Enhanced seismic criteria for piping

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ABSTRACT

In situ, or laboratory, experience have shown that piping systems exhibit a very satisfactory seismic behavior. Seismic motion do not achieve to significantly damage piping systems unless large differential motions of anchorage are imposed. Nevertheless, present design criteria for piping are very severe and lead to require a large number of supports, which overly rigidify the piping systems. CEA, in collaboration with EDF and FRAMATOME, are working on proposals for enhanced design methods, less severe, but still conservative, and compatible with defect justification during operation.

Our approach is based on the difference between the real behavior (or the computed one) with the codified methods. Criteria are applied on an elastically calculated behavior that can be significantly different from the real one : the effect of plasticity may be very meaningful, even with low incursion in the plastic domain. Moreover, and particularly in piping systems, the elastic follow-up effect affects stress distribution, for both seismic and thermal loads.

For seismic load, we have proposed to modify elastic moment limitation, based on the interpretation of experimental results on piping systems. The methods have been validated on more industrial cases, and some of the consequences of the changes have been studied : modification of the drawings and of the number of supports, global displacements, efforts in the supports, stability of potential defects...

The basic aim of the studies undertaken is to make a decision on the stress classification problem, that is not limited to seismic induced stresses and to propose simplified method to cope with.

INTRODUCTION

Since the beginning of the 80th many R&D programs have been devoted to seismic design of piping systems. The reasons why there have been such activity on that subject are manifold :

- Piping systems do have a good seismic behavior
- Present design criteria are overly conservative
- Their application lead to additional supports, that may be harmful in an economic and in a safety point of view.

Common objective to many of these R&D programs has been to reduce the present conservatism, but different means have been proposed to reach this goal. First proposal has been to consider different damping values : the Regulatory Guide 1.84 allows in the general cases to enhance the damping value from 2% to 5% [1]. PVRC has launched activities on the damage modes and associated limits [2] ; the results obtained have been considered by the ASME comity, which has proposed to enhanced the Design Codes limits from $3 S_m$ to $4.5 S_m$ [3]. France R&D program have been focused in the 80th on the determination of the ultimate load, which has led to the modified stress indices D_1 and D_2 of RCC-MR code [4] et [5].

None of these different approaches have really been totally convincing :

- Suggested damping of RG1.84 is a mean value of an experimental data base with very scattered results,
- NRC has not yet accepted to enhanced the limits of ASME equations,
- The use of D_2 stress indices have not yet been accepted by other Design Codes than RCC-MR one.

So R&D programs have been pursued, and are still going on, in order to reach sounder and more justified conclusions. CEA, in collaboration with EDF and FRAMATOME, are working on proposal for enhanced design methods, less severe, but still conservative, and compatible with defect justifications during operation.

The approach is based on the difference between the real behavior (or the computed one) with the codified methods. Criteria are applied on an elastically calculated behavior that can be significantly different from the real one : the effect of plasticity may be very meaningful, even with low incursion in the plastic domain. Moreover, and particularly in piping systems, the elastic follow-up effect affects stress distribution, for both seismic and thermal loads.

REFERENCE TESTS RESULTS

In order to validate Design criteria, or calculation methods, it is necessary to make reference to experimental results. To be useful these experiments must be fully controlled by the team in charge of the tests interpretation : applied loading, measured moments, displacements are to be accurately determined on the tests.

More precisely, as Design Criteria are concerned, one has to derive from the tests an equation in such a form :

$$M < M_{limit} \quad (1)$$

M is the result of an elastic calculation. So the following items are needed :

- Geometry
- Material data
- Loading
- Ultimate behavior

NB : the above equation is written in term of "load" limitation, but it may be written in a similar manner in term of a "deformation" limitation.

Equation must be adapted to the real loading conditions. Then, to be useful, tests have to be performed in representative loading conditions : seismic load, eventually repeated, a few times.

After an accurate literature survey, CEA has reached to the point that only the tests performed in its laboratory may be fully useful for it. Two experimental campaigns have been performed in CEA/Saclay, on pipework submitted to high seismic loading : ELSA ([6] et [7]) and ASG [8]. These tests can be used for criteria proposal. Validation should be further made on more varied or complex configurations.

CHOICE OF THE TYPE OF EQUATION

The above equation :

$$M < M_{\text{limit}} \quad (1)$$

Is to be developed in such a way to be applicable with the codified material value :

$$B f(M, P, \text{geometry}) < S_{\text{ad}} \quad (2)$$

The ingredients being :

- B = stress indices
- M = moment resulting from the applied loading (weight, earthquake, thermal,...)
- S_{ad} = allowable stress (S_m , S, S_a , fatigue limit)

The choice for the design equation concerns these three items. In the present analysis, we have considered, at a first step, only the moment resulting from the inertial part of the seismic load. In present codes, design equations related to seismic load are quite different. One main reason is that the considered damage is different : instability for RCCM Code [9], buckling for RCC-MR Code [5], fatigue and ratcheting for ASME Code [6].

Damage mode under seismic loading is not clearly plastic instability, neither ratcheting. When piping components have been experimentally loading up to failure, cracks have appeared (corresponding to fatigue) but global plastic deformation are very high (plastic hinge or buckling pattern have been observed). Moreover, the number of cycles applied are much larger than the one applied during an earthquake, even considering the replications. Besides, if components have been experimentally failed under a *seismic* loading, it has never been the case for pipework (sine loading have been used for failure). Then it seems that the failure mode under a seismic loading may be : plastic instability, buckling, fatigue, progressive Striction, or a combination of these damaging mode.

Concerning the harmful effect of ratcheting, quasi-static cyclic tests on components have shown that this effect is not significant [10].

Then, the choice between an instability equation or a fatigue equation is not straightforward. But one has to consider the fact that the moment (or the rotation) leading to a fatigue failure in a few number of cycles (typically around 10) is very close to the instability moment (or rotation). Then we have proposed to keep the form of an instability equation.

PRESENT DESIGN CODE EQUATIONS

In order to make useful proposal, we have first analyzed present design codes equations.

RCCM Code

(RCCM, B 3656 and appendix ZF)

$$B_1 \frac{PD}{2e} + B_2 \frac{M}{Z} \leq 3S_m$$

$$B_1 = 0.5, B_2 = 1.3 \lambda^{-2/3}$$

$$S_m = \min (2/3 S_y, 1/3 S_u)$$

M obtained from a spectral calculation with a specified damping value.

RCC-MR Codes

(RB 3651.113)

$$D_1 \frac{PD}{2e} + D_2 \frac{M}{Z} \leq 1.9 S^*$$

$$D_1 = 0.5, D_2 = 1.6 \lambda^{-2/3} \quad g(P, \alpha)$$

$$S^* = \min(0.8 S_y; 0.4 S_u) \Rightarrow 1.9 S^* = 1.52 S_y$$

M obtained from a spectral calculation with a specified damping value.

ASME Code, 1985 edition

$$B_1 \frac{PD}{2e} + B_2 \frac{M}{Z} \leq 3 S_m$$

$$B_1 = -0.1 + 0.4 \lambda, 0.5, B_2 = 1.3 \lambda^{-2/3}$$

$$S_m = \min(2/3 S_y, 1/3 S_u)$$

M obtained from a spectral calculation with a specified damping value.

ASME Code, 1995 edition

$$B_1 \frac{PD}{2e} + B_2 \frac{M}{Z} \leq 4.5 S_m$$

$$B_1 = -0.1 + 0.4 \lambda, 0.5, B_2 = 1.3 \lambda^{-2/3}$$

$$S_m = \min(2/3 S_y, 1/3 S_u)$$

M obtained from a spectral calculation with a specified damping value.

As conservatism is concerned, it is obvious that ASME Code (1995) is much less severe than the other codes. But RCCM and RCC-MR have to be accurately compared.

A former study [11], which result are represented below, have shown the relative position of the different Codes :

- ASME NB3680, edition 1985, which is close to present RCCM equation,
- ASME NB3680, edition 1985, with modified stress indices as proposed by Code Case N319,
- RCC-MR equation

Figure 1 : comparison between RCC-MR code, ASME 85 (or RCCM) Code and Code Case N319

It can be seen that the normalized moment (M/ZS_y) is always greater when considering RCC-MR code, as soon as there is pressure. In other words, RCC-MR equation, which is based on the analyze of a very large experimental data base of monotonic static tests on elbows [4], is always less severe than RCCM one, except for very low pressurized piping (as it is the case in FBR).

APPLICATION TO ELSA AND ASG TESTS

We can define as a code margin by calculating the following value :

$$M = M_{\beta} / M_{\max}$$

avec

$$M_{\max}(\text{RCCM}) = \frac{Z}{B_2} \left(3S_m - B_1 \frac{PD}{2e} \right) \quad M_{\max}(\text{ASME 95}) = \frac{Z}{B_2} \left(4.5S_m - B_1 \frac{PD}{2e} \right)$$

$$M_{\max}(\text{RCC-MR}) = \frac{Z}{D_2} \left(1.9S^* - D_1 \frac{PD}{2e} \right)$$

M_{β} is the moment derived from a spectral calculation with a damping value of $\beta\%$, for an acceleration level corresponding to the failure moment. This level is characterized by the spectra ZPA.

Test description

ELSA experimental device

figure 1 : ELSA experimental device for pipework experiment

$D = 168.3 \text{ mm}$ $e = 7.57 \text{ mm}$ $R = 228.6 \text{ mm}$
 $\lambda = 0.27$ $P = 12 \text{ MPa}$ $S_y = 240 \text{ MPa}$

$S_u = 609 \text{ MPa}$

figure 2 : ASG experimental device for pipework experiment

$$\begin{array}{llll} D = 114.3 \text{ mm} & e = 8.56 \text{ mm} & R = 152.4 \text{ mm} & \\ \lambda = 0.47 & P = 0 & S_y = 350 \text{ MPa} & S_u = 449 \text{ MPa} \end{array}$$

From the experimentally measured characteristics, one may derive the codified values : stress indices, maximum allowable moment ($M_{\max}$).

For ELSA :

$$B_2 = 3.13 \quad D_2(0) = 3.05 \quad D_2(P) = 1.16 \quad M_{\max}(\text{RCCM}) = 19.3 \text{ kN.m}, \quad M_{\max}(\text{RCC-MR}) = 37.4 \text{ kN.m}$$

For ASG :

$$B_2 = 2.15 \quad D_2 = 2.00 \quad M_{\max}(\text{RCCM}) = 14.6 \text{ kN.m}, \quad M_{\max}(\text{RCC-MR}) = 11.9 \text{ kN.m}$$

Present criteria application

In order to calculate Design Codes margins, it is necessary to define a failure level, corresponding to a "failure acceleration" and a "failure moment". As failure has not been reached during the considered tests campaigns, it has been necessary to derive them from other experimental results. Cyclic or monotonic failure tests on elbows have been used, in order to derive a rotation to failure for the most loaded elbow of the pipework [7, 8]. It has been admitted that the failure level of the pipework is the seismic level leading to the failure of one elbow, that may be considered as a conservative assumption.

Estimated failure levels have been determined : 9.2g for ELSA and 8.3g pour ASG. Experimental applied level (high level tests) were : 3.4g for ELSA and 2.76g for ASG. Experimental initial damping (elastic behavior) were : 0.14% for ELSA and 1% for ASG.

From these values, present Design Code margins have been calculated :

Table 1 : Present Design Codes margins

$M/M_{\max}$	RCC-M	RCC-MR	ASME 95
<i>ELSA</i> , $M_{5\%}$	6.6	3.4	4.2
<i>ASG</i> , $M_{5\%}$	3.8	4.6	2.5

The fact that all three codes exhibit quite high margins (greater than 3), justify to propose enhanced criteria.

PROPOSED CRITERIA MODIFICATION

The proposed criteria are based on two main ideas :

- past studied [7, 8] have shown that over conservatism is due to overestimation of the moment value. Beneficial plasticity effect has to be taken into account.
- RCC-MR stress indices and equation limit, are closer to the experimental results. Nevertheless, these coefficient are not easily comparable to usual code equations. One can propose to use a RCCM type equation but taking into account beneficial effect of pressure or elbow angle.

Then the proposed equation may be as follow :

$$B_1 \frac{PD}{2e} + B_2 \frac{M'}{Z} \leq 3S_m \quad (3)$$

B1 and B 2 : enhanced stress indices

M' calculated moment, derived from one of these analyses :

1. Time history non linear calculation (THNL)
2. Equivalent linear calculation
3. Linear analysis plus a reduction factor.

As the first proposal is not useful for industrial calculation, proposal have been made on the two last statements.

JUSTIFICATION OF THE PROPOSED EQUATION

Proposal for reduction factors

Reduction factors (or behavior coefficients) may be obtained on the considered tests by comparing the linearly calculated maximum moment to the one obtained by a THNL calculation.

Table 2 : Reduction factors

	γ/γ_e	$M_{L \beta i}/M_{NL}$	$M_{L 2\%}/M_{NL}$	$M_{L 5\%}/M_{NL}$	M^*/M_{NL}
ELSA (test level)	7.2	5.5	2.6	1.5	1.9
ELSA (failure level)	19.4	11.6	5.1	3.0	3.2
ASG (test level)	2.1	1.73	1.11	0.67	1.2
ASG (failure level)	6.3	5.7	3.25	1.9	2.2

Where : γ is the test acceleration, γ_e is the acceleration corresponding to the end of the elastic behaviour.

$M_{L \beta i}$ is the result of a linear calculation, using the initial (elastic) experimental damping value (0.14% for ELSA, 1% for ASG).

A 2% damping value may be considered as a mean "structural damping value" (without plasticity) for industrial pipework. For this value, the reduction factors depend on the plasticity level : its minimum value is 3.25.

Proposal for an enhanced damping approach

It has been shown [8] that using a CAUGHEY method it is possible to have a good representation of the non linear behavior of ELSA and ASG pipework by using an equivalent linear calculation. Nevertheless, equivalent damping, at the high test level, were very different from one pipework to another, even though plasticity level were similar (deformation up to 1%) : 5.5% for ELSA and 1.7% for ASG.

A more defined analysis has shown that the achieved ductility were quite different : 8.3 for ELSA and 5.5 for ASG. We have so performed a parametric study, on a one degree of freedom oscillator, in order to make our mind up on the more effective parameters : ductility, material behavior, seismic level, initial damping, signal.

This analysis has concluded that : the equivalent damping is quite independent of the initial damping, but is very dependant on the seismic level and the material law.

Comparison between a reduction factor approach and a equivalent damping approach

It has been shown that the use of different damping values leads to the following result :

Table 3 : Application of reduction factors and equivalent damping

	$M_{L\ 2\%}/M_{NL}$	$M_{L\ 2\%}/3M_{NL}$	$M_{L\ 5\%}/M_{NL}$	$M_{L\ 7\%}/M_{NL}$	$M_{L10\%}/M_{NL}$
ELSA (test level)	2.6	0.9	1.5		
ELSA (failure level)	5.1	1.7	3.0	2.8	2.4
ASG (test level)	1.11	0.37	0.67		
ASG (failure level)	3.25	1.1	1.9	1.7	1.4

It can be shown that for failure level similar results are obtained using a large damping value (10%) or a reducing coefficient of 3.

CRITERIA PROPOSAL

The present R&D results leads to propose one of the following criteria :

proposition 1 :

$$B_1 \frac{PD}{2e} + B_2 \frac{M/s}{Z} \leq 3S_m$$

M obtained with a spectral analysis and 2% damping
s = 3

proposition 2 :

$$D_1 \frac{PD}{2e} + D_2 \frac{M/s}{Z} \leq 1.9S^*$$

M obtained with a spectral analysis and 2% damping
s = 3

proposition 3 :

$$B_1 \frac{PD}{2e} + B_2 \frac{M}{Z} \leq 3S_m$$

M obtained with a spectral analysis and 10% damping

proposition 4 :

$$D_1 \frac{PD}{2e} + D_2 \frac{M}{Z} \leq 1.9S^*$$

M obtained with a spectral analysis and 10% damping

Present criteria and above proposal applied to ELSA and ASG tests leads to the following margin results :

Table 4 : Comparison of actual codes and new proposals

ELSA	RCCM (5%)	RCC-MR (5%)	ASME 95 (5%)	
Failure level	6.6	3.4	4.2	
	prop.1	prop. 2	prop.3	prop. 4
	3.7	1.9	5.2	2.7
ASG	RCCM (5%)	RCC-MR (5%)	ASME 95 (5%)	
Failure level	3.8	4.6	2.5	
	prop.1	prop. 2	prop.3	prop. 4
	2.1	2.6	2.8	3.4

Margins obtained from the new proposals vary from 1.9 to 5.2. The gain is significant in comparison to present codes equation. The margins are generally lower or comparable to 1995 ASME version.

CONCLUSION

Present R&D results allow to propose new criteria for the seismic design. At the present time, a formula has been proposed, that allows to reduce extra conservatism and to preserve the codified safety margins :

$$B_1 \frac{PD}{2e} + B_2 \frac{(M_p + M_{si}/s)}{Z} \leq 3S_m \quad (4)$$

M obtained with a spectral analysis and 2% damping

Behavior coefficient : s = 3

Or enhanced damping : $\beta = 10\%$

$B_2 (P, \Phi)$

It is proposed that pressure and angle effect be taking into account in the stress index $B_2(P, \Phi)$, in a similar manner to what has been done in RCC-MR, to be consistent with past R&D work. [4].

The behavior coefficient should be taken at a lower value if the present damping value in the elastic calculation [1], which is usually 5%, is preserved.

The choice between the two proposal (reduction factor or higher damping value) will depend both on the industrial practice and on the results of future validation work. In particular, these proposals have to be applied to more complex piping systems, more representative of the reactor piping network.

It has to be noted that to take into account the plasticity effect not only on design criteria, but also on actual efforts, for crack nocivity assessment, or global displacements, for functionality problems, enhanced and simplified calculation methods are to be developed.

NOMENCLATURE

D	external diameter	Z	modulus of inertia
e	thickness	P	Internal Pressure
r	mean radius	β	damping value
R	elbow bend radius	S_y	conventional yield stress
λ	elbow characteristic parameter	S_u	ultimate tensile stress
$\lambda = eR/r^2$		S_m	code specified allowable stress

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