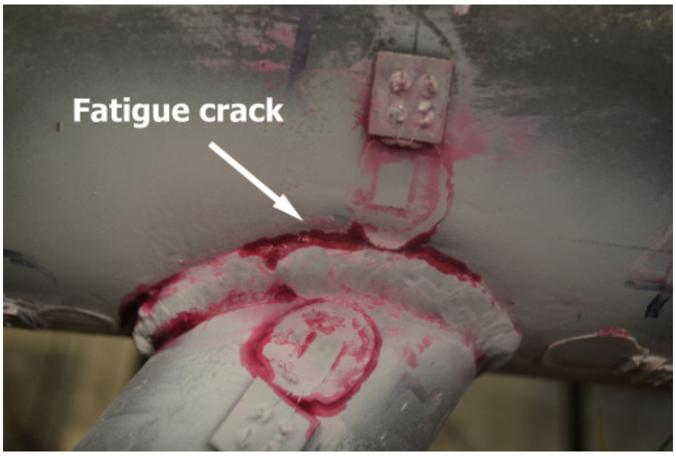


Fig. 4. Fatigue crack position

Except of the necessity of increasing of the loading, distortion of the branch pipe also changed once fatigue crack started to form (Fig. 5). Higher distortion was measured after crack was initiated as a result of connection between header and branch pipe breaking.

3.2. Finite element analysis

During the experimental measures, unidirectional strain gauges were applied to measure stress of the branch connection.

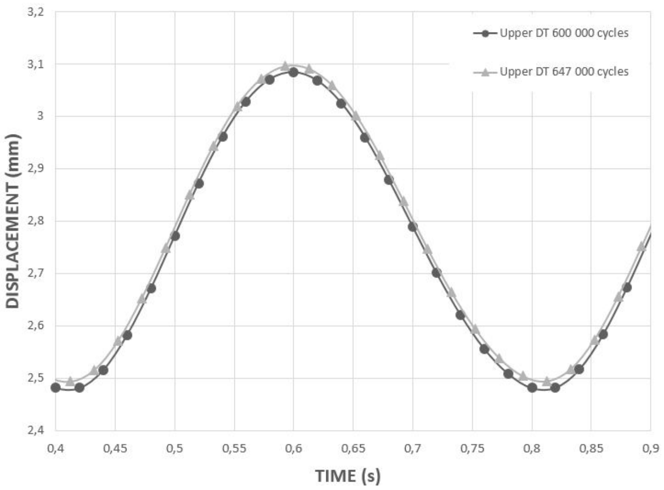


Fig. 5. Displacement change on the upper displacement transducer influenced by initiation and growth of the fatigue crack

Because of it, 1st principal stresses are more suitable for comparison than the equivalent stresses. Distribution of the maximal stress of the branch connection at the testing level 1 are shown in the Fig. 6 for upper view and in Fig. 7 for the bottom view. Results correspond with the experimental measures for the upper and also lower side of the branch connection in the position of strain gauges. High agreement with experimental results was also obtained at the highest (4th) measured level (Fig. 8).

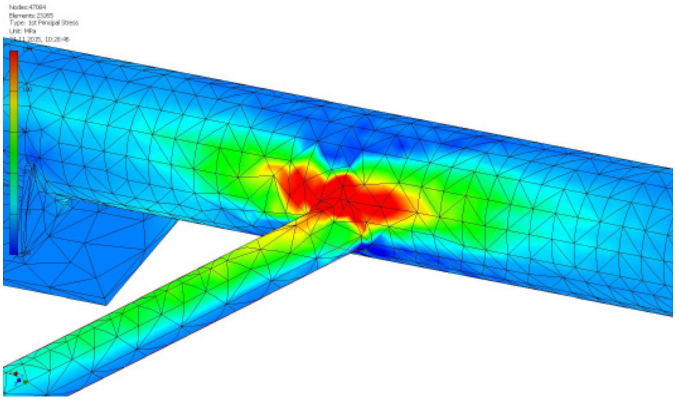


Fig. 6. Distribution of the maximal 1st principal stress at the loading level No. 1 (upper view)

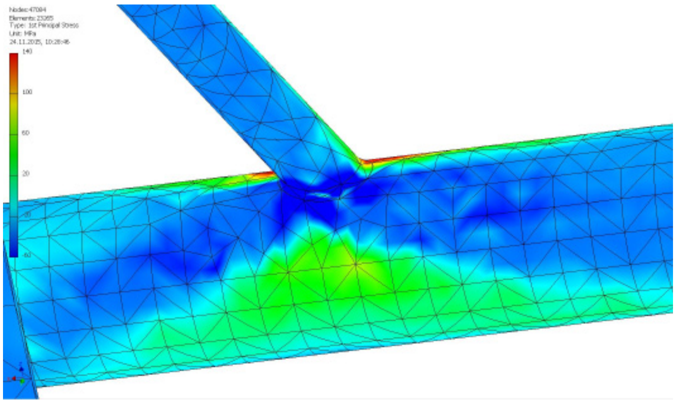


Fig. 7. Distribution of the maximal 1st principal stress at the loading level No. 1 (bottom view)

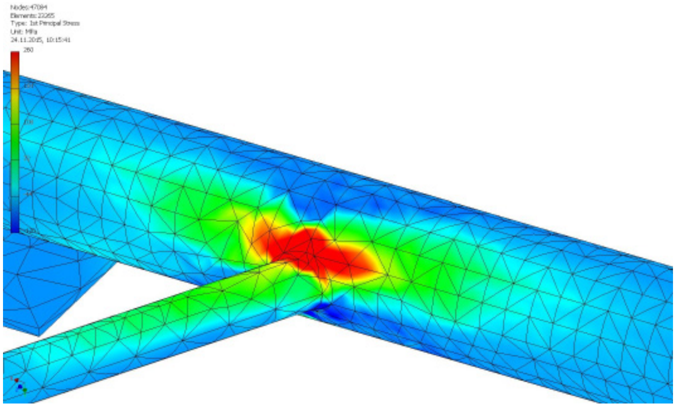


Fig. 8. Distribution of the maximal 1st principal stress at the loading level No. 4 (upper view)

Distortion of the branch connection in maximal and minimal loading value are shown in the Fig 9 and 10. Values obtained by FE analysis highly correlate to the measured values during experimental procedures in the places of displacement transducers. It can be also seen that higher value of maximal distortion was present in the first loading level in the area of force acting. Maximal distortion is in the first case was present at the end of the branch pipe, but in the last measured level is placed between the loading force and the spring. In highest loading levels, higher force is evoked in the spring and lower distortion might be thus measured.

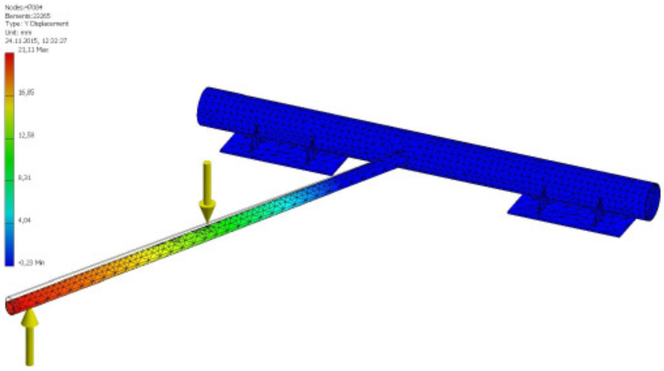


Fig. 9. Distribution of the maximal displacement at the loading level No. 1

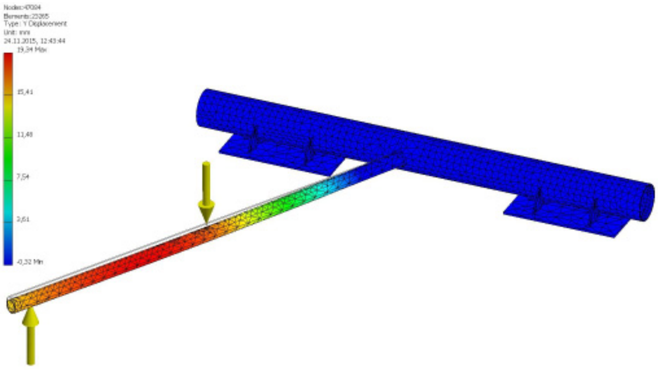


Fig. 10. Distribution of the maximal displacement at the loading level No. 4

4. Conclusions

Design of gas transition pipelines and pressure vessels still requires high attention due to very large amount of construction details, which might lead to defects initiation during operational time. One of the most common and still most dangerous details are branch connections due to additional loading that is often present. Results of the experimental branch connection fatigue testing can be summarized as follows:

1) Branch connection without reinforcement can withstand 647,000 bending cycles with maximal stress of 260 MPa.
2) Heat affected zone of the fillet weld joint on the header pipe is the most critical place for fatigue crack initiation and propagation.
3) Finite element bending analysis might serve as the powerful tool for predictions of stress and distortions of the branch connection.

REFERENCES

[1] S.P. Vaze, E. Corona, Thin. Wall. Struct. **31**, 325-341 (1998).
[2] A. Zrak, R. Koňár, P. Jankejech, Manufacturing Technology **15**, 748-752 (2015).
[3] S.M. Rahman, T. Hassan, E. Corona, Int. J. Plasticity **24**, 1756-1791 (2008).
[4] H.J. Leber, M. Niffenegger, B. Tirbonod, Mater. Charact. **58**, 1006-1015 (2007).
[5] S. Goyal, et al, Procedia Engineering **55**, 136-143 (2013).
[6] K. Takahashi, et al, Int. J. Pres. Ves. Pip. **87**, 211-219 (2010).
[7] L. Mkrtchyan, H. Schau, D. Hofer, in: Transactions SMiRT 21, New Delhi, India 2011.
[8] M.D. Xue, D.F. Li, K.C. Hwang, Int. J. Solids Struct. **42**, 3299-3319 (2005).
[9] S.D. Sajish et al, Procedia Engineering **55**, 361-366 (2013).
[10] P. Darcis, T. Lassen, N. Recho, Weld. J., 19-26 (2006).
[11] G.O. Rading, Weld. J., 307-312 (1993).