

## Experimental Study of Carbon Steel Straight Pipes and Elbows Under Moment Loadings

J.P. Prost

*FRAMATOME, Tour Fiat,  
F-92084 Paris la Défense Cedex 16, France*

C. Amzallag

*Creusot-Loire, Centre de Recherche d'Unieux,  
F-42240 Unieux, France*

The subject of this study is the plastic behaviour (until plastic instability) of piping components under moment loadings. The elbows are of particular importance because they are the most flexible parts of a piping system. Under Design Conditions precautions must be taken to avoid exceeding the range of predominantly elastic response because the resistance to deformation will decrease rapidly with increasing load and may result in failure of the component. Under Faulted Conditions the ovalization of the cross section must be limited to ensure functional capability. The study of straight pipes behaviour is useful in drawing comparisons with elbows.

In order to avoid undesirable plastic response for PWR steam pipe components, tests are performed on carbon steel straight pipes and elbows. These components are subjected to moment loadings for different pressure levels.

The plastic collapse moment considered as a limit for excessive deformation is determined from the load-deflection curve according to ASME III Code-Appendix II [1]. This moment is compared with the maximum moment allowed under Design Conditions (ASME III Code NB-3600)

The plastic instability moment considered as a limit for functional capability is compared with the maximum moment allowed for level C and level D Service Limits.

The principal conclusions are the following :

- For straight pipes, internal pressure of torque sometimes increases, sometimes decreases plastic collapse moment and plastic instability moment.
- For elbows, in-plane bending moments, closing and opening, are the more and less severe loadings respectively. Internal pressure or a decrease of arc angle of elbow increases plastic collapse moment and plastic instability moment.
- ASME rules are more strict for elbows than for straight pipes (for the geometry and material considered).
- For elbows, Design conditions limits ensure a fully elastic behaviour and thus, a high safety margin with regard to plastic collapse moment.
- Level C Service Limits insure also a practically elastic behaviour of elbows and, thus, functional capability. This is also true with level D service limits for elbows with internal pressure.

## 1. Introduction

The subject of this study is the plastic behaviour (until plastic instability) of piping components under moment loadings. The elbows are of particular importance because they are the most flexible parts of a piping system. Under Design Conditions precautions must be taken to avoid exceeding the range of predominantly elastic response because the resistance to deformation will decrease rapidly with increasing load and may result in failure of the component. Under Faulted Conditions the ovalization of the cross section must be limited to ensure functional capability. The study of straight pipe behaviour is useful in drawing comparisons with elbows.

In order to avoid undesirable plastic response for PWR steam pipe components, tests are performed on carbon steel straight pipes and elbows. These components are subjected to moment loadings for different pressure levels.

The plastic collapse moment considered as a limit for excessive deformation is determined from the load-deflection curve according to ASME III Code-Appendix II [1]. This moment is compared with the maximum moment allowed under Design Conditions (ASME III Code NB-3600)

The plastic instability moment considered as a limit for functional capability is compared with the maximum moment allowed for level C and level D Service Limits.

## 2. Description of components

### 2.1. Geometry

The components are PWR steam pipe components at a scale of 1/10. The straight pipes have an outside diameter of 81.45 mm. Wall thickness is 3.15 mm.

The elbows have an outside diameter of 81.9 mm and a bend radius of 120 mm. The wall thickness is 3.4 mm. Arc angles of elbows are 30°, 45°, 60° and 90°.

### 2.2. Material properties

The components are made of SA 216 grade WCC carbon steel. The material properties at room temperature are the following :

COMPONENTS	0.2 % offset yield stress Sy (MPa)	Tensile strength Su (MPa)
Straight pipes 1-4-7-8-11	410	556
Straight pipes 2-3-5-6-9-10-12-13	355	568
Elbows	400	503

These properties are obtained from tensile specimens taken from non-tested components. These tensile specimens have a 25 mm-long gage section and a cross-section area of 11 mm<sup>2</sup>.

## 3. Description of tests

Straight pipes are directly welded to a flange and elbows to pipe extensions of the same thickness. The shorter extension is welded to a flange (Figure 1).

The moments are produced by an external force statically applied to the free end of straight pipes or extensions. Straight pipes are subjected to several combinations of bending moment and torque. The torque is applied with a lever arm perpendicular to the

pipe (Figure 1). Elbows are subjected to in-plane (opening and closing) and out-of-plane bending moments. Moment arms are sufficiently long to produce essentially moment loads on the components (the shear forces are small in comparison with moments). The distance from the flange to the elbow is relatively long (about 2.5 pipe diameters), which makes the effect of the presence of the flange negligible.

The components are kept at a constant pressure throughout the test period.

The force and the deflection at the point of application are measured. For elbows, the ovalization of three cross-sections is also measured (the middle cross-section and the two end cross-sections).

All tests are performed at room temperature.

#### 4. Experimental results and interpretation

The plastic collapse moment considered as a limit for excessive deformation is determined from the load-deflection curve in accordance with ASME III Code-Appendix II 1430 [1] : the moment at which the measured deflection is twice the extrapolated elastic deflection. This moment is compared with the maximum moment allowed under Design Conditions. This moment is obtained from the following equation (ASME III Code-NB 3652) :

$$B_1 \frac{PDo}{2t} + B_2 \frac{DoMi}{2I} = 1.5 S_m \quad (1)$$

where  $B_1, B_2$  = primary stress indices

$P$  = internal pressure

$Do$  = outside diameter

$t$  = wall thickness

$I$  = moment of inertia

$Mi$  = resultant moment

$S_m$  = allowable design stress intensity value

For straight pipes :  $B_1 = 0.5$  and  $B_2 = 1.0$

For elbows, ASME III Code-NB 3681.1 gives  $B_1 = 0.5$  and  $B_2 = 0.75 C_2$  with  $C_2 = 1.95/h^{2/3}$

where  $h = tR/r^2$

$R$  = bend radius of elbow

$r$  = mean pipe radius

In this study we take :

$$B_1 = 0$$

because, for the tested elbows, pressure increases rather than decreases the plastic collapse moment (and the plastic instability moment) and :

$$B_2 = 0.67 C_2$$

as RODABAUGH and MOORE recommend in reference [2].  $C_2$  index takes into account the direction of loading and the arc angle of elbow as recommended in [3] by RODABAUGH and al. :

in the case of in-plane bending :

$$C_2 = 1.95/h^{2/3} \quad \text{for } \alpha \geq 90^\circ$$

$$C_2 = 1.75/h^{.56} \quad \text{for } \alpha = 45^\circ$$

$$C_2 = 1.0 \quad \text{for } \alpha = 0^\circ$$

where  $\alpha$  = arc angle of elbow

Linear interpolation with  $\alpha$  is to be used, but  $C_2$  shall not be less than interpolated value for  $\alpha = 30^\circ$

In the case of out-of-plane bending :

$$C_2 = 1.71 h^{.53}$$

We take  $S_m = (2/3) S_y$  (rather than  $(1/3)S_u$ ) because  $S_y$  seems a better reference for determining plastic collapse moment or plastic instability moment. This choice leads to a greater value of  $S_m$  and, thus, to a conservative interpretation of results.

The plastic instability moment is, by definition, the maximum moment on the load-deflection curve. We use it as an easily definable limit of functional capability for elbows. We compare it to the moment obtained in Equation (1) for level C and level D Service Limits (2.25  $S_m$  and 3  $S_m$  respectively in place of 1.5  $S_m$ ).

#### 4.1. Straight pipes

Tests of straight pipes under moment loadings are not priority-holders because, in a piping system, plastic behaviour generally occurs in elbows first. But they are useful in drawing comparisons with elbows.

Test data are summarized in Table 1.

$S_m$  differs for tests with pressure and tests without pressure. Therefore, a rigorous interpretation of these data is difficult. However, it may be observed that :

- Pressure sometimes increases and sometimes decreases plastic collapse moment or plastic instability moment. But in every case pressure sharply increases safety margins obtained from the application of ASME III Code rules with  $B_1 = 0.5$ .

- Similarly, torque sometimes increases and sometimes decreases plastic collapse moment or plastic instability moment.

As will be seen later, safety margins insured by ASME III Code rules are lower for straight pipes than for elbows.

#### 4.2. Elbows

As shown in Figure 2, in-plane bending moments, closing and opening, are the more and less severe loadings respectively. Under in-plane bending (closing), plastic instability occurs for a very small deflection. This deflection is greater under out-of-plane bending and even greater under in-plane bending (opening).

Figure 3 shows that a decrease of arc angle of elbow increases plastic collapse moment and plastic instability moment for elbows under in-plane bending (closing) without pressure. However, the load-deflection curves have the same aspect. The same remarks can be made concerning Figure 4 for elbows with pressure, although results for  $45^\circ$  and  $60^\circ$  elbows are similar. A comparison of Figures 4 and 5 shows that pressure increases plastic collapse moment and plastic instability moment. This is true for any type of bending.

When plastic instability occurs, the variations of small and large diameters in the middle cross-section of elbows under in-plane bending (opening) and out-of-plane bending are the following.

Test No	Bending	Small diameter (mm)	Large diameter (mm)
12	in-plane (opening)	64	94,5
13	"	71,9	90,7
14	"	74,8	88,8
15	out-of-plane	≥ 70	≤ 92
16	"	69,9	91,2
17	"	74,1	88,2

The variations of these diameters for elbows under in-plane bending(closing)are given in Figure 5. The greater ovalization occurs for test n° 12 : if we assume an elliptical cross-section the reduction of the middle cross section area is about 11 % at the time of instability (both end cross-sections remaining practically circular). This reduction is low and we can use plastic instability moment as an easily definable limit of functional capability.

Test data are summarized in Table 2 and interpreted in relation to ASME III Criteria. They are illustrated in Figures 6 and 7, which clearly show that the modifications of  $C_2$  index (and therefore  $B_2$ ) proposed in [ 3 ] enable ensuring uniformity of safety margin with regard to plastic collapse moment and plastic instability moment.

Under Design Conditions, Equation (1) ensures a high safety margin with regard to plastic collapse moment (  $\geq 2$  except for test n° 14) which leads to a fully elastic behaviour of elbows.

The use of static tests to appreciate functional capability of elbows for dynamic loadings under Faulted Conditions is generally insufficient because damping due to plastic behaviour of components can have a great effect. However, in our particular case, application of level C Service Limits results in a practically elastic behaviour for all tested elbows. Thus, it can be asserted that high safety margins with regard to plastic instability moment ensure functional capability. This is also true with level D Service Limits for elbows with internal pressure. For elbows without pressure, we cannot conclude and dynamic tests would be necessary. However, if  $S_m$  is expressed as  $(1/3) S_u$  instead of  $(2/3) S_y$ , safety margins are to be multiplied by 1.6 and level D Service Limits are amply satisfactory.

##### 5. Conclusions

Experimental data from tests of carbon steel straight pipes and elbows have been presented. They were interpreted in relation to ASME III Code Criteria. The principal conclusions are the following :

- for straight pipes, internal pressure or torque sometimes increases, sometimes decreases plastic collapse moment and plastic instability moment.
- for elbows, in-plane bending moments, closing and opening, are the more and less severe loadings respectively. Internal pressure or a decrease of arc angle of elbow increases plastic collapse moment and plastic instability moment.

- ASME rules are more strict for elbows than for straight pipes (for the geometry and material considered)
- for elbows, Design Conditions Limits ensure a fully elastic behaviour and, thus, a high safety margin with regard to plastic collapse moment
- level C Service Limits ensure also a practically elastic behaviour of elbows and, thus, functional capability. This is also true with level D Service Limits for elbows with internal pressure.

#### References

- [ 1 ] ASME Boiler and Pressure Vessel Code, Section III, Division I, "Nuclear Power Plant Components", ASME, New York, 1980.
- [ 2 ] RODABAUGH, E.C., MOORE, S.E., "Evaluation of the Plastic Characteristics of Piping Products in Relation to ASME Code Criteria", ORNL/Sub-2913/8, July 1978.
- [ 3 ] RODABAUGH, E.C., ISKANDER, S.K., MOORE, S.E., "End Effects on Elbows Subjected to Moment Loadings", ORNL/Sub-2913/7, March 1978.

Table 1 - Summary of data from tests of straight pipes

Test N <sub>o</sub>	β (1)	Pressure P (MPa)	Mc (2,7)	M <sub>I</sub> (3,7)	Mc Do	M <sub>I</sub> Do	M <sub>I</sub> Do
					2I × α <sub>1</sub> Sm (4)	2I × α <sub>2</sub> Sm (5)	2I × α <sub>3</sub> Sm (6)
1	0	0.	669.3	911.7	1.12	1.03	0.77
2	0	7.5	724.2	873.8	1.62	1.24	0.90
3	0	15.0	641.2	821.7	1.71	1.29	0.92
4	10	0.	761.7	1114.1	1.28	1.24	0.93
5	30	7.5	801.4	924.2	1.79	1.31	0.96
6	30	15.0	511.6	820.6	1.81	1.29	0.91
7	45	0.	768.1	871.9	1.29	0.97	0.73
8	60	0.	655.4	797.9	1.10	0.89	0.67
9	60	7.5	643.6	721.6	1.44	1.02	0.74
10	60	15.	516.6	649.3	1.36	1.02	0.72
11	80	0.	574.8	841.8	0.97	0.93	0.70
12	80	7.5	699.1	896.3	1.56	1.27	0.92
13	80	15.	721.5	923.2	1.91	1.45	1.03

- (1) β = Arctg (Torque/Bending moment)
- (2) Collapse moment according to ASME III Code-Appendix II - 1430 (daNxm)
- (3) Plastic instability moment (daNxm)
- (4) α<sub>1</sub> Sm = 1.5 Sm - PD<sub>o</sub>/4t (Design Conditions)
- (5) α<sub>2</sub> Sm = 2.25 Sm - PD<sub>o</sub>/4t (Level C Service Limits)
- (6) α<sub>3</sub> Sm = 3 Sm - PD<sub>o</sub>/4 t (Level D Service Limits)
- (7) Moments are computed in the center of the cross-section where collapse appears.

Table 2 - Summary of data from tests of elbows

Test N <sub>o</sub>	α (1)	B <sub>2</sub>	Moment (2)	Pressure (MPa)	M <sub>c</sub> (3,5)	M <sub>I</sub> (4,5)	B <sub>2</sub> M <sub>c</sub> D <sub>o</sub>	B <sub>2</sub> M <sub>I</sub> D <sub>o</sub>	B <sub>2</sub> M <sub>I</sub> D <sub>o</sub>
							2I x 1.5Sm	2I x 2.25Sm	2I x 3Sm
1	90	3.15	M <sub>IC</sub>	0.	401.7	401.7	2.00	1.33	1.00
2	90	3.15	M <sub>IC</sub>	7.5	484.7	522.1	2.42	1.73	1.30
3	90	3.15	M <sub>IC</sub>	15.0	512.4	540.1	2.55	1.79	1.34
4	90	3.15	M <sub>IO</sub>	0.	567.8	692.4	2.83	2.29	1.72
5	90	3.15	M <sub>IO</sub>	7.5	678.6	761.7	3.38	2.53	1.90
6	90	3.15	M <sub>IO</sub>	15.0	706.3	761.7	3.53	2.53	1.90
7	90	2.31	M <sub>O</sub>	0.	520.3	541.1	1.90	1.32	0.99
8	90	2.31	M <sub>O</sub>	7.5	610.5	688.2	2.23	1.68	1.26
9	90	2.31	M <sub>O</sub>	15.0	582.7	693.7	2.12	1.69	1.27
10	60	2.69	M <sub>IC</sub>	0.	476.0	476.0	2.02	1.34	1.01
11	60	2.69	M <sub>IC</sub>	15.0	632.1	666.1	2.69	1.89	1.42
12	45	2.45	M <sub>IC</sub>	0.	518.2	518.2	2.01	1.34	1.01
13	45	2.45	M <sub>IC</sub>	15.0	612.4	673.0	2.38	1.75	1.31
14	30	1.97	M <sub>IC</sub>	0.	592.3	592.3	1.85	1.23	0.92
15	30	1.97	M <sub>IC</sub>	15.0	725.4	772.0	2.26	1.60	1.20

(1) Arc angle of elbow (degrees)

(2) M<sub>IC</sub> = In plane Moment (closing), M<sub>IO</sub> = In plane Moment (opening), M<sub>O</sub> = Out of plane Moment

(3) Collapse Moment according to ASME III Code-Appendix II - 1430 (daNxm)

(4) Plastic Instability Moment (daNxm)

(5) Bending Moment in computed in the center of the middle cross-section

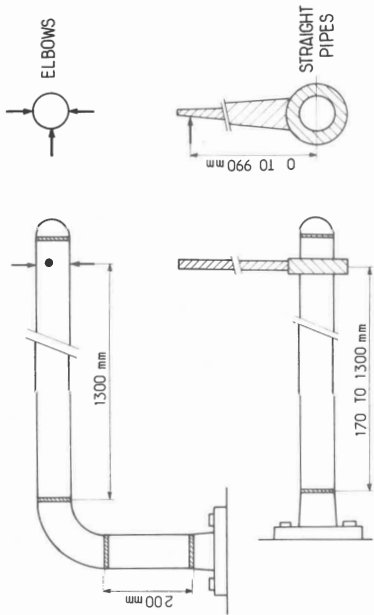


Figure 1 : Diagram of test setup

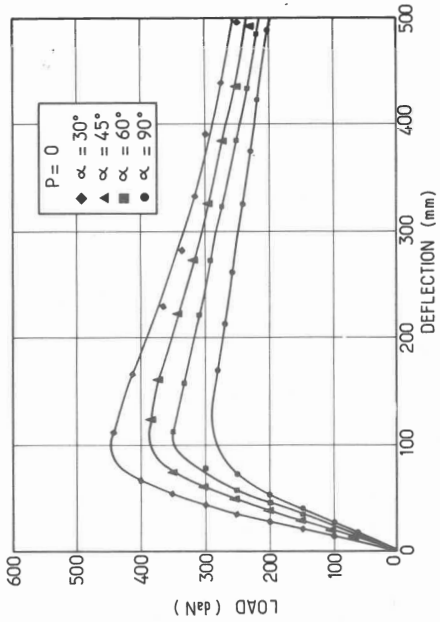


Figure 3 : Comparison of load-deflection curves under in-plane bending (closing) for different arc angles of elbow (without internal pressure)

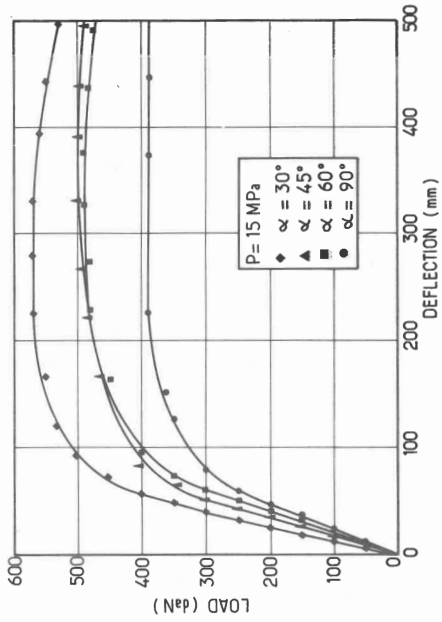


Figure 4 : Comparison of load-deflection curves under in-plane bending (closing) for different arc angles of elbow (with internal pressure)

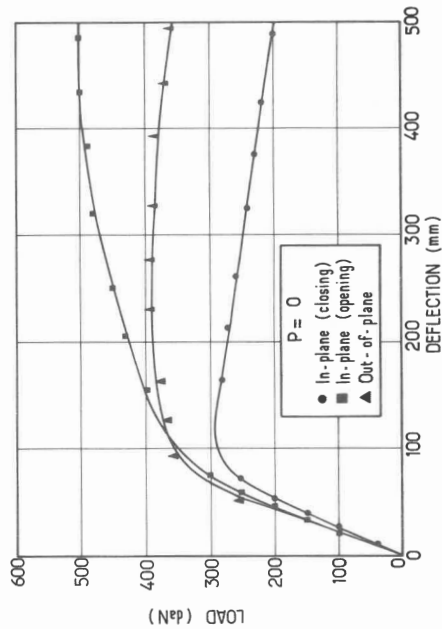


Figure 2 : Comparison of load-deflection curves for 90° elbows under different types of bending (without internal pressure)

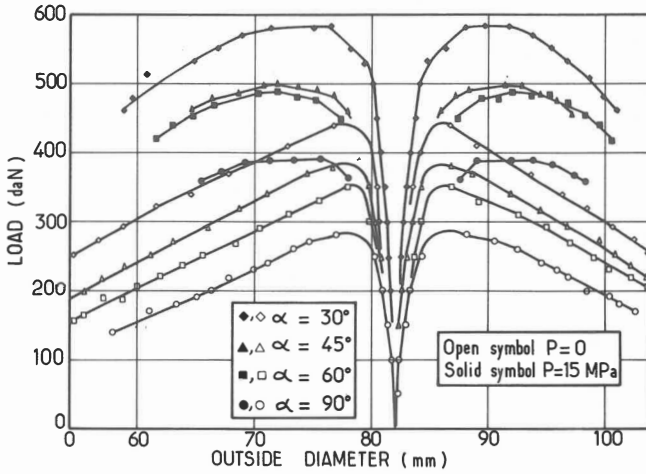


Figure 5 : Variations of the smaller and larger diameters of elbows under in-plane bending (closing)

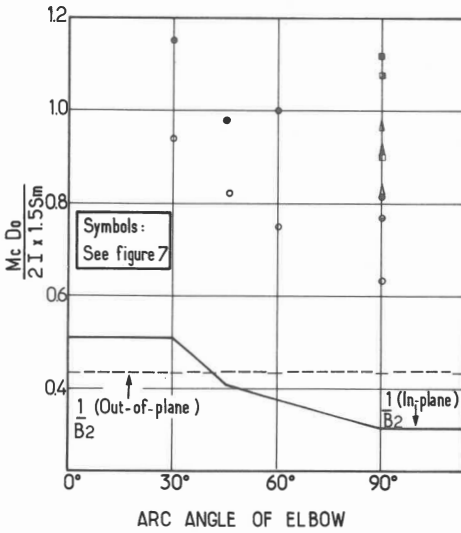


Figure 6 : Correlation of plastic collapse moments obtained for elbows.

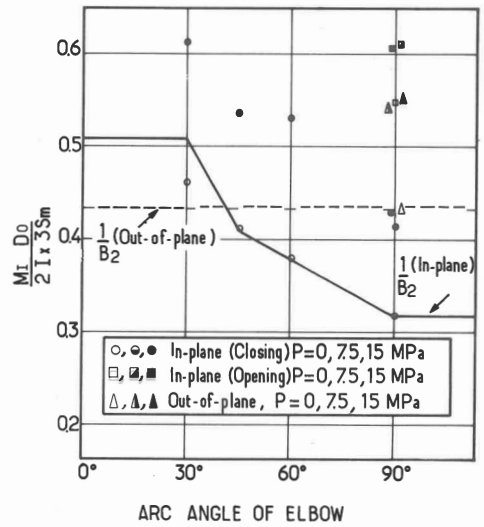


Figure 7 : Correlation of plastic instability moments obtained for elbows.

