Pipe bend behaviour at load levels beyond design

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ABSTRACT: The objective of the studies performed was the determination of the quasistatic deformation behavior of elbows and curved pipes in the range of nonlinear material behavior and the delineation of local and global failure behavior as a function of load history. The paper concentrates on experimental and numerical results of three 90° pipe bends made of ductile ferritic material. The components with a nominal bore of 400 mm were subjected to in-plane bending and out-of-plane loading without internal pressure. Regarding the failure behavior pipe bends loaded in in-plane closing mode are of most interest concerning safety considerations. Only for this load case a collapse load exists. In displacement controlled loading the functional capability of the pipe bends was given even at load levels with high plastic strains (up to 5·10⁻² m/m).

NOTATION

B₁, B₂ stress indices for primary stresses
C₂ stress index for primary plus secondary stresses
D₀ mean outer diameter
D₁ mean inner diameter
F loading force
I moment of inertia
k flexibility factor = FLX
L₅ length of straight pipe subjected mainly to bending load
L₇ length of straight pipe subjected mainly to torsional load
M₉P in-plane bending moment (CM = closing mode, OM = opening mode)
M₀P out-of-plane bending moment
M₉ torsional moment
M₉ resulting cross-sectional moment = \(\sqrt{M_{9P}^2 + M_{9P}^2 + M_9^2}\)
Pᵢ internal pressure
rₘ mean cross-section radius = \((D₀ + D₁) / 4 = Dₙ / 2\)
R bend radius of curvature
Sₘ allowable stress value
t mean wall thickness
U₀ degree of ovality
u diameter ratio = \(D₀ / D₁\)
uₜ vertical deflection
Z section modulus of pipe
θ bend angle
λ bend factor
1 INTRODUCTION

In the field of industrial plant engineering the quality of piping is of great interest with respect to safety and plant availability. The pressure retaining components used in piping systems must be capable of restraining all loads imposed on them throughout their design service life without loss of integrity. In piping systems these loads include membrane primary stresses caused by internal pressure as well as local primary stresses resulting e.g. from loads imposed by supports or hangers and the secondary stresses induced by restricted thermal expansion which occur under operational, emergency and faulted conditions.

By the use of ductile base materials and weldments in accordance to the requirements of Authorities of the Federal Republic of Germany [1,2,3] piping has a high capacity for plastic deformation which guarantees an inherent safety reserve. However, energy dissipation by plasticization of material - a factor which has a pronounced effect on system behavior under transient loading - does not damp the system to any considerable degree unless large parts of the material volume participate in the plasticization.

Curved pipes and welding elbows are important component parts within the piping systems of power stations. Because of their lower stiffness in comparison with the attached straight pipes, they are capable of dissipating reaction forces and moments within a system by undergoing deformation. This is especially true for piping systems which are operated at higher temperatures. Resulting bending moments lead to cross-sectional deformations which can result in localized concentrations of stress and strain at certain places within the shell of the bend. The dimensions of curved pipes and welding elbows are governed by the layout of the piping and by the technical requirements of the corresponding system. Design is carried out according to the guidelines established by the design codes which, in general, are based on the internal pressure, and with limitation of the maximum stress according to the appropriate safety requirements.

There is no difference in the principle deformation behavior of curved pipes and welding elbows under bending loading. With regard to localized behavior, however, fabrication related variations in wall thickness, ovality and material properties can affect the stress/strain behavior. In the following, the expression pipe bend will be used as a generic term for both curved pipes and welding elbows in statements which refer to both.

In recent years several component tests on thin- and thick-walled pipe bends made of ferritic and austenitic piping material were carried out at MPA Stuttgart within various research programs [4]. The present paper concentrates on experimental and numerical results of three pipe bends made of ductile ferritic material. These pipe bends with a nominal bore of 400 mm were subjected to large elastic-plastic deformations resulting from bending in in-plane closing mode, in-plane opening mode and out-of-plane loading. The objective of these investigations was to determine and to assess the deformation and failure behavior with respect to the current design rules for level D events. The experiments were accompanied by non-linear finite element calculations. It was the emphasis to validate state-of-the-art finite element computer simulations of complex components under complex loading by comparing measured and calculated results.

2 DEFORMATION BEHAVIOUR OF PIPE BENDS

For the determination of stresses and strains, straight sections of piping can be treated as prismatic bodies. In the region of pipe bends, however, the Bernoulli-Euler hypothesis that the cross-sections remain planar is no longer fulfilled under bending loading.
Shell effects become dominant here, whereby the degree of resulting cross-sectional
deformation depends upon the geometry of the pipe bend. I.e., the more thin-walled a
bend is, the more evident shell behavior becomes. With increasing wall thicknesses, the
deformation behavior approaches that of a prismatic body.

Further factors of influence are the bend angle $\Theta$, the radius of curvature $R$ as well as
diverse stiffening effects from components connected to the bend, such as straight
pipes, nozzles and flanges.

Apart from geometrical parameters, the deformation behavior and the stress/strain
characteristics of pipe bends are influenced by the type of loading. The basic loading
modes are internal pressure $p_i$, opening or closing of the bend by in-plane bending, $M_{IP}$,
bending perpendicular to the plane of the bend, $M_{OR}$ and torsional loading, $M_T$.

2.1 Classification of pipe bends

The terms chosen for certain regions of the bend shell in order to permit clear description
of pipe bends are shown in Fig. 1, together with the angular definitions.

![Fig. 1: Definition of terms and angles for pipe bends](image)

![Fig. 2: Limit load determination procedure](image)

In general, a pipe bend is characterized by its pipe bend factor $\lambda$

$$\lambda = \frac{R \cdot t}{r_m^2} = \frac{2 \cdot R}{D_m} \cdot \frac{t}{r_m} = 4 \cdot \frac{R}{D_m} \cdot \frac{u-1}{u+1}$$

and by its flexibility factor $k$.

The flexibility of pipe bends is depending on internal pressure, end effects and the
size of the bend angle $\Theta$. In the ASME BPVC Section III, Code Case N 319 [5] equa-
tions are defined which allow the influence of internal pressure, the bend angle and the
type of loading to be taken into account. The equations to calculate $k$ for pipe bends
with bend angles $\Theta = 90^o$ subjected to bending without internal pressure are as follows:

$$FLX_{IP} = k = \frac{1.3}{\lambda}$$

$$FLX_{OP} = k = \frac{1.25}{\lambda}$$
Prediction of typical deformation behavior can be made on the basis of the characteristic values $\lambda$ and $k$ together with additional information about the wall thickness of the bend concerned, provided by the diameter ratio $u$. A limiting value of $u = 1.25$ for the transition from thin-walled to thick-walled behavior can be ascertained from our investigations [4].

The maximum stress arising in a pipe bend due to moment loading can be calculated by the simple equation

$$\sigma_{max} = C_2 \frac{M_i}{I}$$

The stress index $C_2$ is a function of the characteristic pipe bend factor $\lambda$.

$$C_2 = 1.95 \cdot \lambda^{-2/3}$$

In the linearelastic regime good or at least conservative results will be obtained for a wide range of $u$ and $\lambda$ values and for various bend angles [4].

3 DESIGN RULES FOR LEVEL D EVENTS

According to the German KTA-Rules [3] the limit primary stresses due to internal pressure and bending load for level D events are expressed in the form

$$\sigma_I = B_1 \frac{p_i \cdot D_o}{2 \cdot t} + B_2 \frac{M_i \cdot D_o}{2 \cdot I} \leq 3S_m$$

$B_1$ and $B_2$ are stress indices for pressure and moment load respectively.

$$B_1 = 0.5$$

$$B_2 = 1.3 \cdot \lambda^{-2/3}$$

The definition of the stress index $B_2$ relies on a requirement of the ASME [5] that the limit moment of a pipe bend should not exceed a value of 1.5 times the moment which causes first local yielding. Thus $B_2 = (2/3) C_2$.

In absence of internal pressure the theoretical limit moment $M_{i, \text{max}}$ is given by the equation

$$M_{i, \text{max}} \leq \frac{2I \cdot 3S_m}{B_2 \cdot D_o} = \frac{Z \cdot 3S_m}{1.3 \cdot \lambda^{-2/3}}$$

If adequate experimental data are available an alternative procedure for the determination of limit load can be applied. Following the procedure described in the ASME BVPC, Section III, Appendix II-1430 [5] a relation between the loading and a representative distortion respectively the maximum principal strain of the component is required. This so-called collapse load corresponds to the minimum load value which is given by the intersection of the load versus displacement plot or the load versus strain plot and the collapse limit line as defined in Fig. 2.
4 EXPERIMENTAL AND NUMERICAL INVESTIGATIONS

Within the scope of the research project "Inelastic Analysis of Pipe Bends" [6] the main emphasis was put on the determination of the deformation behavior of 90° pipe bends within the range of non-linear material characteristics. It was a main objective to describe the load bearing behavior and the formation of plasticized zones as well as to find an answer to the question whether there exists an experimental collapse load within an certain strain range.

ABAQUS [7] and SAN [8] finite element programs were used for numerical simulation of pipe bend behavior. Additional to the three-dimensional models built up by shell (SAN) and solid elements (ABAQUS) calculations were made with special pipe and pipe bend elements (ABAQUS) which are very economical and can be used like one-dimensional member elements.

Initially, the program included the determination of the material properties and the as-manufactured geometries of the pipe bends under investigation. Isotropic behavior was found in the pipe bend material 15 MnNi 6 3. Residual stresses were at a low level. The material properties are comprised in Table 1.

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Type of pipe</th>
<th>( R_{p,2RT} ) [MPa]</th>
<th>( R_{m,RT} ) [MPa]</th>
<th>( C_{V,RT} ) [J]</th>
<th>( C_{V,upper shelf} ) [J]</th>
<th>Young's modulus [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKA 1</td>
<td>curved pipe¹</td>
<td>397</td>
<td>541</td>
<td>&gt; 180</td>
<td>&gt; 185</td>
<td>212 000</td>
</tr>
<tr>
<td>IKA 2</td>
<td>elbow</td>
<td>387</td>
<td>520</td>
<td>&gt; 210</td>
<td>&gt; 230</td>
<td>208 000</td>
</tr>
<tr>
<td>IKA 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. The samples were taken from a straight pipe section adjacent to the inductive manufactured pipe bend

With regard to wall thickness and outer diameter distributions, the curved pipe showed a strong but symmetrical variation across the circumference, whereas both elbows exhibited asymmetries concerning the bend symmetry planes. However, these asymmetries and the differences between mean values and as manufactured data were within permissible tolerances, Table 2.

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>( D_o ) [mm]</th>
<th>( t ) [mm]</th>
<th>( R ) [mm]</th>
<th>( \lambda )</th>
<th>( u )</th>
<th>( U_o ) [%]</th>
<th>( L_R ) [mm]</th>
<th>( L_T ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKA 1</td>
<td>472.1</td>
<td>41.7</td>
<td>950</td>
<td>0.86</td>
<td>1.22</td>
<td>2.07</td>
<td>2900</td>
<td>-</td>
</tr>
<tr>
<td>IKA 2</td>
<td>489.0</td>
<td>30.5</td>
<td>900</td>
<td>0.52</td>
<td>1.14</td>
<td>0.88</td>
<td>5100</td>
<td>-</td>
</tr>
<tr>
<td>IKA 3</td>
<td>489.2</td>
<td>30.6</td>
<td>900</td>
<td>0.52</td>
<td>1.14</td>
<td>0.84</td>
<td>5050</td>
<td>1275</td>
</tr>
</tbody>
</table>

4.1 Experimental results

Technical reasons prevented the realization of a pure bending moment to stress the pipe bends. Moment loading in the bend areas was realized by transverse forces at the end of long adjacent pipe sections to the pipe bends.

In the IKA 1 test the in-plane opening load was imposed by a 15 MN horizontal tensile testing device, Fig. 3, which exerted a member force combination of normal and lateral force on the pipe, together with a bending moment. However, the long pipe leg
(lever) meant that the bending moment imposed the dominant stress in the pipe bend. In the IKA2 test the pipe bend with adjacent straight pipes at both ends was loaded with an in-plane bending moment in closing mode. The testing device was set up horizontally and the load was imposed between the end of two straight pipe sections by means of a displacement-controlled hydraulic cylinder, Fig. 4. Because of the internal force balance it was not necessary to fix the test rig with a special device.
In the IKA3 test the pipe bend was loaded with a combined out-of-plane and a torsional moment. The testing device was set up horizontally, Fig. 5. A hydraulic cylinder was imposed vertically at the long end of the two adjacent straight pipe sections of different length. A special fixpoint device had to balance the member forces resulting from the applied transverse force at the load introduction point. The bending moment loading of the long pipe section changes in the bend area into a torsional moment loading which is constant along the short pipe section.

In all load cases the elbow mid-sections were dominantly stressed by moment loading. The relations between the measured forces at the load introduction points and the bending moments in the pipe bend mid cross-sections are given below:

**in-plane bending:**

\[ F = \frac{M_{IP}}{\frac{1}{2} \cdot (L_B - R) + R} \]

**out-of-plane loading:**

\[ F = \frac{M_i}{\sqrt{2R^2 + L_B^2 - 2R^2 \sin \alpha + 2R \cdot L_B \cos \alpha}} \]

Characteristic load deflection curves of the three experiments as well as the remnant cross-sectional deformation at the end of the tests are depicted in Figs. 7-12.

During test IKA 1 the pipe bend behavior was completely linear-elastic up to a load of \( F = 0.52 \text{ MN} \), Fig. 7. Thereafter, initial plasticization first appeared at the wall inner fibres of the bend flanks. At the load \( F = 1.03 \text{ MN} \), the pipe bend was plasticized over practically its entire length. At the end of the test at \( F = 2.2 \text{ MN} \) and local strain values of up to \( 60 \cdot 10^{-2} \text{ m/m} \) the pipe bend had not collapsed. On account of the strain hardening effects of the material and a steady state increase in the bending section modulus, Fig. 8, the pipe bend retained a load bearing capacity reserve even beyond the fully pla-
stic state. An overall linear behaviour between applied force and resulting deflections beyond the point of the first local yielding could be seen in the global behaviour. This means that the global pipe bend behaviour can be calculated with a constant flexibility factor up to 1.8 times the load point of the first local yielding, Fig. 13.

![Fig. 9: Load deflection curve for in-plane closing mode experiment IKA 2](image1)

![Fig. 10: Remnant cross-sectional deformation at the end of experiment IKA 2](image2)

![Fig. 11: Load deflection curve for out-of-plane loading experiment IKA 3](image3)

![Fig. 12: Remnant cross-sectional deformation at the end of experiment IKA 3](image4)

The experimentally determined flexibility factor $FLX_E$ for in-plane bending is defined as the quotient of the real (measured) component flexibility $f = \Delta\Theta/M_{IP}$ and the theoretical flexibility of a straight pipe according to the elementary theory of bending (ETB) $f_{ETB} = (R\Theta)/(EI)$

$$FLX_E = \frac{\Delta\Theta}{M_{IP}} \cdot \frac{E \cdot I}{R \cdot \Theta}$$
Fig. 13 shows a comparison between the experimentally determined and the analytically calculated flexibility factor. The analytically determined factor on basis of the ASME equation mentioned in chapter 2.1 is about 30% lower than the experimentally determined value.

During test IKA2 the pipe bend was loaded travel-controlled above the point of the maximum sustainable load (collapse load) up to local strain values of 50-10^{-3} \text{ m/m}. This collapse load was reached at \textit{F} = 372 \text{ kN}, Fig. 9. The ratio of collapse load and load at local initial yielding was 1.9. The first yielding was initiated in the area of the elbow flanks at the inner surface. In spite of the present wall thickness variation around the circumference the pipe bend showed to a great extent a symmetrical deformation behavior. An overall linear behavior between applied force and resulting deflections beyond the point of the first local yielding could be seen in the global behavior. This means that the global pipe bend behavior can be calculated with a constant flexibility factor up to 1.6 times the load point of the first local yielding, Fig. 14. The comparison between the experimentally determined and the analytically calculated flexibility factor is quite good. Both values differ only by 7.5%.

For in-plane bending the overall linear pipe bend behavior is valid up to the primary stress limitation load level \textit{F}_{3Sm}.

The complexity of stress and deformation behavior of an out-of-plane loaded pipe bend could be seen in the measured data of experiment IKA 3, Fig. 11. The failure behavior was characterized by both ovalization of the pipe bend and torsional stressing of the fixed adjacent straight pipe section to the pipe bend. At the beginning of the loading maximum stresses were concentrated in the pipe bend region. Upon reaching the shear flow stress of the torsionally loaded straight pipe, further stressing of the pipe bend was reduced and the externally applied load caused mainly plasticization in the torsionally loaded pipe. On reaching the strain hardening of the pipe material in the torsionally loaded pipe at strain values beyond 20-10^{-3} \text{ m/m} the stressing increased again in the pipe bend. The test was completed at a maximum deflection of 2.4 m at the load introduction point and corresponding local strain values of 35-10^{-3} \text{ m/m}. On account of the strain hardening effects of the material and an increase in the bending section modulus, Fig. 12, the pipe bend retained a load bearing capacity reserve even beyond the fully plastic state. An overall linear behavior between applied force and resulting deflections beyond the point of the first local yielding could be seen in the global behavior. This means that the global pipe bend behavior can be calculated with a constant flexibility factor up to 1.5 times the load point of the first local yielding, Fig 15.

The experimentally determined flexibility factor \textit{FLX}_E for out-of-plane loading is defined as the quotient of the relative vertical distortion \Delta u_{z,pipebend} between the beginning (\alpha = 0^\circ) and the end (\alpha = 90^\circ) of a pipe bend and the relative vertical distortion \Delta u_{z,pipe} of a curved straight pipe section without undergoing ovalization and warping. The value \Delta u_{z,pipe} was determined numerically by a finite element calculation using PIPE elements from ABAQUS computer code.

\[
FLX_E = \frac{u_z(\alpha = 90^\circ)_{pipebend} - u_z(\alpha = 0^\circ)_{pipebend}}{u_z(\alpha = 90^\circ)_{pipe} - u_z(\alpha = 0^\circ)_{pipe}}
\]

Fig. 15 shows a comparison between the experimentally determined and the analytically calculated flexibility factor. The analytically calculated factor on basis of the ASME BPVC, Code Case N 319 equation for out-of-plane loading is about 30% higher than the experimentally determined value.
Fig. 13: Flexibility Factor as function of load history (experiment IKA 1, in-plane bending opening mode)

Fig. 14: Flexibility Factor as function of load history (experiment IKA 2, in-plane bending closing mode)

Fig. 15: Flexibility Factor as function of load history (experiment IKA 3, out-of-plane loading)
With regard to failure behavior only the pipe bend which was subjected to in-plane bending in closing mode exhibited a maximum sustainable load, beyond of this the pipe bend would have shown uncontrolled deformation under load control. For in-plane bending in opening mode and out-of-plane loading no maximum sustainable load could be reached up to local strain values in the pipe bend region of $80 \times 10^{-3}$ m/m (IKA 1) and $35 \times 10^{-3}$ m/m (IKA 3). Concerning the limit load determination the following results came up. For in-plane loading the experimentally determined limit load is higher than the corresponding limitation of primary stresses $M_{3Sm}$, resp. $F_{3Sm}$. In case of in-plane bending in closing mode the experimentally determined limit load on basis of the ASME BVPC, Section III, Appendix II-1430 procedure is equal to the maximum sustainable load of the pipe bend. This means there is no margin against collapse. For out-of-plane loading the limitation of primary stresses $M_{3Sm}$, resp. $F_{3Sm}$ is higher than the experimentally determined limit load. Here it has to be considered, that the global deformation behavior of the assembly pipe bend/pipe is mainly influenced by the sudden overall yielding of the torsionally loaded pipe without any stress redistribution after reaching the shear yield strength.

4.2 Numerical results

The comparison between measured and calculated data concerning the in-plane opening mode experiment IKA 1 brought about considerable differences in the global and local behavior. The onset of the non-linear behavior in the computed results was at higher load values when compared to the experimental behavior. In qualitative terms there was an acceptable coincidence between measured and calculated data although the load values differed up to 15 %. The reason for this systematic difference is due to the used stress-strain relation in the FEM calculation. The stress-strain curve was received from a sample, which was taken from a straight pipe section adjacent to the inductive manufactured pipe bend IKA 1. From literature it is known, that the material 15 MnNi 6 3 might reveal a decrease in yield strength due to the inductive bending process. A recalculation with a simple model built up by ELBOW31 elements from ABAQUS program and a modified stress-strain curve corresponded well with the measured data.

All finite element calculations concerning the load case in-plane bending in closing mode (IKA 2) showed the collapse behavior of the pipe bend. The study carried out using shell elements from the SAN computer code provided a maximum load of 390 kN. The calculation using a three-dimensional model built up by 20-node solid elements from ABAQUS computer code resulted in a maximum load of 374 kN. The calculation of the bend behavior with PIPE31- and ELBOW31-elements available in ABAQUS computer code provided as maximum load 387 kN. The first plastification was indicated on the elbow inner surface in the area of the elbow flanks by all calculations. The measured data of the global behavior of the test component corresponded well with the data from all calculations. In the case of calculations using shell elements (SAN) and three-dimensional solid elements (ABAQUS) the comparison of the local behavior agreed well with the experimental values. The calculation of local strain values using the simplified ELBOW31 elements (ABAQUS) provided satisfactory results taking into consideration the simple model set-up and the short computing time.

The results computed for out-of-plane loading (IKA 3) showed a stress concentration in the pipe bend section mainly loaded by bending at the beginning of the loading. After exceeding the shear yield stress in the pipe section loaded by torsion, the global component behavior was mainly controlled by deformation of the torsionally loaded pipe sec-
tion. The three-dimensional computations were terminated at a maximum vertical deflection of the load introduction point of 600 mm, when considerable strain increments could not be found anymore in the pipe bend area.

The comparison between measured and calculated data brought about considerable differences in the global behavior of the test components. These differences are due to an undesired and unknown gap in the fixpoint construction during the performance of the test. The measured and calculated cross-section deformations and local strains are coincident within the range of linear material behavior. The onset of the non-linear behavior in the computed results was at higher load values when compared to the experimental component behavior. In qualitative terms there is an acceptable coincidence between measured and calculated data although the load values differ up to 15 - 20 %. The reason for this systematic difference is the unknown stress-strain characteristic of the pipe section loaded by torsion. In qualitative terms the results of the calculation using a simple model built up by ELBOW31 elements from ABAQUS computer code, which was performed up to a maximum deflection of the load introduction point of 2.4 m, correspond well with the measured data.

5 CONCLUSIONS

In general terms, pipe bends subjected to in-plane bending moment in opening mode or to out-of-plane loading displayed considerable reserves of load bearing capacities, without any visible sign of damage and plastic collapse far beyond the design limit. Only bends which are subjected to in-plane bending in closing mode exhibit a maximum sustainable load, beyond of this the bend would reveal uncontrolled deformation under load control. Under displacement controlled loading the functional capability, e.g. the flow cross-section, is given even above the point of the maximum sustainable load (collapse load). From the investigations it became clear that the pipe bends became plasticized over a large area without any over proportional increase in overall deformation even at load levels beyond the design limits.

An overall linear behavior between applied force and resulting deflections up to at least 1.5 times the point of the first local yielding could be seen in the global behavior.

In the elastic regime finite element simulations of the pipe bend behavior showed excellent agreement with measured data. With exception of the load case in-plane bending in closing mode the non-linear behavior was only sufficiently described. Reasons of discrepancies were due to unknown differences in the material properties of different parts of the pipe/pipe bend assembly, which were not considered in the calculations.

6 REFERENCES


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