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EXPERIMENTAL ANALYSIS
OF AUSTENITIC STAINLESS STEEL STRAIGHT PIPES AND ELBOWS UNDER PRESSURE AND MOMENT LOADINGS

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The subject of this analysis is the plastic behaviour (to plastic instability) of piping components under moment loadings. Elbows are of particular importance because they are the most flexible part in a piping system, and the most susceptible to ovalization.
Under Design conditions, caution must be exerted to avoid exceeding the range of predominantly elastic response as resistance to deformation decreases with increasing load, and may result in component failure. Under Faulted conditions, ovalization of cross sections must be limited to ensure functional capability. In order to avoid undesirable plastic response in PWR primary system components, tests were performed on 1/10 scale pipes and elbows made from AISI 316 austenitic stainless steel. L/D ratios were from 0.56 to 4.50 mm, arc angles of elbows were 30°, 45°, 60° and 90°. Pipes were subjected to bending moments at 3 internal pressure levels. They were tested to determine the mode of failure and served as a reference for elbows. Elbows were subjected to in-plane (closing and opening) and out-of-plane bending moments, at 3 pressure and 2 temperature levels. During these tests, loadings and displacements of components were monitored. Ovalization of sections was measured regularly.
The experimental plastic collapse moment corresponding to excessive deformation was compared to the maximum allowable moment under Design conditions. The experimental plastic instability moment considered as a limit for functional capability was compared to the maximum allowable moment for Level C and D service limits.
The main conclusions are as follows :

- For straight pipes, failure occurs by collapse for long pipes and by ductile fracture for short pipes.
- For elbows, in-plane closing and opening bending moments are the more and less severe loadings respectively.
- Internal pressure decreases plastic collapse and increases plastic instability moments. A decrease in elbow arc angle increases both plastic collapse and instability moments.
- Design condition limits ensure a high safety margin with regard to plastic collapse moment.
- Level C service limits ensure predominantly elastic behaviour of elbows and thus functional capability.

1. Introduction

The subject of this study is the plastic behaviour (to plastic instability) of austenitic piping components under moment loadings. The following criteria are examined :

- Under Design conditions : caution must be exerted to avoid exceeding the range of predominantly elastic response because resistance to deformation decreases with increasing load, and may result in component failure.
- Under Faulted conditions : ovalization of cross sections must be limited to ensure functional capability .

Elbows are of particular importance because they are the most flexible part of a piping system and the most susceptible to ovalization. Straight pipes served as a reference. Tests were performed on austenitic steel straight pipes and elbows. These components were subjected to moment loadings at different pressure and temperature levels. The plastic collapse load, defined as a limit for excessive deformation, was determined from the Moment-Rotation curve in accordance with ASME III - Appendix II [1] . This moment was compared with the maximum moment allowed under Design conditions (ASME III - NB 3600). Plastic instability moments were compared for the different failure modes of straight pipes. For elbows, the plastic instability moment considered as a limit for functional capability is compared to the maximum allowable moment for level C and D service limits.

2. Description of components

2.1. Geometry and fabrication

The components are 1/10 scale PWR Reactor coolant piping. Straight pipes have an outside diameter of 88.9 mm and a wall thickness of 7.65 mm. Elbows have a mean outside diameter of 89.3 mm, and a mean wall thickness of 8.2 mm. The bend radius is 114.3 mm. Arc angles of elbows are 30°, 45°, 60°, and 90°. Elbows were bent at room temperature with several intermediate heat treatments, and were finally annealed.

2.2. Material properties

The components are made of AISI 316 austenitic stainless steel with the following mechanical properties.

	0.2% offset yield stress (Sy) (MPa)		Ultimate tensile strenght (Su) (MPa)	
Temperature	20°C	340°C	20°C	340°C
Elbows	230	120	540	400
Straight pipes	270	180	595	445

These properties were obtained from tensile specimens,taken from non-tested components, with a 25 mm gage section and a 12.5 mm^2 cross sectional area.

3. Test description and instrumentation

Straight pipes were directly welded to a flange. Elbows were welded to pipe extensions, of the same diameter and thickness. The shorter extension was welded to the fixed flange (See figure 1). Moments were produced by an external force statically applied to the free end of straight pipes or extensions. The straight pipes were subjected to bending moments. The elbows were subjected to in-plane (closing and opening) and out-of-plane bending moments. Moment arms were long enough for moment loads to be predominant.(Shear forces were small in comparison). The distance from flange to elbow (150 mm)was such that the effect of the flange was negligible.

Pressure and temperature were kept constant throughout the test. Force and deflection were measured at the loading point, as well as rotations of both ends of the elbows and of the traction lever. For straight pipes only one rotation was measured, at the free flange.

4. Experimental results and interpretation

4.1. The experimental plastic collapse moment (Mc) was determined from the Moment Versus Rotation curve, in accordance with ASME III - Appendix II/1430 [1]. It is the moment for which the measured rotation is twice the extrapolated elastic rotation. This moment was compared to the maximum allowable moment under Design conditions, obtained from the following equation : (ASME III - NB 3652)

$$B_1 \frac{PDo}{2t} + B_2 \frac{Do\ Mi}{2\ I} = 1.5\ Sm \qquad \text{eq. (1)}$$

where : B_1, B_2 = primary stress indices
P = internal pressure
Do = outside diameter
t = wall thickness
I = Moment of inertia
Mi = bending moment
Sm = allowable design stress intensity value.

ASMEIII - NB 3680 gives :

For straight pipes : $B_1 = 0.5$ and $B_2 = 1$
For elbows : $B_1 = 0.5$ and $B_2 = 0.75\ C_2$
where $C_2 = 1.95/h^{2/3}$
and $h = tR/r^2$
where R = bend radius of elbow and r = mean pipe radius.
C_2 shall not be less than 1.5.
Thus : $B_2 = 2.13$ for elbows.

4.2. In this study the adequacy of B_2 values recommended for elbows by RODABAUGH et al was evaluated :

. In ref [2] : $B_2 = \frac{2}{3} C_2$

. In ref [3] : The C_2 index takes into account the direction of loading and the arc angle of elbow for in-plane bending, which gives : $C_2 = 1.95/h^{2/3}$ for $\alpha = 90°$
$C_2 = 1.75/h^{0.56}$ for $\alpha = 45°$
$C_2 = 1$ (and $B_2 = 1$) for $\alpha = 0°$
where α is the arc angle of elbow.

Linear interpolation is to be used, but C_2 shall not be less than the interpolated value for $\alpha = 30°$. In the case of out-of-plane bending, $C_2 = 1.71/h^{0.53}$.
The corresponding B_2 values are plotted on figures 2 and 3.

4.3. According to ASME requirements for austenitic stainless steel, for a test run at temperature T, Sm is chosen as $\left[1/3\ Su_T\ ;\ 2/3\ Sy_{20°C}\ ;\ 0.9\ Sy_T\right]$ whichever is the minimum.

The Sm values for the components tested are (MPa) :

Temp. / Component	20°C	320°C
Elbows	133	108
Straight pipes	140	124

4.4. The plastic instability moment (Mi) defined as the maximum moment on the Moment-Rotation curve, is used as an easily defined limit of functional capability for elbows and was compared to the moment obtained in eq (1) for level C and D service limits (2.25 Sm and 3 Sm respectively, instead of 1.5 Sm).

5. Results on straight pipes

Test data are summarized in table 1 and figure 2. On this figure, the light plotted curves represent probable plastic instability limits versus pipe length. It may be observed that :

- Failure can occur by ductile fracture for short pipes, and by collapse for long pipes.
- The plastic instability moment is higher in the case of fracture than in the case of collapse
- In the case of tearing, Mi decreases when pressure increases
- In the case of collapse, Mi increases when pressure increases.
- The critical length for fracture increases as pressure increases.
- The ASME definition of Sm guarantees similar margins at room and service temperatures for Mi. For Mc, margins are higher at room temperature than service temperature.
- In the case of tearing, application of level D service limits ensures a safety margin greater than or equal to 1.5 with regard to the plastic instability moment.

6. Results on elbows :

As shown in table 2 and figure 3, in-plane bending moments closing (Mic) and opening (Mio), are the more and less severe loadings respectively. Deflection at the plastic instability point is slight for an in-plane closing moment, greater for an out-of-plane moment and greater still for an in-plane opening moment. Figures 4 and 5 show that a decrease in elbow arc angle increases Mc and Mi under an in-plane closing moment, with and without pressure. However the Moment-Rotation curves have the same aspect. A comparison of these two figures shows that high pressure decreases Mc and increases Mi. This is also true for both other types of bending. (In the case of the in-plane opening moment, Mi was not reached, but Moment-Rotation curves are very close for large strains). Figure 6 shows the variations of diameters during the test period, for in-plane closing moments on 30°, 45°, and 60° elbows.
The greater ovalization occurs for test on a 60° elbow with pressure. If we assume an elliptical cross section, the reduction of the middle cross sectional area is about 7% at the onset of instability (both end cross sections remained circular). Ovalization was probably a little more marked for 90° elbows. Nevertheless, this is a small reduction, and we can use the plastic instability moment as a conservative and easily defined limit for functional capability. Test data are summarized in table 2 and interpreted in relation to ASME III criteria. They are illustrated in figures 7 and 8. Under Design Conditions application of eq.(1) with ASME and ref.(2,3) indices generally ensures a high safety margin with regard to the plastic collapse moment. consequently fully elastic behaviour of elbows was obtained, except for test 10 (in-plane closing moment at 340°C without internal pressure). Nevertheless for this specific test, application of eq.(1) only allows a 1° rotation with ASME indices, and a 2° rotation with ref (2) indices. As for straight pipes, margins are higher at room temperature than at 340°C. The plastic instability moment is always higher than the level C limit moments using ASME indices. However the use of static tests to determine functional capability of elbows for dynamic loadings under Faulted Conditions, is generally insufficient (but probably conservative) because damping due to plastic behaviour of the component can [illegible]

significant effect. In this case, application of level C service limits with ASME and ref.[2] indices results in predominantly elastic behaviour for all elbows tested, except for test n°10. In this case, dynamic tests would be necessary. (Room temperature tests show that introduction of internal pressure would significantly increase safety margins, and respect of level C service limits would guarantee small plastic strain). With this exception, it can be asserted that high safety margins with regard to Mi ensure functional capability. (with ASME and ref.[2] indices). Figures 7 and 8 show that safety margins with regard to Mc and Mi increase with decreasing elbow arc angle. The use of ref. [2,3] B_2 indices ensures more uniform margins, than ASME indices.

7. Conclusion

Experimental data from tests on austenitic stainless steel straight pipes and elbows have been presented. They were interpreted in relation to ASME III criteria. The main conclusions are the following :

- For straight pipes, plastic instability can occur by tearing (short pipes) or collapse (long pipes). In the case of tearing, application of ASME level D service limits ensures a safety margin greater than or equal to 1.5 with regard to the plastic instability moment.
- For elbows, in-plane (closing and opening) moments are the more and less severe loadings respectively. A decrease in elbow arc angle increases plastic collapse and plastic instability moments. Pressure generally leads to a decrease in the plastic collapse moment and an increase in the plastic instability moment. Design condition limits ensure fully elastic behaviour and thus a high safety margin with regard to the plastic collapse moment, except for the in-plane closing moment at service temperature. Level C also ensures predominantly elastic behaviour of elbows and thus functional capability, with the same exception as for Design conditions.
- For elbows, the use of B_2 indices proposed in ref.[2,3] ensures more uniform margins than ASME indices with regard to plastic collapse moment and plastic instability moment.

References

/ 1 / ASME boiler and pressure vessel code / Section III / division 1 "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 1979

/ 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 on straight pipes

Test NO	Pipe length (mm)	Pressure (MPa)	Temp. (°C)	M_c (1,3)	M_i (2,3)	$\frac{B_2 D_o M_c}{2I (\alpha_1 S_m)}$ (4)	$\frac{B_2 D_o M_i}{2I (\alpha_2 S_m)}$ (5)	$\frac{B_2 D_o M_i}{2I (\alpha_3 S_m)}$ (6)	$\frac{B_2 D_o M_i}{2I (S_m)}$
1	50	0	20	1700	3316 [0]	1.722	2.239	1.679	5.037
2	50	0	320	1160	2488 [0]	1.429	2.043	1.532	4.597
3	60	16	20	1500	3118 [0]	1.835	2.378	1.728	4.736
4	100	16	20	1250	2065 [0]	1.529	2.185	1.587	4.352
5	120	0	20	1320	2257	1.337	1.524	1.143	3.429
6	120	16	20	not measured	2698		2.058	1.495	4.098
7	120	32	20	990	2458 [0]	1.529	2.154	1.503	3.734
8	400	0	20	1130	1700	1.144	1.148	0.861	2.502
9	400	16	20	not measured	2023		1.543	1.121	3.073
10	400	0	320	700	1404	0.862	1.153	0.865	2.594

KEY TO TABLES 1 AND 2

(1) Plastic collapse moment in accordance with ASME III - Appendix II (m.daN).

(2) Plastic instability moment (m.daN).

(3) Moments are computed in the center of the cross section where collapse or tearing appears.

(4) $\alpha_1 S_m = 1.5 S_m - B_1 \frac{PDo}{2t}$

(5) $\alpha_2 S_m = 2.25 S_m - B_1 \frac{PDo}{2t}$

(6) $\alpha_3 S_m = 3 S_m - B_1 \frac{PDo}{2t}$

(7) Arc angle of elbows (degrees).

(8) Mic = In-plane closing moment ; Mio = In-plane opening moment ; Mo = out-of-plane moment

(*) For some tests we could not reach Mi. In these cases, the highest moment value attained is used as the plastic instability moment.

(0) Failure obtained by tearing.

TABLE 2 - Summary of data from tests on elbows with B_2 ASME = 2.13

Test NO	α (7)	Temp. (°C)	Moment (8)	Pressure (MPa)	M_c (1,3)	M_i (2,3)	$\frac{B_2 \; D_o \; M_c}{2I \; (\alpha_1 \; S_m)}$ (4)	$\frac{B_2 \; D_o \; M_i}{2I \; (\alpha_2 \; S_m)}$ (5)	$\frac{B_2 \; M_o \; M_i}{2I \; (\alpha_3 \; S_m)}$ (6)	$\frac{B_2 \; D_o \; M_i}{2I \; (S_m)}$
1	90	20	M_{ic}	0	725	856	1,73	1,36	1.02	3.07
2	90	20	M_{ic}	17	755	1085	2,26	2,00	1.44	3.89
3	90	20	M_{ic}	32	600	1252	2,31	2,67	1.85	4.48
4	90	20	M_{io}	0	750	1685 *	1.79	2.68	2.01	6.04
5	90	20	M_{io}	17	670	1727 *	2.00	3.18	2.29	6.19
6	90	20	M_{io}	32	590	1571 *	2.27	3.35	2.32	5.63
7	90	20	M_o	0	790	1360 *	1.89	2.17	1.62	4.87
8	90	20	M_o	17	680	1520 *	2.03	2.80	2.02	5.45
9	90	20	M_o	32	590	1514 *	2.27	3.23	2.23	5.42
10	90	340	M_{ic}	0	275	478	0.93	1.08	0.81	2.43
11	90	340	M_{io}	0	380	1359 *	1.29	3.07	2.30	6.90
12	90	340	M_o	0	465	948 *	1.57	2.14	1.60	4.81
13	60	20	M_{ic}	0	850	1043	2.03	1.66	1.25	3.74
14	60	20	M_{ic}	32	670	1383	2.58	2.95	2.04	4.95
15	45	20	M_{ic}	0	1000	1200	2.39	1.91	1.43	4.30
16	45	20	M_{ic}	32	850	1514	3.27	3.23	2.23	5.42
17	30	20	M_{ic}	0	1000	1421	2.39	2.26	1.70	5.09
18	30	20	M_{ic}	16	1070	1456	3.15	2.65	1.92	5.22

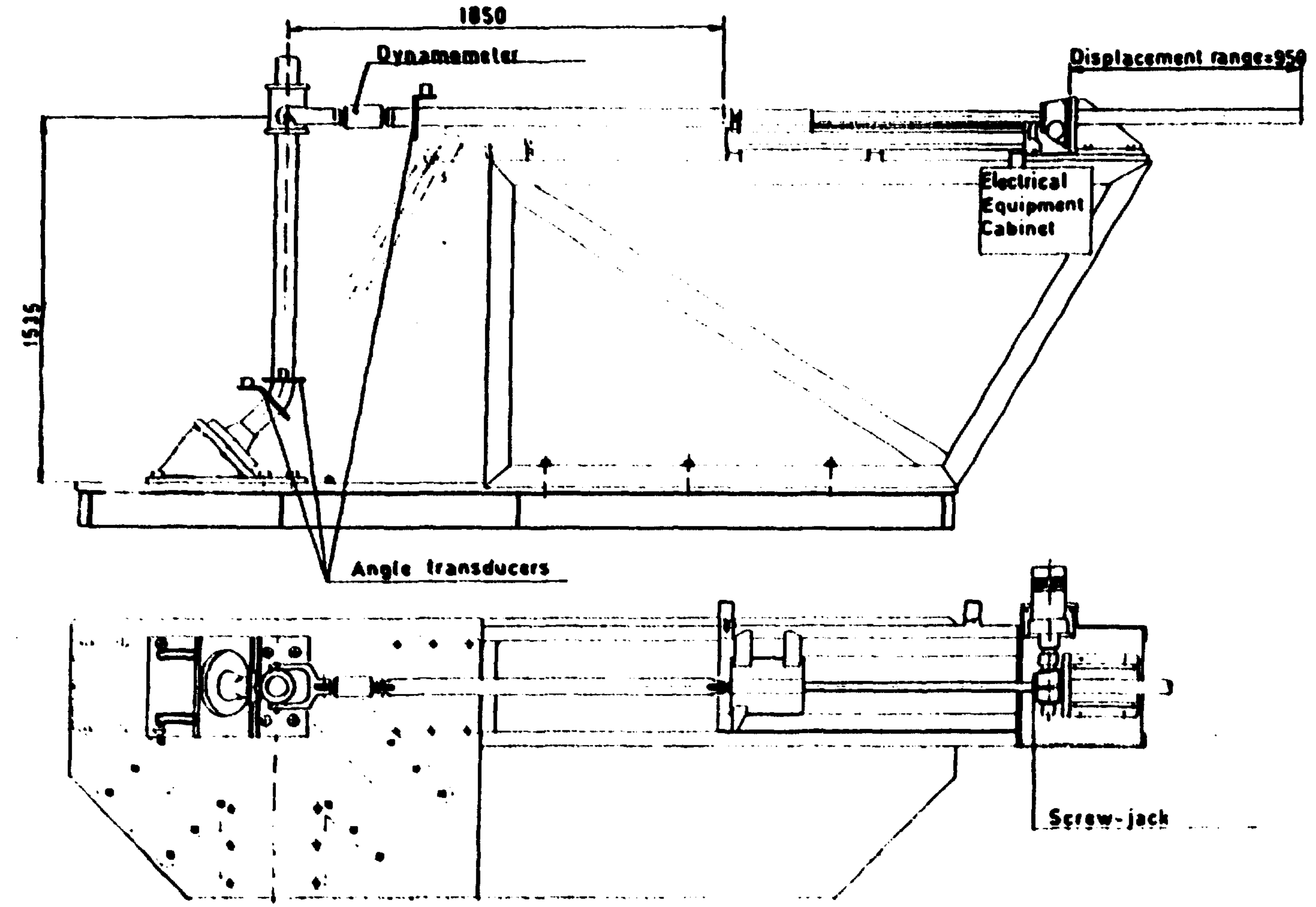

__Figure 1 :__ Testing machine with 45° elbow and support

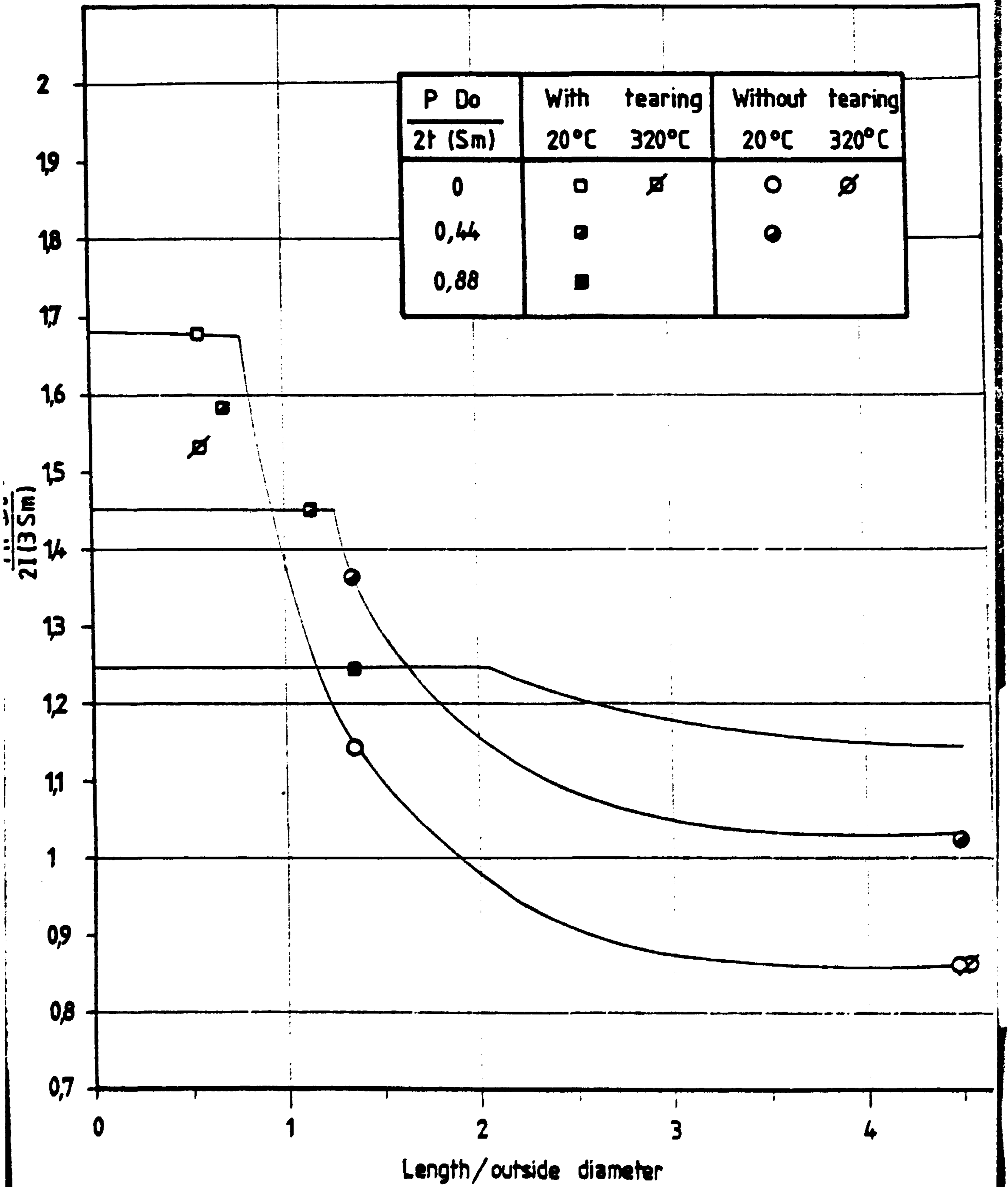

Figure 2 : Correlation of plastic instability moment obtained on straight pipes.

<u>Figure 3</u> : Comparison of Moment-Rotation curves for 90° elbows under different types of bending (without internal pressure).

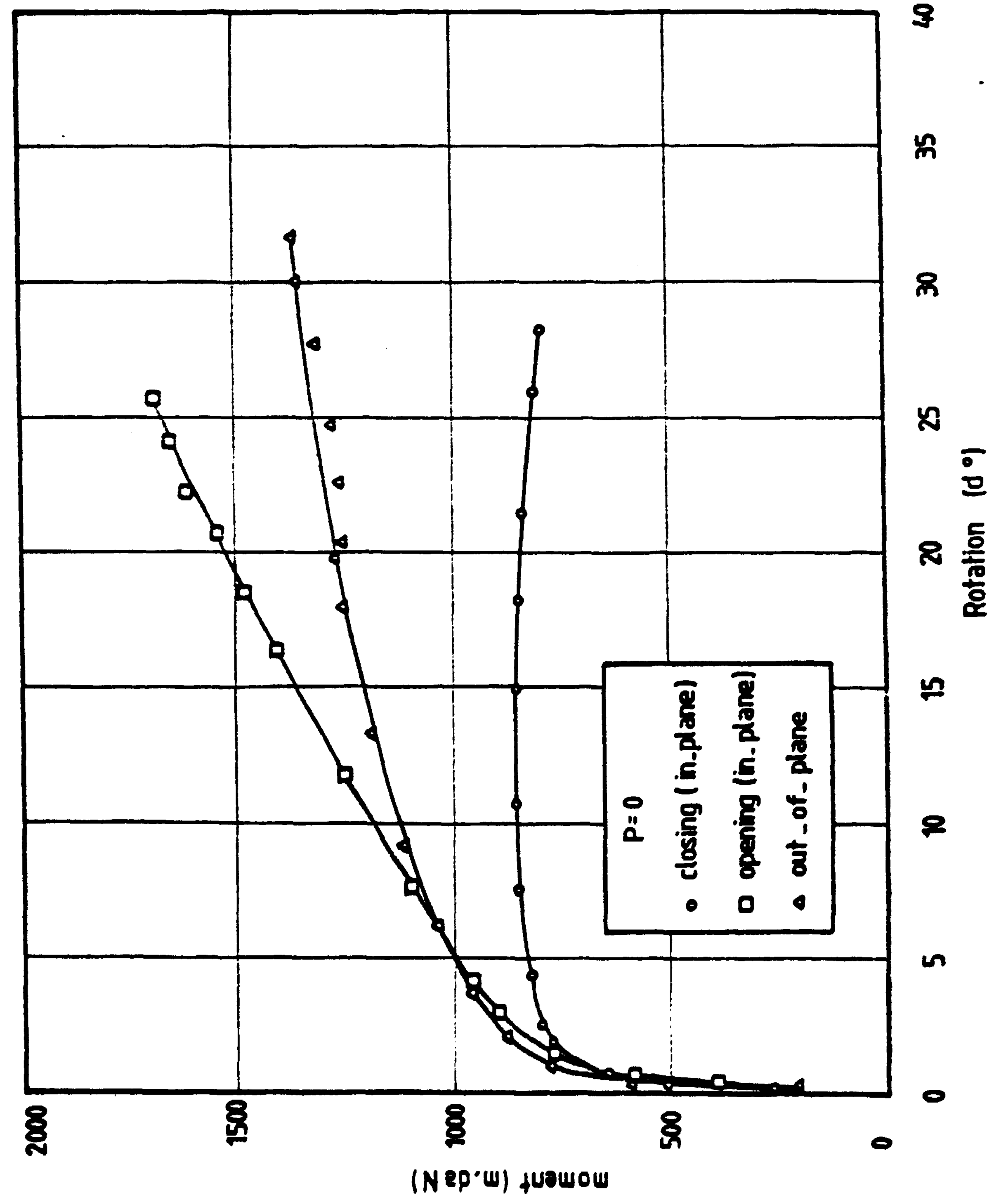

Figure 4 : Comparison of Moment-Rotation curves under in-plane closing bending moment for different elbow arc angles (without internal pressure)

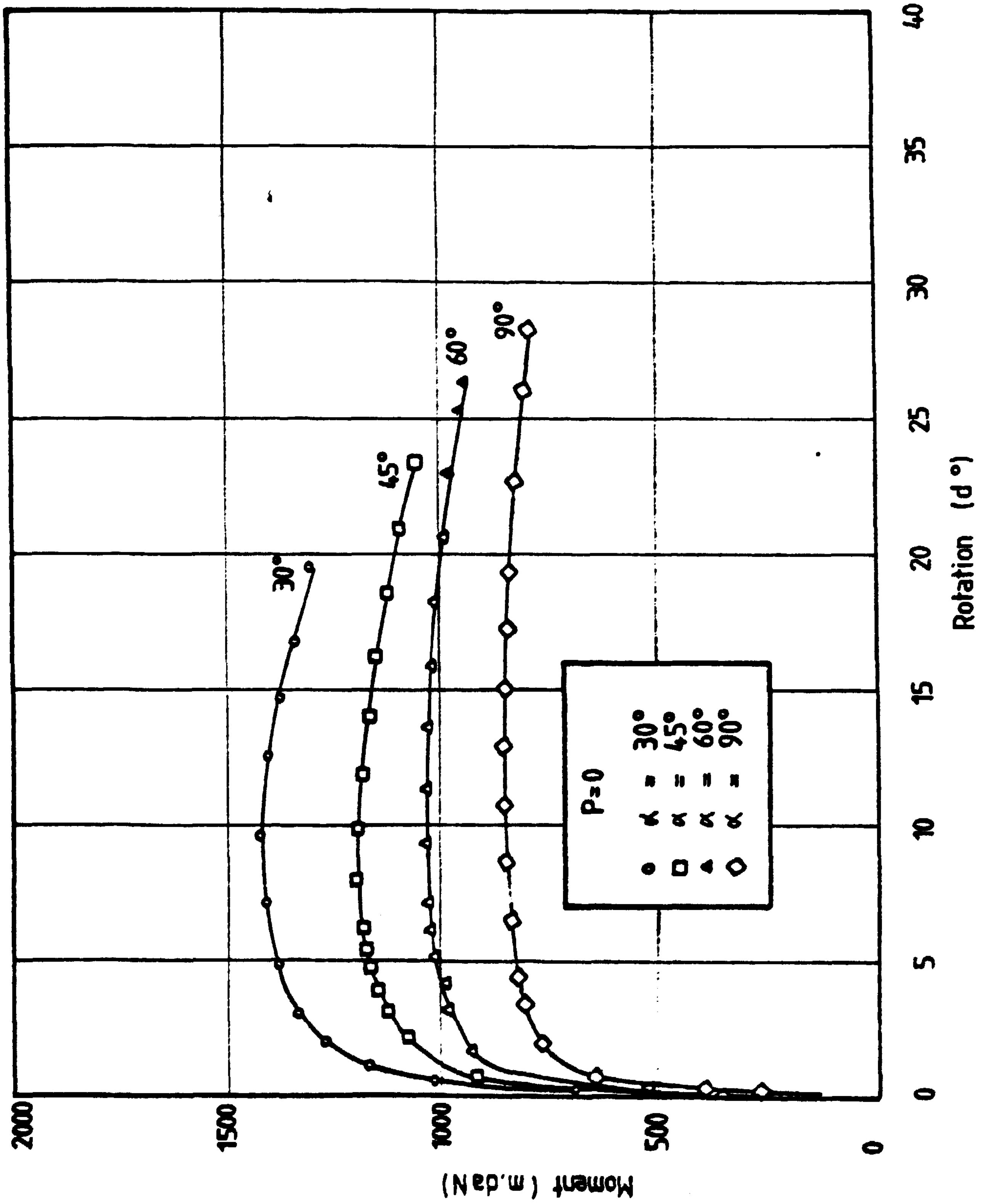

Figure 5 : Comparison of Moment-Rotation curves under in-plane closing bending moment for different elbow arc angles (with internal pressure).

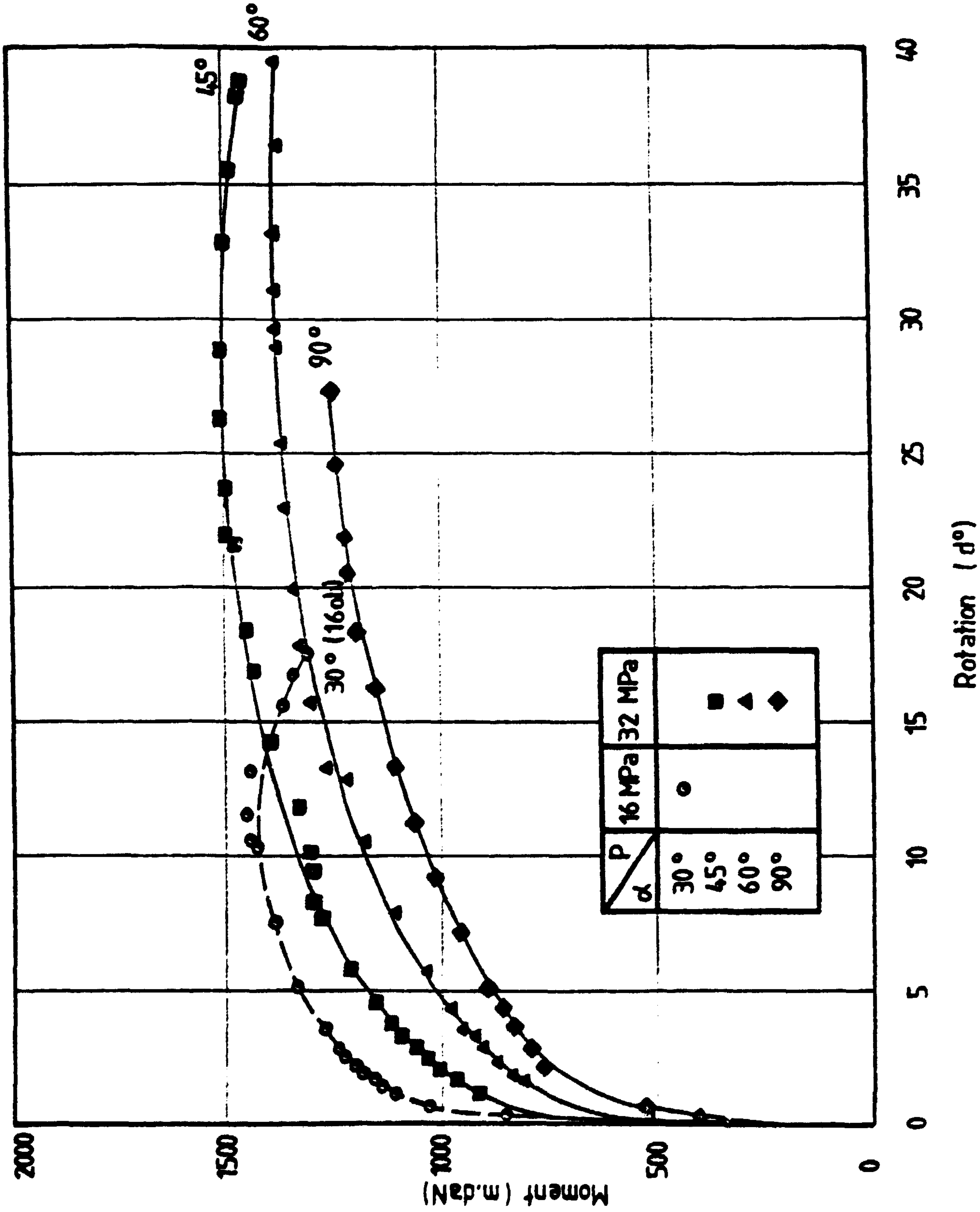

Figure 6 : Variations of small and large diameters of elbows under in plane closing bending moment.

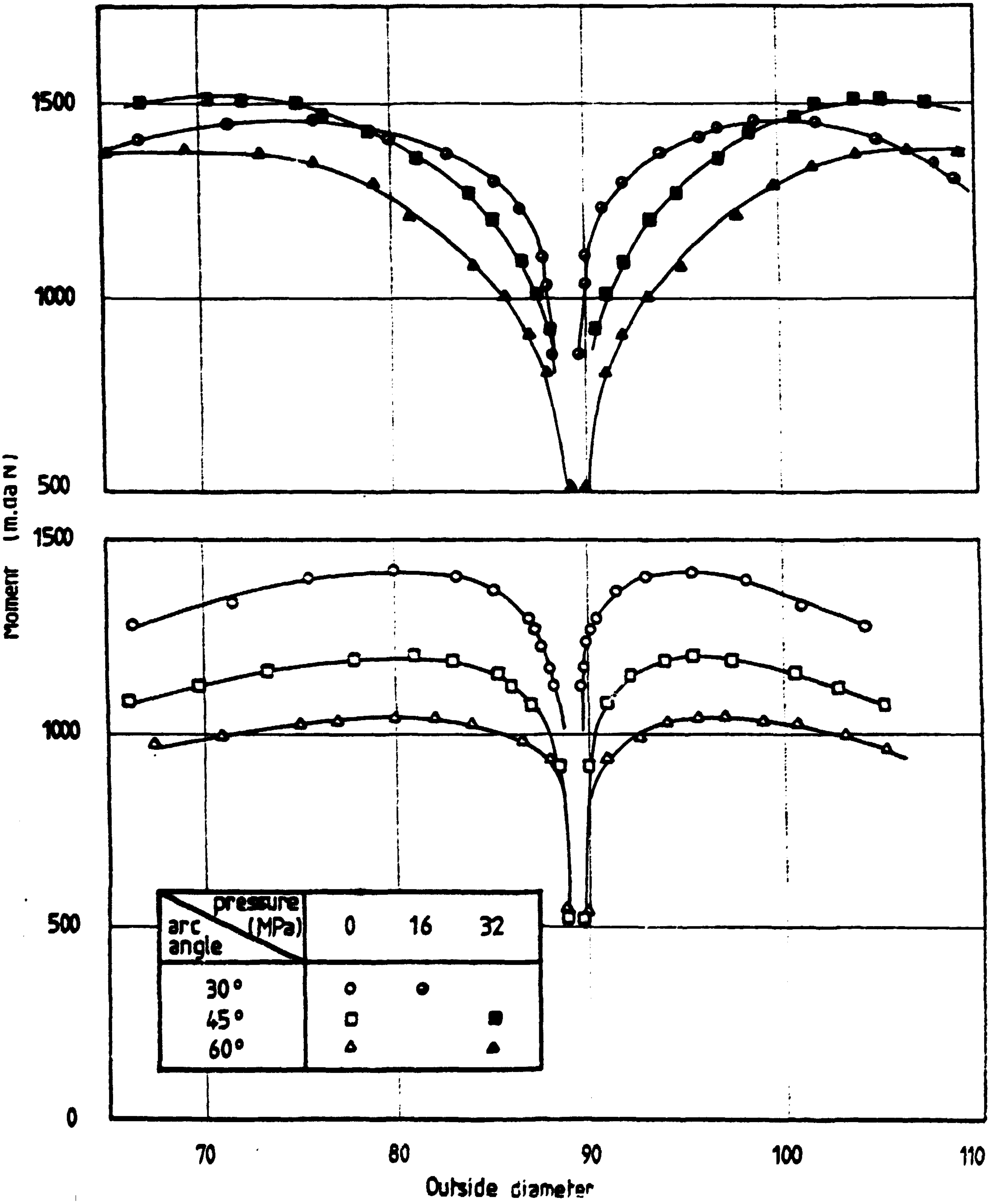

Figure 7 : Correlation of plastic collapse moments obtained on elbows.

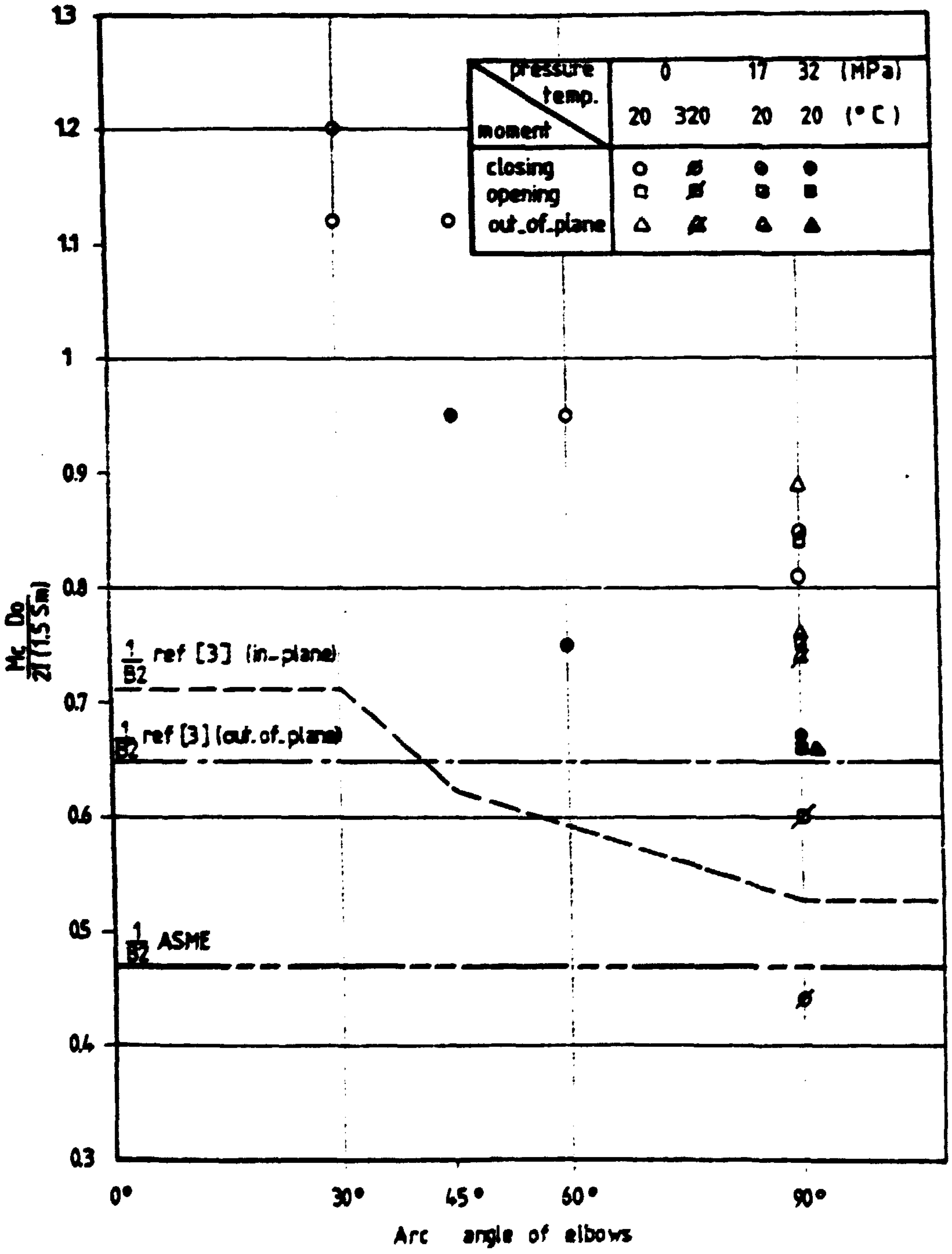

Figure 8 : Correlation of plastic instability moments obtained on elbows.