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Stress Analysis Criteria for Piping. RCC-M 2002 Rules and Validation.

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1 ABSTRACT

The 2002 addendum RCC-M code introduced a new rule for stress classification of seismic loads in piping systems stress analysis. It allows the application of a reduction factor on the elastically calculated seismic moment in order to quantify the primary part which shall be introduced in the stress limitation equations.

In linear response spectrum analysis using widely broadened spectra, with an usual low damping ratio ξ, this reduction factor is equal to : $\tau = \sqrt{\xi / 10}$. This reduction is valid for usual piping systems which have not their main frequencies in the high frequency region of seismic spectra. It is a behavior coefficient, similar to those used in structural design codes, equivalent to the use of inelastic spectra.

Equations in piping design codes for faulted loading conditions are compared and applied to piping test results. The application of the new rule with level D criteria gives allowable loads two times lower than allowable loads derived from piping tests. Available test results validate the new RCC-M 2002 criteria for seismic design of piping. Seismic stresses are only partly a primary loading. As this new rule provides margins in piping analysis still larger than two, the industrial practice remains consequently severe.

2 INTRODUCTION

In situ or laboratory tests have shown the very good behavior of piping systems under seismic loads. Seismic movements do not significantly damage piping systems unless large differential anchor motions are applied. Nevertheless, severe piping design criteria lead to require a large number of supports which overly rigidify the piping systems and reduce overall safety.

During the eighties and nineties, many R&D programs have been devoted to seismic design of piping systems. Common objective to many of these R&D programs was to reduce the current conservatism, using different means. First proposal considered higher damping values, from 2% to 5%. PVRC and ASME activities on piping behavior, damage modes and associated limits led to the increase of ASME design limits, from 3 S_m to 4.5 S_m (ASME, 1995), or to the reduction of stress index in elbows and tees, firstly by 33% (ASME, 2004) and lastly by 25% (ASME, 2007).

All these different approaches could be questionable :

- 5% damping is a mean value of an experimental data base with very scattered results,
- ASME equations enhanced limits or stress index reduction were not accepted by NRC.

So some R&D programs are still going on, in order to reach sounder and more justified conclusions. Criteria are applied on an elastically calculated behavior that is significantly different from the real one : the effect of plasticity is considerable, even with low incursion in the plastic domain. The aim is to reduce the difference between the real behavior (or the computed one) and the codified design methods.

The paper presents elements that justify the RCC-M code modification in stress classification of seismic loads for piping systems stress analysis (RCC-M, 2002), which partially reduces this difference.

3 STRESS CLASSIFICATION

3.1 Introduction

The objective of stress analyses is to ensure that appropriate safety margins exist against various types of damages. It shall be noted that most types of damages imply plastic deformations. However, code rules are based on the widest possible application of the theory of linear elasticity.

Two consequences result from this apparent contradiction :

- Criteria to be applied to results of elastic analyses will have to be related to the elastic-plastic behavior of components,
- Stresses have to be classified as a function of the damages to which they may lead.

In the RCC-M code, two main classes are defined (primary and secondary stresses) in chapter dedicated to elastic analyses.

Primary stresses are the category of stresses that contribute directly to satisfying equilibrium of mechanical loads. For this reason, they continue to exist in the event of plastic deformation.

Secondary stresses are those stresses which, once primary stress limits have been taken into account, must be limited so as to ensure general structural adaptation. Once these definitions are given, the designer is facing the difficulty to translate them in a practical way.

3.2 Main Definitions

Primary stresses are the category of stresses that contribute directly to satisfying equilibrium of mechanical loads. They are not reduced by definition in the event of plastic deformation of the material, and their value depends consequently only weakly on the method used to determine them. Any stress field statically acceptable and meeting the criterion of plasticity of the material is thus acceptable towards the prevention of the risk of excessive deformation (the safety margin having to be integrated into the criteria).

In practice, nevertheless, the situations can be complex. For example, a restrained thermal expansion of piping can be considered as equivalent to a deformation imposed to the piping at the point where it is restrained. This deformation leads to a stress with a secondary character in the piping, but it is seen by the equipment as a load transmitted to it by a spring with the piping flexibility (elastic follow up effect).

The primary or secondary character of stresses in equipment is a function of respective flexibilities of components in presence, and of the level of deformation which is acceptable :

- If the piping is very stiff, it controls the equipment deformation : the equipment stress is high, but it is essentially secondary,
- If the piping is very flexible, the equipment stress is very low, but it is essentially primary.

The secondary stresses decrease and even disappear after a sufficient deformation of the structure : they are self-limiting. However, if this deformation is larger than the one corresponding to the ruin of the structure, the stress state under consideration is partially primary, because it is maintained (even if it is reduced) up to this ruin. This fact is important and led to maintain requirements of minimal ductility for materials : seen by a material with very low ductility, any stress state is essentially primary.

If we cannot find a plausible deformation of the equipment, compatible with its integrity, from which would result a disappearance of the load transmitted by the piping, this load is partly a primary load. Conversely, the reaction of the equipment is seen as secondary by a flexible pipe, because it is easy to find a deformation of the pipe from which would result a disappearance of the force transmitted by the equipment. When the pipe is very stiff, pipe stresses due to these forces are partially primary loads.

3.3 RCC-M History

When establishing RCC-M rules (issued from ASME III rules), the French regulation applicable to the Main Primary Systems of Light Water Reactors was the 1974 order, which did impose safety margins against various types of damages.

The justification of stress classification was based on the types of damages to which given types of stresses could lead (D'Escatha, 1981). Such requirement does not exist under the same form in the new regulation, but leads basically to the same consequences as far as appropriate safety margins shall be applied depending on the hazard analysis which is under the responsibility of the manufacturer (Grandemange, 2007).

Even if tables of stress classification were not integrated in the code, sentences were kept in the first editions of B 3100 and B 3600 for piping allowing classifying thermal expansion stresses as secondary until the results of developments were available. In parallel, stresses resulting from the inertial effects of dynamic loads were classified primary, according to the general consensus.

In the mid nineties, developments at the international level on dynamic loads did lead to ASME modifications. Similar discussions were conducted in the RCC-M sub-committees, although under a different – but equivalent – form. Such proposals were discussed with the Safety Authority, which did lead simultaneously to :

- Suppressing in the 2000 edition of the RCC-M sentence recognizing in every case the secondary nature of expansion stresses,
- Allowing taking only a fraction of the inertial effects of dynamic loads as the primary loading.

To summarize, those effects which were previously considered 100% secondary may be considered partly secondary and partly primary depending on available justifications, and those effects which were considered 100% primary may be considered partly primary, partly secondary depending on analysis method and damping ratio.

The rule integrated in the 2002 addendum of the RCC-M B 3652 and C 3654 paragraphs for determining the primary portion of dynamic earthquake moments is detailed hereafter.

4 DYNAMIC LOADS STRESS CRITERIA

4.1 Piping Stress Equations

The limitation of primary stresses in pressure piping codes usually includes an equation having the following general form, leading in particular to equation (9) in class 1 piping sub-sections of ASME III and RCC-M codes (hereafter equation 1), or to equation (10) for RCC-M class 2 piping (hereafter equation 2) :

$$B_1 P D/2t + B_2 M/Z_1 \leq k S_m \quad \text{where} \quad Z_1 = 2I/D \qquad (1)$$

$$P D/4t + 0.75\, i\, M/Z_2 \leq k S_h \quad \text{where} \quad Z_2 = \pi r^2 t \qquad (2)$$

Where B_1, B_2 and i are the stress indices applicable respectively to pressure P and to the primary resultant moment M, D the outer diameter, t the thickness, r the mean radius, I the area moment of inertia, Z the inertia modulus, S_m or S_h the material allowable stress, and k a factor depending on loading condition category and component class (for class 1 components, $k = 1.5$ for design conditions and $k = 3$ for faulted conditions).

The question of stress classification did appear when trying to justify piping systems under faulted conditions with consideration of a high level of Safe Shutdown Earthquake moments. Designers quickly discovered that meeting criteria while considering all inertia effects as primary led to potential drawbacks : piping may be too stiff as a result, with adverse effects on supports, active components and mechanical behavior under normal expansion loads.

Three improvements of the codified equations may be considered to solve this issue : multiplying the value of k, dividing the value of M or dividing the value of B_2.

Each of these approaches has its own clear significance, and was considered by codes committees.

- The first idea is to justify a higher value for k, multiplied by 1.5. Such a change gives a new significance to the right term of the equation. It is no more a limitation of primary stresses (for which such a limitation would be too high) but a limitation of primary plus a part of secondary stresses, thus recognizing that the real damage likely to appear under high seismic loads is a progressive deformation under repeated mechanical loads. This approach was proposed by ASME committees (ASME, 1995), but not accepted by the NRC.

- The second approach is to recognize that if the potential damage is progressive deformation, then such damage has to be covered in another equation, equation (9) addressing exclusively excessive deformation and plastic instability damages for which primary stresses must be limited. Equations aiming at preventing progressive deformation are verified under normal and upset conditions. They do not exist in accident conditions for two reasons : progressive deformation under accident conditions is not required in the regulation, and the number of accident cycles likely to lead to progressive deformation is anyway not sufficient to lead to a real risk of rupture under progressive deformation, which explains the regulatory position.
  The conclusion of such an approach is to keep unchanged the right term of the equation, which corresponds to a limitation of primary stresses and was justified as preventing risks of excessive deformation and instability with adequate margins, and to apply a reduction factor on the moment term M to retain only its primary part, which is by definition the only one likely to lead to excessive deformation or instability risk. This approach was retained by the RCC-M committees and is presented below.

- The third approach consists in modifying the stress index, which corresponds to the ratio of the limit moment which can be imposed on a given piping product before apparition of a given damage, and the limit moment which can be imposed on the standard straight pipe on which the product is to be installed (Heng, 1991). This is the approach chosen recently by the ASME committees, where B_2 coefficient was divided by 1.5 for elbows and tees (ASME, 2004), but multiplied by 1.33 for welds in thickness transitions. This proposal was accepted under conditions by the NRC.
  Of course the stress classification may depend on the relative rigidities of the piping products, but one shall understand that putting the whole effect on the stress index is like giving a completely primary character to seismic moments when applied to straight pipes, and a partially primary character when evaluating other piping products, which is unlikely. This may nevertheless be a pragmatic approach, by reducing earthquake effects for products for which the stress limitations are the most difficult to meet, while reducing the allowable moments in welds connected to fittings, thus allowing additional margins for potential defects in welds.

4.2 Modification in 2002 Addendum of RCC-M Code 2000 Edition

The following approach was chosen in the RCC-M 2002 addendum. Before seismic (or other specified reversible dynamic) loads are introduced in B 3652 equation (9) and C 3654 equation (10) for class 1 and 2 components, the primary part of the inertial effect resulting moments shall be quantified.

This primary part shall be taken equal to the elastically computed moment when the damping ratio used in piping analysis already includes an equivalent additional damping coming from the elastic-plastic behavior, which is the case for piping systems when the total damping considered is higher than 10%. A reduction factor may be applied to the computed moment if the used damping ratio do not take into account the piping global plastic behavior and mainly represents the damping coming from support behavior.

This reduction factor can be applied only if a linear response spectrum analysis is used, which is the common calculation method for elastic analyses of piping systems. Other validity conditions are also defined in the code :

- Such analysis shall use widely broadened spectra, at least ±15%, in order to cover the frequency shift induced by global plastic deformation.
- The main piping frequencies shall be located below or in the high amplification zone of the seismic spectra, in no case higher than twice the main frequency of the seismic excitation, otherwise the response is rather quasi-static and the acceleration loading becomes an almost primary loading.

If the damping ratio ξ used in dynamic analysis is taken between 2% and 5%, the primary part M_E of dynamic earthquake M_{Dyn} resultant moment can be determined as follows :

$$M_E = \tau M_{Dyn} \quad \text{with} \quad \tau = \sqrt{\xi / 10} \quad \text{where } \xi \text{ is expressed in \%} \qquad (3)$$

The limitation of this rule to the range from 2% to 5% was retained to be consistent with designer needs, but it could be extended in the future to 10%, as far as this rule leads to a correction factor of 1 for a damping ratio of 10%, thus providing a continuity with the general rule allowing applying a reduction factor below this threshold value.

For a damping ratio from 4% to 5%, the above formula leads to a reduction factor applied to the loads close to the factor on stress indices included in the ASME code.

Some validity conditions included in the ASME code are not explicitly required in the RCC-M code, because implicitly fulfilled in a good design (deadweight stress lower than 0.5 S, pressure concomitant to the seismic loading lower than design pressure).

This reduction factor on seismic loadings can be used in all loading conditions, for all levels of criteria (0, B, C, D). This is consistent with the rules applying margin factors on loadings.

The modification introduced in the RCC-M code is based on the following R&D validation.

5 R&D VALIDATION

5.1 Methodology

First of all, one shall not forget that engineering rules have the objective of preventing damages to the structures. In that context, the analysis of real earthquakes is essential. This experience feedback shows that under real earthquakes, piping systems exhibit a satisfactory behavior even when not specifically calculated for seismic loads. Damages experienced concern mainly excessive building movements (which are considered secondary), interactions with supports or other components (which are not improved when choosing stiffer pipes), or weakened pipes in particular due to corrosion (which have to be dealt with separately anyway). Inertial effects did not lead to failure.

From a mechanical point of view, seismic loads are partly self limiting, which is the definition of secondary stresses : the higher the stress is, the more important the equivalent structural damping is, through energy dissipation, thus limiting the stress level (provided this is not compensated at design stage by choosing stiffer pipes following the application of too stringent code equations).

For the above reasons, research and development works were engaged in France in the beginning of the nineties in collaboration between CEA, EDF and Framatome (now Areva) in order to quantify the available margins and develop simplified methods allowing a balanced design strategy.

The first cooperative action had the objective to evaluate the behavior under mechanical fatigue-ratchet mechanism (Touboul, 1995). Cooperative actions followed in 1993-2000 in order to evaluate alternative criteria, in particular those of the WRC 379 (Antaki, 1993 ; Touboul, 1998), based on seismic test ELSA (Le Breton, 1995 ; Touboul, 1997 & 1998). Research followed in parallel between CEA and French Safety Authority to quantify available margins under seismic loading (Touboul, 1999).

Seismic tests ELSA were simulated with CASTEM 2000 software, using elastic-plastic analyses with a kinematic-hardening material model, which was judged the best suited to simulate available tests (Touboul, 1997bc).

Damage mode under seismic loading is not clearly plastic instability, neither ratcheting. When piping components have been experimentally loaded up to failure, cracks have appeared (corresponding to fatigue) but global plastic deformation was very high (plastic hinges or buckling patterns have been observed). Moreover, the number of cycles applied was 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 pipelines (sine loadings have been used for failure). Then the experiment results lead to the conclusion that the failure mode under a seismic loading is a combination of different damaging modes (plastic instability, buckling, fatigue, progressive striction).

Concerning the harmful effect of ratcheting, quasi-static cyclic tests on components have shown that this effect was not significant (Touboul, 1995). Then, the choice between an instability equation and a fatigue equation was 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). Therefore the form of an instability equation was kept.

Tests did show that the failure by mechanical ratchet was obtained for a loading level close to the one corresponding to instability, leading to justify that a criterion based on primary stress limitation could be appropriate. In addition, in case the loading is not purely primary, to put the margin on a primary stress criterion provides a higher margin on the real damage risk.

Considering nevertheless that the RCC-M criteria could be applied to conditions including real primary stresses, it was not judged appropriate to change the right term of the equation limiting primary stresses. The other two possibilities were to apply a reduction factor to seismic loads or to retain a damping factor providing equivalent margins. As far as damping factors were defined since a long time in regulatory documents, the most appropriate and physical way was to recognize the partly secondary character of dynamic loads and to place a reduction factor on applied moments.

The choice between the two proposals (reduction factor or equivalent damping value) has been solved by the definition of a reduction factor depending on the used damping value.

5.2 Reference Tests Results

In order to validate design criteria, or calculation methods, test results are used. An equation is derived from tests in the following form : $M < M_{all}$, where M is the result of an elastic calculation and M_{all} is the allowable limit. To be applied, the following items are needed : geometry, material data, loading, ultimate behavior. The above equation is written in term of a load limitation, but it may be written in a similar manner in term of a stress or strain limitation.

Application of this equation must be fitted to real loading conditions. Then, to be useful, tests were performed in representative loading conditions : seismic load, eventually repeated a few times.

Two test campaigns have been performed in CEA/Saclay, on pipelines submitted to high seismic loadings : ELSA (Touboul, 1997c) and ASG (Touboul, 1999). These tests have been used for criteria validation. Further validations have been made on more varied or complex piping systems.

The approach is based on the difference between the real behavior (or the computed one) and the codified methods. Criteria are applied on an elastically calculated behavior that is significantly different from the real one : the effect of plasticity is considerable, even with low incursion in the plastic domain.

5.2.1 ELSA Test Device

The ELSA test pipeline is a simplified and scaled mock-up of one part of an auxiliary line (Fig. 1). It is a double Z-bend run, 11 m length of 6”sch40S pipe, made in 316L austenitic stainless steel. The boundary conditions are two rigid end anchors and a vertical stop (connecting rod) located close to the lumped mass (276 kg modeling a valve), welded on the upper straight section. The pipe is pressurized by water (P = 12.5 MPa).

The following geometric and material characteristics were measured :

$D = 168.3$ mm $t = 7.57$ mm $R = 228.6$ mm $S_y = 260$ MPa $S_u = 609$ MPa

The seismic excitation is applied in the X direction (orthogonal to the vertical loop), Z being vertical direction. The piping behavior is mainly controlled by its first mode at 4.4 Hz, inducing a X-displacement of the mass and in-plane bending Y-rotations in the two lowest elbows. The main loaded component is the first elbow close to the fixed point on the short section (in-plane bending).

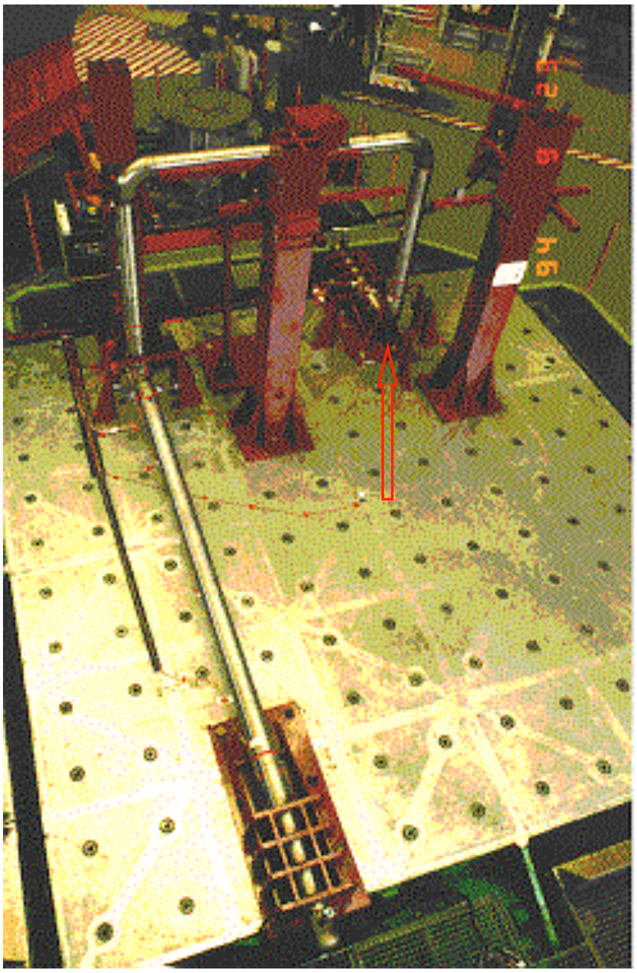

Figure 1**.** ELSA Test Device

5.2.2 ASG Test Device

The ASG (Auxiliary Feed Water) test pipeline is a mock-up of one part of a secondary line (Fig. 2), 9.3 m length of 4”sch80 pipe, made in TU42C carbon steel and filled of water.

The boundary end conditions are : a fixed anchor at one end and a longitudinal guide at the other end (in X transversal and Y vertical directions). A rod restrains the displacement of the lumped mass (120 kg modeling a valve) in the Z longitudinal direction.

The following geometric and material characteristics were measured :

D = 114.3 mm t = 8.56 mm R = 152.4 mm S_y = 350 MPa S_u = 449 MPa

The seismic excitation is applied in the X transversal direction. The main loaded component is the first elbow close to the fixed point (out-of-plane bending).

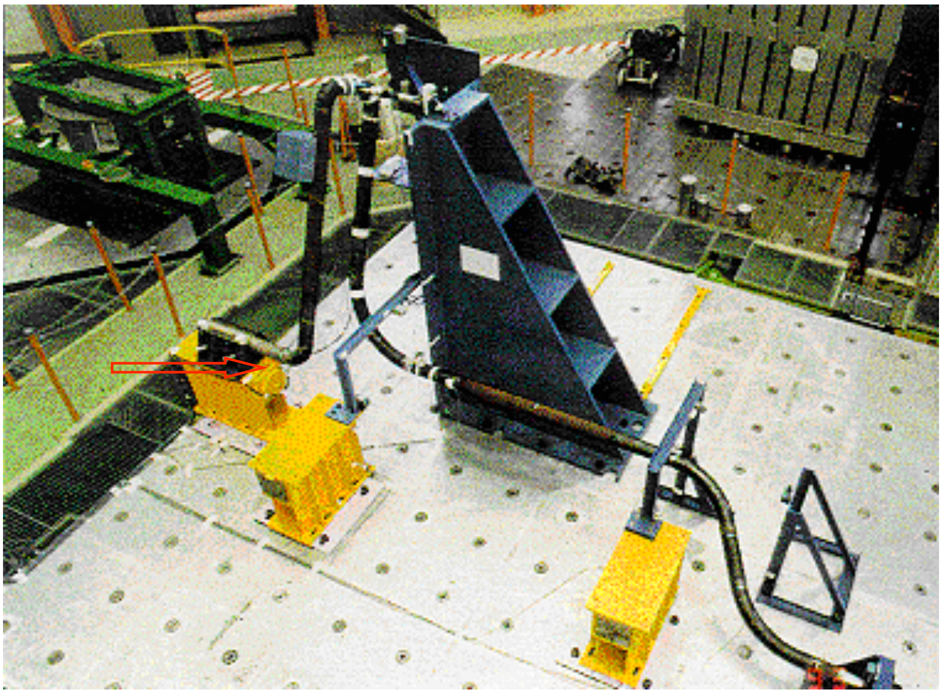

Figure 2. ASG Test Device

5.3 Current Design Code Equations

Current equations in piping design codes for faulted loading conditions are compared and applied to piping test results, for elbows, the most loaded component.

The elastically calculated resultant moments M included in these equations are obtained from a response spectrum calculation with a low specified structural damping value (2% to 5%).

5.3.1 RCC-M Code, B 3656, Class 1 Equation 9, 1993 Edition

- $B_1 P D/2t + B_2 M/Z_1 \leq 3 S_m$ $B_1 = 0.5$ $B_2 = 1.3 h^{-2/3}$ $S_m = \mathrm{Min}(2/3\, S_y ; 1/3\, S_u)$
- The additional equation in Z F 1360 requiring that the moment stress alone shall be limited to 2.5 S_m is not verified.

5.3.2 RCC-M Code, B 3656, Class 1 Equation 9, 2000 Edition, 2002 to 2007 Addenda

- $B_1 P D/2t + B_2 M_E/Z_1 \leq 3 S_m$ $M_E = \tau M$ $\tau = \sqrt{0.1\xi}$
- Without P or with a low pressure stress (lower than 0.5 S_m), an additional equation requires that the moment stress shall be limited to 2.5 S_m. As an alternative procedure, the same equation (9), with the 3 S_m criterion, is usually verified with a minimum pressure stress equal to 0.5 S_m.

5.3.3 ASME Code, NB-3656, Class 1 Equation 9, 1992 Edition

- $B_1 P D/2t + B_2 M/Z_1 \leq 3 S_m$ $B_1 = \mathrm{Min}(-0.1 + 0.4\, h ; 0.5)$
- M can be calculated with a variable 5-2% damping value (code case N411).

5.3.4 ASME Code, NB-3656b, Class 1 Equation 9, 1995 Edition

- $B_1 P D/2t + B_2 M/Z \leq 4.5 S_m$
- M can be calculated with a 5% damping value (appendix N).

5.3.5 ASME Code, NB-3656b, Class 1 Equation 9, 2004 Edition

- $B_1 P D/2t + B_2' M/Z_1 \leq 3 S_m$ $B_2' = B_2 / 1.5$

- ASME Code 1995 and 2004 editions give the same allowable moments as there is no pressure stress ($B_1 = 0$ for ELSA and $P = 0$ for ASG). The same allowable moments are given for class 1 and class 2 components in NB-3656b and NC-3655b.

5.3.6 RCC-M Code, C 3656, Class 2 Equation 10, 1993 Edition

- $P\,D/4\,t + 0.75\,i\ M/Z_2 \leq 2.4\ S_h$ $i = 0.9\ h^{-2/3}$ $S_h = \mathrm{Min}(2/3\ S_y\ ;\ 1/4\ S_u)$

5.3.7 RCC-M Code, C 3656, Class 2 Equation 10, 2002 Addendum

- $P\,D/4\,t + 0.75\,i\ M_E/Z_2 \leq 2.4\ S_h$ $M_E = \tau M$ $\tau = \sqrt{0.1\xi}$
- Without P or with a low pressure stress (lower than $0.5\ S_h$), an additional equation requires that the moment stress shall be limited to $1.9\ S_h$. As an alternative procedure, the same equation 10 (with the $2.4\ S_h$ criterion) is verified with a minimum pressure stress equal to $0.5\ S_h$.

5.4 Code Allowable Moments

From the measured geometric and material characteristics, the following code values are derived in Table 1 : stress index B_2 or i, allowable reference stress S_m or S_h, inertia modulus Z, allowable moments M_{all} for level D criteria.

Table 1 : Code Allowable Moments

Piping Test			ELSA				ASG			
Code	**Edition**	**Class**	**Stress index**	**S_m or S_h (MPa)**	**Z (cm^3)**	**M_{all} (kNm)**	**Stress index**	**S_m or S_h (MPa)**	**Z (cm^3)**	**M_{all} (kNm)**
RCC-M	1993	1	$B_2 = 3.13$	173	147	21.2	$B_2 = 2.16$	150	70	14.5
RCC-M	2002	1	$B_2 = 3.13$	173	147	20.4	$B_2 = 2.16$	150	70	12.1
ASME	1992	1	$B_2 = 3.13$	173	147	24.4	$B_2 = 2.16$	150	70	14.5
ASME	2004	1	$B'_2 = 2.09$	173	147	36.6	$B'_2 = 1.44$	150	70	21.8
RCC-M	1993	2	i = 2.17	152	154	28.9	i = 1.50	112	75	18.1
RCC-M	2002	2	i = 2.17	152	154	27.4	i = 1.50	112	75	14.3

5.5 Current Codes Criteria Margins

In order to calculate design codes margins available in tests, a failure loading is defined, corresponding to a failure acceleration or a failure moment. As failure has not been reached during the considered test campaigns, they are derived from other test results. Cyclic or monotonic failure tests on similar elbows are used, in order to derive a rotation at failure for the most loaded elbow of the pipeline (Touboul, 1997b). It is assumed that the failure loading of the pipeline is the seismic loading leading to the failure of one elbow.

Test initial damping values (elastic behavior) were : 0.14% for ELSA and 1% for ASG. The accelerations A_e corresponding to the end of the elastic behavior were : 0.5 g for ELSA and 1.3 g for ASG. Test applied acceleration loadings A (high level tests) were : 3.5 g for ELSA and 2.8 g for ASG. Calculated failure loadings are respectively found equal to 2.7 and 3.0 times higher than high test loadings : 9.4 g for ELSA and 8.3 g for ASG.

From the M_ξ maximum moments calculated by the linear elastic response spectrum method, using the damping value ξ, current design codes calculated margins are given in Table 2 for these failure loadings. As the RCC-M 2002 code still exhibits quite high margins (from 3 to 5), the new criteria are justified. The

ASME 2004 (or 1995) code is less severe than the RCC-M 2002 code for class 1 pipes, but the margins are still larger than 2.

Table 2 : Current Margins in Design Codes

Piping test			**ELSA**			**ASG**		
Code	**Edition**	**Class**	**$M_{2\%}/M_{all}$**	**$M_{5\%}/M_{all}$**	**$M_{10\%}/M_{all}$**	**$M_{2\%}/M_{all}$**	**$M_{5\%}/M_{all}$**	**$M_{10\%}/M_{all}$**
RCC-M	1993	1	10.2	6.0	4.8	6.5	3.8	2.8
RCC-M	2002	1	4.7	**4.4**	5.0	3.5	**3.2**	3.4
ASME	1992	1	8.9	5.2	4.2	6.5	3.8	2.8
ASME	2004	1	5.9	**3.5**	2.8	4.3	**2.5**	1.9
RCC-M	1993	2	7.5	4.4	3.5	5.2	3.1	2.3
RCC-M	2002	2	3.5	**3.3**	3.7	3.0	**2.7**	2.9

5.6 Reduction factors

Reduction factors (or behavior coefficients) are obtained in Table 3 for the considered tests by comparing the maximum elastic moment M_ξ to the maximum moment M_{NL} calculated by the Non Linear elastic-plastic time-history method.

A damping value between 2% and 5% is usually considered for industrial pipelines. For these values, the reduction factors depend on the plasticity level : at the failure level, they range from 2 to 5.

Table 3 : Reduction Factors and Equivalent Damping

Test	**ELSA**				**ASG**			
Load	**A / A_e**	**$M_{2\%}/M_{NL}$**	**$M_{5\%}/M_{NL}$**	**$M_{10\%}/M_{NL}$**	**A / A_e**	**$M_{2\%}/M_{NL}$**	**$M_{5\%}/M_{NL}$**	**$M_{10\%}/M_{NL}$**
Test	7.2	2.6	1.5	-	2.1	1.1	0.7	-
Failure	19.4	5.1	3.0	2.4	6.3	3.2	1.9	1.4

5.7 Equivalent Damping Approach

It has been shown (Touboul, 1999) that it is possible to have a good representation of the non linear behavior of ELSA and ASG pipelines by using an equivalent linear calculation (CAUGHEY method). Nevertheless, equivalent damping, at the high test level, was very different from one pipeline to another, even though plasticity level was similar (strain up to 1%) : 5.5% for ELSA and 1.7% for ASG. A more refined analysis has shown that the achieved ductility (ratio between the maximum and elastic values of a global displacement or rotation that controls the pipe behavior) was quite different : 8.3 for ELSA and 5.5 for ASG. Analysis has concluded that the equivalent damping is quite independent of the initial damping, but it is strongly dependent on the seismic level and the material law.

The use of a 10% equivalent damping value leads to maximum moments still lower than the non linear elastic-plastic calculation (Table 3).

6 SYNTHESIS

Available R&D results validate the new RCC-M 2002 criteria for seismic design of piping, where elastic moment limitation was only slightly reduced, as in the ASME code 1995/2004 editions.

The application of the new rule to experimental tests did show that it provides margins larger than 2 under level D criteria, instead of 1.1 as required by the 1974 French regulation. The industrial practice as codified in the 2002 addendum remains consequently severe.

Pressure and elbow angle effects can still be taken into account in the stress index B_2

The new criteria have also been validated by non linear calculations on more industrial cases. Some consequences of the criteria modification have also been studied (Baratte, 2000) : design modification, in particular the number of supports, global displacements, loads on supports…

To take into account the plasticity effect, not only on moment loading introduced in design criteria, but also on actual piping loads, for crack assessment, or on global displacements, for functional verification, enhanced and simplified calculation methods are still to be developed.

7 CONCLUSION

Criteria in the RCC-M Code have the objective of preventing different types de damages, with appropriate safety margins. Such approach is not particular to the RCC-M. What is more particular is the explicit link made in the code between damages and stress classification.

In this context, stresses resulting from dynamic loads have only partly a primary character, and RCC-M 2002 addendum has introduced a formula defining the primary portion of dynamic earthquake loads.

It is expected that further code evolution will include, following developments, more detailed guidance for stress classification of stresses resulting from applied controlled displacements, for seismic loadings or restraint of thermal expansion (Pétesch, 2007), as permitted by recent regulations.

In parallel, additional limitations may appear appropriate in view of facilitating the justification of potential defects, but this is another matter, which can be dealt with separately from seismic design.

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Symbols

D	Pipe outer diameter	m
t	Pipe thickness	m
r	Pipe mean radius	m
R	Elbow bend radius	m
h	Elbow characteristic parameter : $h = t R / r^2$	-
Z	Modulus of inertia	m^{-3}
P	Internal Pressure	MPa
ξ	Damping value	-
S_y	Conventional yield stress	MPa
S_u	Ultimate tensile stress	MPa
S_m	Code allowable stress	MPa

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