Deformation and Failure Behaviour of Elbows

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Abstract

In this paper, various experimental investigations of elbows under internal pressure and subjected to bending load are introduced. A brief description of the tests is followed by a presentation of the test results for the deformation behaviour of elbows and a comparison with theoretically determined predictions. The paper concludes with a description of the modes of failure of pipe elbows subjected to cyclic bending load.

1. Introduction

Pipe elbows are incorporated into pipework systems to enable modifications of the isometric routing. Moreover, due to their increased flexibility in comparison to straight piping sections, they allow a reduction of the reaction forces and moments within the system as a whole by virtue of their elastic deformations.

Several cases of damage which have occurred in the region of pipe elbows in power stations /1/ have prompted the initiation of various investigations at the MPA Stuttgart with regard to deformation and failure behaviour of pipe elbows /2-5/ within the framework of the HDR safety programme. Parallel to these, theoretical analyses of the deformation of the elbow mid-sections according to the ASME-Code /6/ were made and a modified finite element (FE) model calculation for pipe elbows was applied /7,8/.

As the experimental investigations could only be performed on the outside surface of the component, it was intended that the theoretical analyses would enable predictions of the inside wall loadings.

2. Test Matrix

The investigations, which were made at room temperature, involved testing of four elbows of austenitic material and three of ferritic material, different sizes of elbow being used in each case (Table 1).

The first five investigations were performed on the MPA pipe test bench with the elbows under internal pressure and using air-saturated water as the pressurizing medium (Fig 1). In order to measure deformation behaviour, initially a static in-plane bending load was applied, followed by a cyclic in-plane bending load in order to conclude the tests to failure.

Supplementary to these, static tests with transverse bending load and without internal pressure were performed on two further elbows (elbows 6 and 7 of the test matrix).

3. Experimental results with regard to deformation behaviour

3.1 Cross-sectional deformation in the elbow mid-section for in-plane bending

When bending load is applied, in addition to prismatic bending, cross-sectional deformation or ovalization occurs in the region of elbows, the extent of which is a function of the elbow dimensions (Do/Di,λ). The investigation of thin-walled (Figs 2 and 3) and of thick-walled (Figs 4 and 5) elbows has demonstrated that the cross-sectional deformation, characterized by circumferential strain, decreases with elbows for increasing thickness, e.g. of the type that are used at present in West Germany as "basis safety" components.

3.2 Propagation length of ovalization

As shown by these and other investigations /9-11/, ovalization of the elbow mid-section under bending load is propagated - in some cases to a marked extent - along the straight pipes. In order to allow weakening of the state of two-axis stress in the elbow mid-section to one of single-axis stress (i.e. prismatic bending), a length of about 2 x Do (elbows 1-3,5) to 4,5 Do (elbow 6) was determined for the thinner-walled elbows. For the thicker-walled elbow 4, the propagation length was about 1 x Do. In general, it is possible to derive a relationship between influence length and pipe elbow geometry as shown in schematic form in Fig 7.

4. Comparison of test results with theoretical values

In the ASME Code, equations for determination of the stress distribution in the elbow mid-section are given which are applicable to pipe elbows whose pipe factor $\lambda \geq 0.2$ /6/. Comparison of the test results with the theoretical values converted to strains for a thick- and for a thin-walled elbow show that the deformation behaviour of the cross-sections concerned can only be described by the analytical equations to a limited extent. Whereas the qualitative behaviour of the thin-walled elbows exhibits good agreement down to the intrados regions (Fig. 8), the deviations for the thick-walled elbow are considerable (Fig. 9). In this case, inadequate representation of the longitudinal strains in the intrados region could result in incorrect interpretations with regard to possible failure behaviour. Because of the lack of agreement between the measured and the calculated values on the outside wall, it is not possible to draw any conclusions with regard to the loading of the inside wall.

More exact results for the strain distribution are provided by the calculation for a thin-walled elbow (Fig 10) as described in /8/. The good agreement between measured and calculated values for the outside of the wall leads to the assumption that the calculated values for the inside wall are also correct.

The calculations show that the loading on the inside wall of the elbow in the circumferential direction is greater than that on the outside wall. Due to the non-linear strain distribution cross the wall thickness, this effect becomes more marked as wall thickness increases.

5. Failure behaviour

Following the tests of deformation behaviour, the elbows were tested to destruction on the pipe test rig under constant internal pressure (at room temperature and using water as the pressurizing medium) by the application of cyclic in-plane bending loads. Failure of the thin-walled elbows (nos. 1 to 3 of the test matrix) was - as shown by the deformation behaviour in Fig 10 - mainly due to a longitudinal crack starting at the inside wall in the area of the flank of the elbow mid-section (Fig 11). In constrast, the thicker-walled elbow (no. 4) failed due to a circumferential crack at the intrados of the elbow mid-section whose starting point was the outside wall (Fig 12). In all cases investigated, failure of the component took the form of a leak.

6. Conclusion

On the basis of the tests performed, the following conclusions can be drawn:

- in the regions of elbows, in addition to prismatic bending, cross-sectional deformation (ovalization) occurs whose degree is a function of elbow geometry
- this ovalization is propagated in connecting straight pipe runs to a length which is also a function of the geometry
- as the wall thickness of the elbow increases, the orientation of the stress maximum changes from the circumferential direction (at the elbow flank) to the circumferential direction (at the intrados)
- the ASME equations for "Detailed Analysis of Elbows" indicate the trend of stress at the elbow mid-section, but the values calculated are not always on the conservative side. More exact results are civen by a modified FE calculation which also allows the loading on the inside wall to be inferred
- for cyclic bending load, thinner-walled elbows fail due to longitudinal crack formation starting at the inside wall in the region of the elbow flank. In contrast, thicker-walled elbows may lose their integrity by a circumferential crack, initiating at the outside wall of the intrados
- in all cases investigated, the elbow's loss of integrity took the form of a leak.

7. Future prospects

To conclude, it remains to point out the part played by stress corrosion cracking as caused by static or corrosion fatigue by cyclic loading in exacerbating the danger to components where there is an unfavourable combination of part material and transported medium. This applies in particular to thin-walled elbows which might have high stress concentrations on the inside wall. It is intended to continue investigations in this direction.

References

/1/ KUSSMAUL, K., BLIND, D., JANSKY, J., "Safety Analysis of Circumferential Cracked Feed Water Piping of Light Water Reactors",
SMIRT 7-Post Conference Seminar No. 6, Monterey, California, August 29.-30., 1983

/2/ JANSKY, J., DIEM, H., MUELLER, K.U., "Betriebsbegleitende Messungen an druckführenden Bauteilen",
Proceedings of the 10th Session of DVM Working Group "Betriebsfestigkeit", Munich, Germany, February 1984

/3/ DIEM, H., MUELLER, K.U., "Einsatz von Dehnungsmeßstreifen zur Verfolgung des Versagensablaufes von zyklisch beanspruchten Bauteilen",
VDI-Berichte Nr. 514, 177-185 (1984)

/4/ MUELLER, K.U., DIEM, H., HUNGER, H., "Investigations on Stressing and Failure of Pipe Bends under Complex Loading",
Nucl. Eng. Design, to be published in 1985

/5/ BEISSWAENGER, F., DIEM, H., MUELLER, K.U., JANSKY, J., "Fachbericht Rohrbogenbeanspruchung"
KfK-PHDR-Report 56/84, Karlsruhe, Germany, 1984

/6/ ASME Boiler and Pressure Vessel Code, "Detailed Analysis of Elbows",
Section III, Subsection NB 3685, 1980

/7/ NAEHRIG, TH., HOFMANN, H., "Pipe bends - Analysis of their elastic behaviour",
NUCLEX, Basel, Paper H 10, October 1981

/8/ NAEHRIG, TH., GASCHEN, J.P., "Ermittlung der Spannungsverteilung im Scheitel eines 90°-Rohrkrümmers des Rohrprüfstandes",
KfK-PHDR-Report-2.212/83, Karlsruhe, Germany, 1983

/9/ OHTSUBO, H., WATANABE, O.; "Flexibility and Stress Factors of Pipe Bends - An Analysis by the Finite Ring Method",
Journal of Press. Vess. Techn., 1977, pp 281-290

/10/ MILLARD, A., ROCHE, R.L., "Propagation of Ovalization Along Straight Pipes and Elbows",
SMIRT 6, Paper M 10/1, Paris 1981

/11/ THOMSON, G., SPENCE, J., "Maximum Stresses and Flexibility Factors of Smooth Pipe Bends with Tangent Pipe Terminations under In-plane Bending",
Journal of Press. Vess. Techn., 1983, pp 329-336

Table I Test Matrix

ELBOW	ARC LENGTH	D_0 1) [mm]	t [mm]	D_0/D_i	λ	MATERIAL	MANUFACTURE	TEST STAND	LOADING (RT) BENDING	LOADING (RT) INTERNAL PRESSURE 2) [bar]	RESULTS
1	90°	88,9	5,6	1,14	0,37	AUSTENITIC	SEMI MONOCOQUES, LONG. WELDED	PIPE TEST RIG	IN-PLANE (CONST. + CYCLIC)	100	DEFORMATION FAILURE
2	90°	88,9	5,6	1,14	0,37	AUSTENITIC	SEAMLESS BENDED	-"-	-"-	100	-"-
3	90°	88,9	5,6	1,14	0,37	FERRITIC	-"-	-"-	-"-	100	-"-
4	90°	118,0	16,0	1,37	0,94	AUSTENITIC	-"-	-"-	-"-	160	-"-
5	90°	281,0	20,0	1,14	0,45	FERRITIC	-"-	-"-	-"-	100	DEFORMATION
6	90°	140,0	4,0	1,08	0,14	FERRITIC	-"-	LABORATORY TEST	LATERAL FORCE BENDING	0	-"-
7	180°	33,7	3,6	1,27	1,43	FERRITIC	SEAMLESS COLD BENDED	-"-	-"-	0	-"-

1) NOMENCLATURE ACCORDING ASME - NB3685
2) WATER, RT

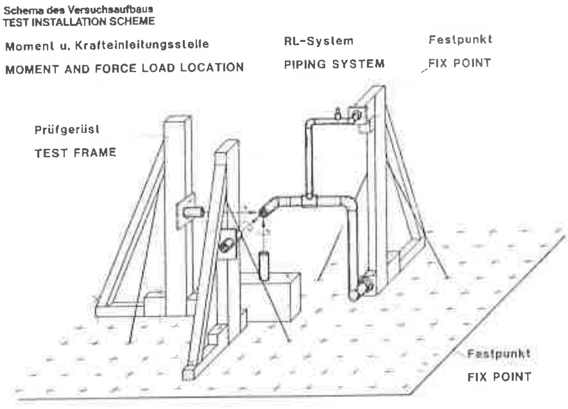

Fig. 1 Scheme of MPA pipe test installation

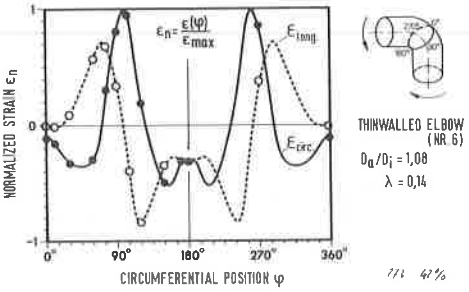

Fig. 2 Results of strain measurements (elbow 6, outside)

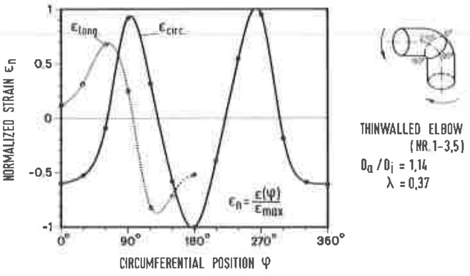

Fig. 3 Results of strain measurements (elbows 1-3 and 5, outside)

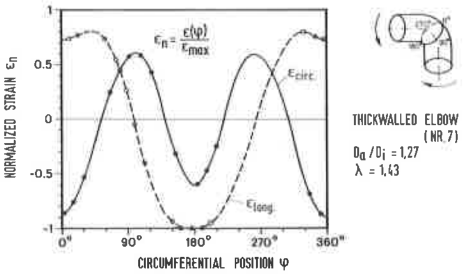

Fig. 4 Results of strain measurements (elbow 7, outside)

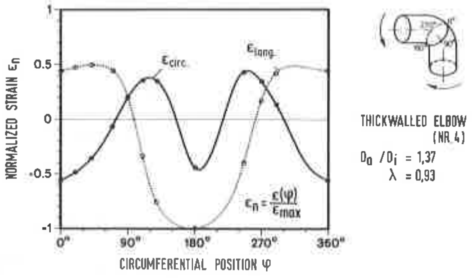

Fig. 5 Results of strain measurements (elbow 4, outside)

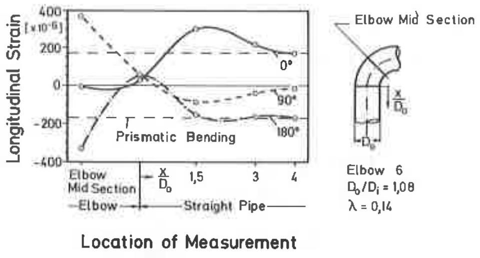

Fig. 6 Evaluation of the influence length of elbow ovalization by outside strain measurements (elbow 6)

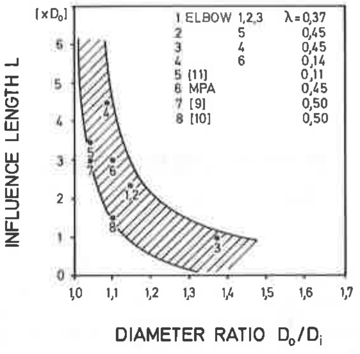

Fig. 7 Relation between elbow geometry and influence length of elbow ovalization

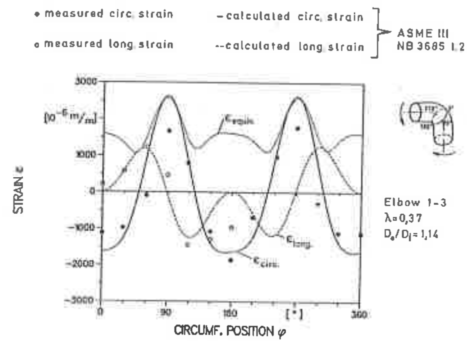

Fig. 8 Comparison of measurement and analysis according ASME (thinwalled elbow)

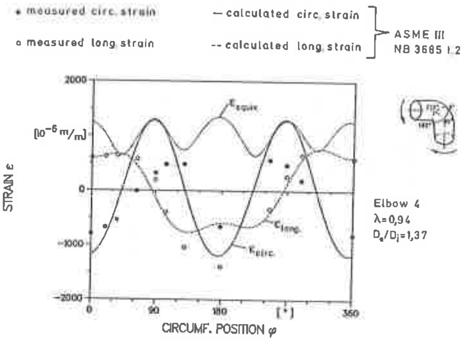

Fig. 9 Comparison of measurement and analysis according ASME (thickwalled elbow)

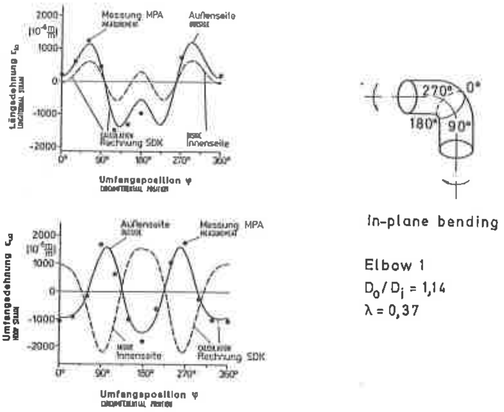

Fig. 10 Comparison of measurement and modified FE-analysis

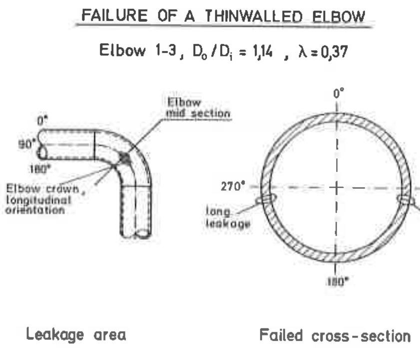

Fig. 11 Failure of a thinwalled elbow under cyclic in-plane bending

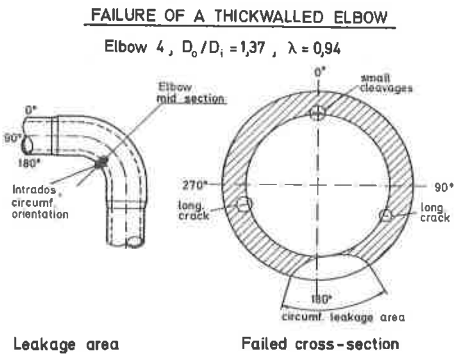

Fig. 12 Failure of a thickwalled elbow under cyclic in-plane bending