# Design criteria for piping components against plastic collapse Application to pipe bend experiments

F.Touboul, M.Ben Djedidia & D.Acker
*DEMT, CEA-CEN Saclay, Gif-sur-Yvette, France*

## INTRODUCTION

Recent years have witnessed developments in piping design criteria, initiated by the work of Rodabaugh and Moore (1), which led to significant differences between the criteria proposed by the latest design codes (2, 3, 4, 5). The requirements aimed to limit primary bending stresses in piping are expressed in the form :

$$(1) \qquad B_1 \frac{PD}{2e} + B_2 \frac{M}{Z} < S_A$$

The codes differ in the formulation of the indices $B_1$ and $B_2$ and in the value of $S_A$. For the ASME, indices $B_1$ and $B_2$ are by definition $B_1 = \sigma . \frac{2e}{PD}$, where $\sigma$ is the elastic stress due to the pressure in the elbow, and $B_2 = \sigma Z/M$, where $\sigma$ is the corresponding stress at the limit load of the elbow in bending. For applications, we use the values required by (2,3,4) and given tables 1, 2 and 3. Furthermore, the design of new reactors in which the piping components exhibit geometric characteristics quite different from those of pressurised water reactors, requires confirmation of the validity of the rules for these types of component. With these objectives in mind, we analyzed the experimental results of tests conducted at the CEA/DEMT in the past twelve years, in the sense of the codes and standards.

This paper presents an appraisement of level D design rules for elbows under in plane bending primary moments.

## NOTATIONS

P = Internal pressure
D = Pipe Diameter
Z = Inertia modulus
Sy = Conventional yield strength
Sa = allowable stress
Su = conventional ultime strength at temperature
Rm = conventional ultime strength at room temperature

M = Bending moment
e = pipe wall thickness
$\alpha$ = Bend angle

## EXPERIMENTS

The tests whose interpretation is presented here were performed between 1974 and 1986 at the CEA/DEMT in eight campaigns employing different experimental rigs. For each of these campaigns, we have the geometric measurements taken on the test components and the characteristics of the material obtained on an identical component. This enabled us to determine the characteristic parameter $\lambda = eR/r_m^2$ based on the actual geometry of the components, as well as the allowable stress Sm, from the properties measured on the material, thus avoiding an ultra conservatism due to the tabulated properties. Combined these tests enabled us to determine :

- The influence of the material (26 elbows of austenitic steel and 8 elbows of ferritic steel).
- The influence of the characteristic geometric parameter $\lambda$. For our different series of tests, this parameter ranged between 0.076 and 0.68, values that can be compared to those characterising nuclear reactor : $\lambda = 0.16$ for fast reactors and $\lambda = 0.3$ for pressurised water reactors.
- The influence of the bend angle between $\pi$ and $\pi/6$ radians.
- The influence of pressure, characterised by the nominal stress $\sigma_p = PD/2e$ varying between 0 and 0.72 Sy.
- Using equation (1), we accordingly calculated the critical moment allowable by the codes :

$$M_{cr} = Z/B_2 \; (\alpha \, Sm - B_1 \, PD/2e)$$

For each test campaign, we also have all the recordings made as well as a precise description of the experimental rigs. For each test, this enabled us to determine the limit moment $M_L$ corresponding to a total deflection of the elbow equal to twice the elastic deflection, and the collapse moment $M_R$ corresponding to the maximum moment on the moment-deflection curve (figure 2).

The safety margin offered by the rule is thus defined by the ratio $m = M_R/M_{cr}$. If m is greater than 1, the collapse moment predicted by the rule is lower than the actual moment, and the rule is safe. If, by contrast, m is less than 1, the rule is unsafe.

## RESULTS

### RIGHT-ANGLE BENDS WITHOUT PRESSURE

Figure 1 shows the margin offered by the rules of the ASME section III of the RCC-M and of RCC-MR, as a function of the characteristic geometric parameter of the material. It may be observed that, while the three codes are prudent for ferritic steels, none of them is safe for austenitic steels. For the ASME, the average margin ranges between 0.71 and 0.88 for austenitic steels, and between 1.03 and 1.49 for ferritic steels. This margin appears to be independent of parameter $\lambda$ , which therefore seems to be taken into account correctly in the expression of $B_2$.

### ANGLE EFFECT

Figure 4 shows the variation in the margin as a function of bend angle. This margin can be seen to decrease as the angle increases. While for ferritic steel elbows it is still in the neighbourhood of 1 for a 180° angle, for austenitic steel elbows it reaches this value for an angle of about 60° and 0.68 for a 180° angle. This effect is not taken into account by the present rules.

## PRESSURE EFFECT

Figure 3 shows the influence of pressure, characterised by the parameter $\sigma_p/Sy = PD/2eSy$ on the margin offered by ASME section III. It may be observed that the influence of this parameter increases as the elbow becomes thinner.

The present formulation of index $B_1$ in NB 3680 (2) is hence quite inadequate to take account of the pressure effect.

## DISCUSSION

### ANGLE EFFECT

In our tests, to obtain a constant margin as a function of the angle, it suffices to multiply index $B_2$ by a coefficient of $(\pi/\alpha)^{0.4}$. For right-angle bends, this amounts to assuming that $B_2 = 1.21\lambda^{-2/3}$, by applying this correction to the index determined from the limit analysis of Spence and Finley (6), which was carried out without taking account of the straight parts, and is valid for an "infinite" elbow. It is admit here that this index $B_2 = 1.6\lambda^{-0.6}$, is available for 180° bends.

### PRESSURE EFFECT

To describe the pressure effect, we assume that $B_2$ (P) can be expressed in the form chosen by Dodge and Moore (7) for the flexibility indices :

$$B_2\ (P) = B_2\ (0)/(1+f(\lambda)\ g(P)\ )$$

By also setting $B_1 = 0.5$, it is easy to infer from our tests that

$$g\ (P) = \sigma_p/Sy \quad \text{and} \quad F(\lambda) = 0.7\,\lambda^{-1}$$

### ALLOWABLE LIMITS

The foregoing sections lead us to assume

$$(2) \quad B_2 = 1{,}6\ \lambda^{-2/3}\ \left(\frac{\alpha}{\pi}\right)^{0{,}4}\ (1 + 0{,}7\,\sigma_p/\lambda Sy))^{-1}$$

This formulation does not improve the margins determined from equation (1), and therefore raises the problem of allowable limits. By examining the criteria proposed by the ASME (8) for structures other than piping subjected to level D loadings, it can be pointed out that the maximum allowable loading is 0.9 times the ultimate loading determined by a limit analysis (such as the one carried out by Spence and Finley) for which the flow stress adopted is Min(2.3 Sm, 0.7 Rm). For piping components, this rule leads to assuming that $S_A$ = Min (2.07 Sm ; 0.63 Rm).

To avoid a distortion of the allowable limits at elevated temperature in relation to the actual properties of the material, it is preferable to write this equation in the form :

$$(3) \quad S_A = \text{Min}\ (1{,}4\ Sy\ ;\ 0{,}63\ Su)$$

If we decide to make an experimental analysis, the authorised limit is $M_L$ and the margin in relation to collapse, for the tests without pressure presented here, has a mean value of 1.1 (figure 5). We can compare this value to the one obtained on the overall tests by applying equation (1) with $B_1 = 0.5$, with $B_2$ defined by equation (2) and the limits given by equation (3) (figure 6). The mean value of the margin obtained is thus 1.19, with a minimum value of 1.03 and a maximum value of 1.30 for austenitic steels, and 1.8 with a minimum value of 1.53 and a maximum value of 2.05 for ferritic steels.

This means that the margins obtained by these two methods are consistent. Our proposal is more accurate for pressurised elbows but more conservative for ferritic steel unpressurized elbows.

## CONCLUSIONS

By interpreting the tests conducted on elbows at the DEMT in the past 12 years, we found that the design rules for level D loadings offered by the codes were not prudent and did not allow consideration of the pressure and bend angle effect. Based on the limit analysis carried out by Spence and Finley and on our experimental results we propose expression for a more suitable $B_2$ index and the use of ASME limits applicable to all components.

## REFERENCES

1 Rodabaugh E.C., Moore S.E., 1968. Evaluation of the plastic characteristics of piping products in relation to ASME code criteria, NUREG report CR 0261.
2 ASME boiler and pressure vessel code, 1983, div.1, section III, sub-section NB article NB 3600.
3 RCCM, Règles de conception et de construction des matériels mécaniques des îlots nucléaires PWR, 1985, part 1, vol.B, chap.B 3600, pub. by AFCEN.
4 RCC-MR, Règles de conception et de construction des matériels mécaniques des îlots nucléaires RNR, 1985, part 1, vol.C, chap.C 3600, pub. by AFCEN.
5 ASME boiler and pressure vessel code, 1983, code cases nuclear components, case N 319, pub. by ASME.
6 Spence J.S., Findlay G.F., 1973, Limit loads for pipe bends under in plane bending, Proc.of the 2nd Int.Conf.of Pressure Vessel Technology, paper 1-28, pub. by ASME.
7 Dodge W.G., Moore S.E., 1972, Stress indices and flexibility factor for moment loadings on elbows and curved pipe, W.R.C.bulletin 79, pub. by Welding Research Council.
8 ASME boiler and pressure vessel code, 1983, div.1 section III, appendix F, pub. by ASME.

Table 1

Allowable Stress $S_A$

| Code | RCCM | RCC-MR | ASME |
|---|---|---|---|
| Level D Limits | $S_A = 3$ Sm | $S_A$ = min<br>(3 Sm,0.9 Rm) | $S_A$ = min<br>(3 Sm, 2 Sy) |

## Table 2
Definition of Sm

| Code | RCCM-ASME | RCC-MR |
|---|---|---|
| Aciers ferritiques | $Sm = \min\left(\frac{2}{3} Re, \frac{1}{3} Rm, \frac{2}{3} Sy, \frac{1}{3} Su\right)$ | $Sm = \min\left(\frac{2}{3} Re, \frac{1}{3} Rm\ \frac{2}{3} Sy, \frac{1}{3} Su\right)$ |
| Aciers austénitiques | $Sm = \text{mini}\left(\frac{2}{3} Re, \frac{1}{3} Rm, 0{,}9\ Sy, \frac{1}{3} Su\right)$ | $Sm = \text{mini}\left(\frac{2}{3} Re, \frac{1}{3} Rm, 0{,}9\ Sy, \frac{1}{2.7} Su\right)$ |

## Table 3
Definition of indices B

| Code | RCCM | ASME-RCC-MR |
|---|---|---|
| $B_1$ | 0.5 | $-\ 0.1 + 0.4\lambda < 0.5$ |
| $B_2$ | $1.3 / \lambda^{2/3}$ | $1.3 / \lambda^{2/3}$ |

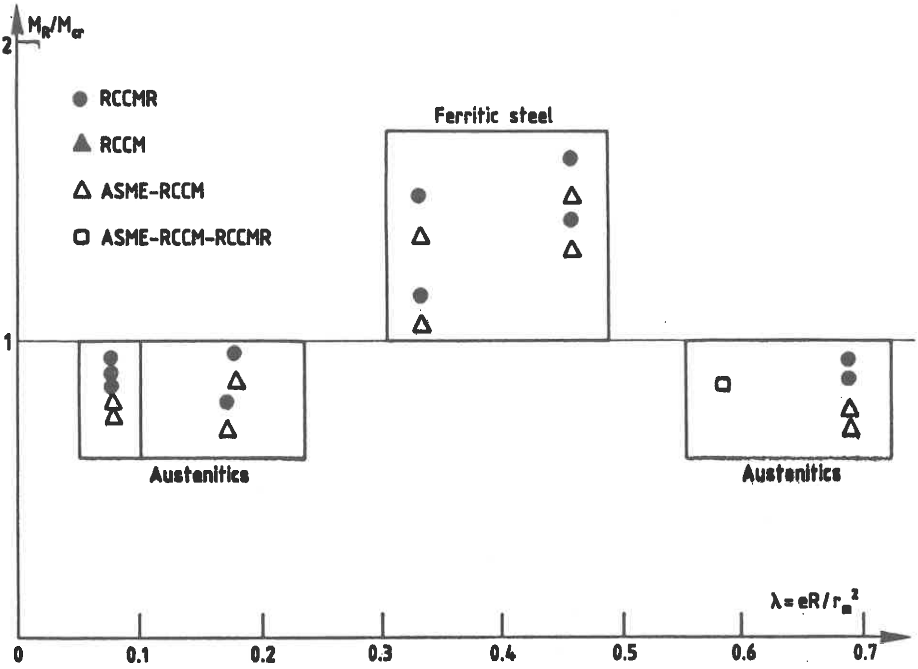

Figure 1 - λeffect on the Level D safety margins for 90° elbows without pressure.

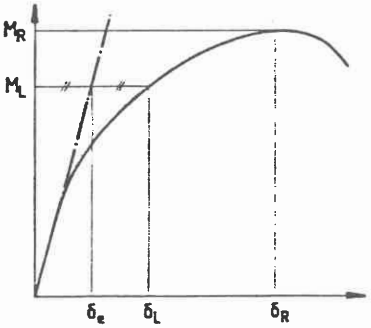

Figure 2. Limit and collapse moments definitions.

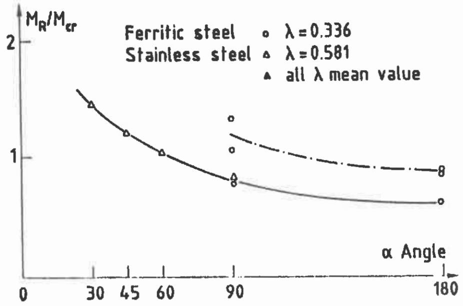

Figure 4. Effect of angle on ASME Level D Safety margins.

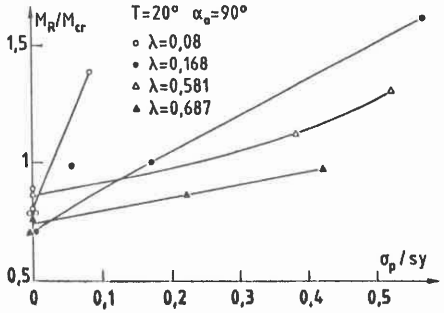

Figure 3. Effect of Pressure on ASME Level D Safety margins.

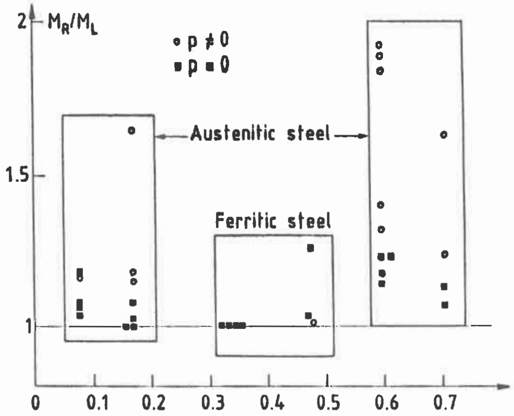

Figure 5. ASME Level D Safety margins by experimental analysis.

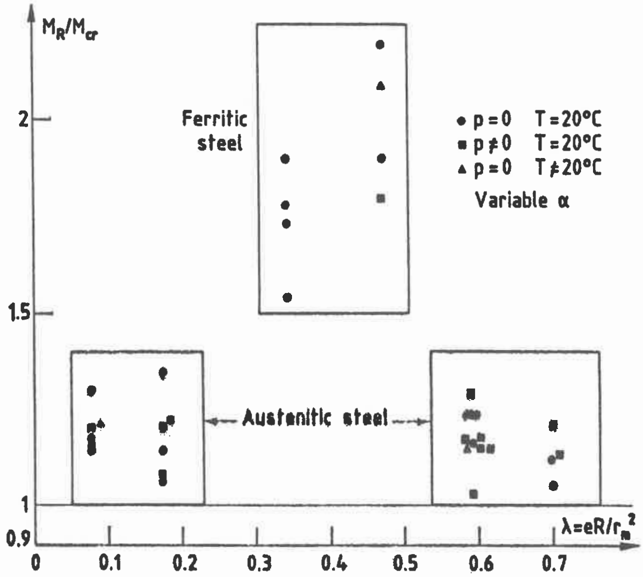

Figure 6. Level D Safety margins with modified $B_2$ and Limits for in-plane bending elbowsof angles between 30° and 180°.