



Piping seismic design criteria : tests simulations

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ABSTRACT

CEA, EDF and FRAMATOME have launched a large program, with experimental and computational aspects, in order to improve seismic design criteria for pipings. In this framework, the computation tools used for seismic evaluation of piping systems have been qualified. Calculations using a global beam formulation piping element give satisfactory results when the circumferential stress due to pressure is introduced in the plasticity criterion and when a kinematic hardening model is used for plasticity.

NOMENCLATURE

| | | | |
|---|--------------------------|--------|--------------------------------|
| D | external diameter | h | elbow characteristic parameter |
| e | thickness | | $h = eR/r^2$ |
| r | mean radius of the pipe | P | Pressure |
| R | mean radius of curvature | k | Flexibility |
| | | C1, C2 | stress indices |

INTRODUCTION

It is well-known, from industrial or laboratory experiences, that present piping design for seismic event is unduly conservative. This fact results mainly from an exceedingly prudent elastic analysis method and an improper classification of resulting stresses.

CEA, EDF and FRAMATOME have launched a large program in order to improve seismic design criteria for piping, with experimental and computational aspects. This program intends to evaluate the margin included in present design rules. The final target is to propose enhanced seismic design rules including analysis methods and criteria.

METHOD

A piping system representative of a PWR geometry, has been tested under seismic loading. The tests have been performed in the TAMARIS laboratory in CEA/Saclay, on the 2D shaking table AZALEE.

In order to complete the information resulting from the seismic piping tests, and especially, in order to obtain the failure mode, piping components similar to the piping system ones, have been tested in cyclic quasi-static conditions, in the RDMS laboratory in CEA/Saclay.

Meanwhile, the computation tools have been correlated to the tests results, obtained from the instrumentation. In order to ascertain the more appropriate rule for seismic evaluation of piping, the ability of finite element calculations to adequately simulate such seismic event, with an accurate plastic model, has been verified.

In order to estimate the seismic event which may lead to a visible fatigue damage, the qualified computational tools have been used in amplified loading conditions, and the results correlated to statically determined failure criteria. These calculations have been used to define the characteristics of a final cyclic quasi-static test on one elbow, that has confirmed this evaluation.

Simplified methods, based on static or dynamic rationale, have been qualified; some developments have been elaborated in order to complete these procedures or to generate more accurate results.

More details on tests results and criteria applications are presented in two other papers in this session [1] [2].

TEST DESCRIPTION

Geometry and material

The nominal geometrical characteristics are :

$D = 168.3 \text{ mm}$ $e = 7.11 \text{ mm}$ $R = 228.6 \text{ mm}$

elbow characteristic parameter : $h = 0.25$

flexibility : $k = 1.65/h = 6.6$

stress indices : $C_1 = \frac{2R - r}{2(R - r)} = 1.27$, $C_2 = 1.95 h^{-2/3} = 4.91$

Material is 316L stainless steel.

Tests on the piping system

The tested austenitic stainless steel piping system appears as a spatial double Z-bend (fig. 1). The limit conditions are two rigid anchors, one at each extremity of the pipe. A mass representative of a valve is welded on the upper straight part. IN order to be realistic, a vertical support (connecting rod) is placed near this mass.

The experimental campaign results in 27 tests. During the whole campaign, 77 sensors have been located on the pipe in order to monitor displacements, accelerations, moments and local strains. Modal tests, pressurization tests (about 12.5 MPa), static and linear seismic tests have been performed, in order to validate the piping model. The non-linear seismic test has been performed at the maximum capacity of the shaking table, leading to a signal with a

maximum acceleration equal to 3.5 g (fig. 2). The reference seismic loading is defined by a typical envelop floor response spectrum of the internal structures of a reactor building. The computed accelerogram is filtered, amplified and uniformly applied by the table, in the X direction [3].

As the piping system did not exhibit visual damage at the end of this test, two complementary non-linear seismic tests have been performed at the same level but in less supported conditions: without the connecting rod.

Components tests

The accompanying quasi-static tests consist of the application of a cyclic and symmetrical displacement in the in-plane bending direction to a 90° elbow with two attached tangents, of two diameters length. Constant pressure is applied (11.7 MPa), corresponding to a circumferential stress equal to half of the actual yield stress. The first campaign has included nine tests: three cyclic displacement levels imposed on each of three elbows.

The second campaign has been defined to evaluate fatigue damage criteria. For that tests, the value of the applied displacement results from the time-history calculation for amplified loading conditions (9.45 g). Under this loading, fatigue usage factor has been calculated: 0.16. The equivalent displacement history corresponds to the application of increasing cycles: 16 cycles of a low displacement range, 6 cycles of a medium displacement range, 6 cycles of a large displacement range. One elbow has been submitted to repeated sequences of this loading, and fatigue failure, as predicted, appears at the end of the sixth sequence: $6 \times 0.16 \approx 1$.

TEST RESULTS

Static tests

Quasi-static tests have been of great interest for the understanding of the fatigue ratchetting behavior of piping components in high cyclic conditions [4].

One of the test result, is the global « cyclic curve », that gives the moment-rotation curve for a given number of cycles. This curve can be used as a global material behaviour curve in a finite element computation

Seismic tests

From the results of the linear seismic test, an elastic damping value of 0.14% has been calculated.

Final seismic tests lead to plastification of the most loaded elbows (Elbow 1 and Elbow 4). Global residual swelling of the medium section of the elbows is visible, but visual inspection of both outer and inner skin does not reveal any damage (surface alteration, cracks).

Strain gages have been placed on the elbows crowns. The plastification is too low ($\approx 1\%$) to significantly damage the component, but sufficiently high to observe the effect of the plasticity on the resulting moments. Strain gages have been judiciously placed (on straight parts, which behave elastically) in order to obtain a measure of the moments. When high level

accelerogram (3.5g) is applied, resulting moment is five times and displacements three times less than those extrapolated from the linear test.

Analysis of experimentally recorded stress-strain loops indicates that plasticity hardening is neither purely isotropic nor dominantly kinematic.

MODELISATION

Linear and non linear calculations have been performed using the computational tool CASTEM 2000, developed by CEA.

Finite element computations have been developed in order to evaluate the ability of 1D models (global formulation piping beam element) to reproduce the experimentally observed behavior. Particular attention has been brought to the modelisation of the geometrical and mechanical characteristics, as well as the applicability of different plasticity models.

1D piping element considers a unique value for the thickness. However, circumferential variations of thickness is important, particularly in an elbow section. Nevertheless, 1D piping element gives satisfactory results using mean geometrical characteristics.

Concerning pressure effect, the plasticity criterion must include not only the longitudinal stress $\frac{PD}{4e}$ (as it is usually done) but also the circumferential stress. In order to evaluate this effect, an additional stress has been introduced in the plasticity criterion in CASTEM 2000 : $\lambda \frac{PD}{2e}$, λ being adjusted in order to take into account pressure stress intensification in elbows.

The exact value of the pressure hoop stress in an elbow cross section is :

$$\sigma_h = \frac{PD}{2e(\theta)} \frac{2R + r \sin\theta}{2(R + r \sin\theta)}, \text{ with } \theta \text{ azimuthal angle, varying from } -\pi/2 \text{ to } \pi/2.$$

So, λ value depends on the thickness variation in the section. λ should be in the range from 1 to $C_1 = \frac{2R - r}{2(R - r)}$.

For the tested elbow, λ has been adjusted on the test results : $\lambda = 1$.

Comparisons have been made between 1D element calculation and shell element calculation ; by comparison to one component test result (linear part and monotonic non linear part of the test). Elbow analysis using shell elements does not give satisfactory results as the shell coefficient (used for the plasticity criterion) must be fitted in each case. Indeed, its value depends on the amount of membrane and bending stress in the most loaded region.

When calculations are conducted in the plastic domain, no hardening model is really valid as hardening is neither purely isotropic nor purely kinematic.

Isotropic model describes well the cyclic hardening during tests with constant or increasing load ranges: It has been successfully applied to the quasi-static tests. The model produces a rapid shift of the results when applied to a seismic input (fig. 3) : as soon as a low cycle follows a high cycle, displacements are overestimated by the calculation.

Kinematic hardening gives satisfactory estimation of the seismic test results as soon as sufficient material hardening is introduced in the material law (fig. 4). Indeed, using the monotonic stress-strain curve is not correct, as, for kinematic hardening, the actual yield

stress is not modified by cycling. The material law introduced for the calculation has to represent the material hardening after some cycles.

When available (cf. RCC-MR [5]), the code prescribed « cyclic curve » is valid, even though the « cyclic curve » corresponds to a stabilization state under the given strain range. Stabilization often occurs after several tens or several hundreds of cycles, and for seismic excitation the number of concerned cycles is close to ten.

So, it has been shown that present computational tools (CASTEM 2000), with an appropriate procedure for taking into account geometry and material law, allow for a satisfactory simulation of the seismic behaviour of a piping system.

SIMPLIFIED ELASTO-PLASTIC DYNAMIC METHODS

Present design rules are based on the results of elastic spectrum analyses. Results from such analyses are maximum moments. Other results as time-history variation, displacements, support loads, may be useful for fatigue analyses, support design, functional capability,...Moreover, as seismic load is neither force nor displacement controlled, elastic analyses give unrealistic results both in loads and in displacements.

Non linear time-history analysis, as described above, leads to accurate estimation of the seismic response but is time consuming. Simplified elasto-plastic dynamic analyses have been carried out in order to propose alternative methods to the spectral analysis, which are less time consuming than the complete time-history non-linear analysis.

Equivalent linear calculations have been proposed, based on a modification of the structural rigidity as well as the damping value, in order to account for plasticity.

The first application has been made on the non-linear dynamic test with the connecting rod, in which the response is mainly in its fundamental mode. In that case, it has been possible to build a model of the structure, based on a 1 DOF non-linear oscillator, calibrated on the displacement of the upper mass in the X direction (DXVAN). An equivalent linear oscillator has then been determined using Caughey method [5], which minimizes the differences between the non-linear and the equivalent linear responses.

An equivalent linear calculation for the system is then derived from this oscillator. Two approaches have been studied:

- Uniform equivalence : the total rigidity of the structure is modified (by Young's modulus adjustment) in order to obtain a first natural frequency equal to the equivalent one. Applied damping value, for all the frequencies is the one derived from the Caughey equivalence.
- Selective equivalence : the modifications only concern the first mode.

The second approach gives more accurate results (fig 5). In all cases, linear equivalent calculations result in accurate values in term of displacements (both maximum values and time-history), for the ones that are important in a design point of view (fig. 6). On this figure, it can be seen that the time-history response is a bit different between non-linear and linear equivalent calculations, although maximum values are similar. Nevertheless, when considering fatigue damage, the number and the amplitude of major cycles (that are significant for fatigue) are matching.

As equivalence is based on displacements, the results are less accurate on global stresses (forces, moments) than on rotations. Maximum moment is 50% higher than the one obtained

by a non-linear time-history analysis, but much lower than the one derived from a linear calculation.

A tentative application of the simplified methods to the test without the connecting rod has been made. In this case, two natural frequencies contribute to the seismic response. Two 1 DOF non-linear oscillators have been defined, with no coupling between modes. The equivalent linear calculations give good results. However, it is not prudent to generalize such results without a better estimation of possible coupling of modes in plasticity.

CONCLUSION

Above seismic tests allow for a better understanding of piping behavior under seismic conditions. An accurate and abundant instrumentation provide data to qualify computational tools, both advanced elasto-plastic dynamic methods and simplified methods.

A 1D piping beam element gives satisfactory results with mean geometrical characteristics when the pressure circumferential stress is introduced in the plasticity criterion. Kinematic hardening model gives satisfactory estimation of the seismic test results as soon as sufficient material hardening is introduced in the material law.

Simplified elasto-plastic dynamic analyses, based on Caughey linearization method, have been successfully tested on a piping system which responds primarily in its fundamental mode. As this method is established on an equivalence for displacements, it should be connected to criteria based on the limitation of the rotations. More generally, as 1D calculations allow for the calculation of only global values, they should be connected to global collapse criteria, in term of applied moment or applied curvature. Other simplified methods, as those based on the introduction of plastic hinges are attractive and will be matched with the available tests results, in the future.

Applicability of such simplified methods in the case of cracked pipes should be interesting.

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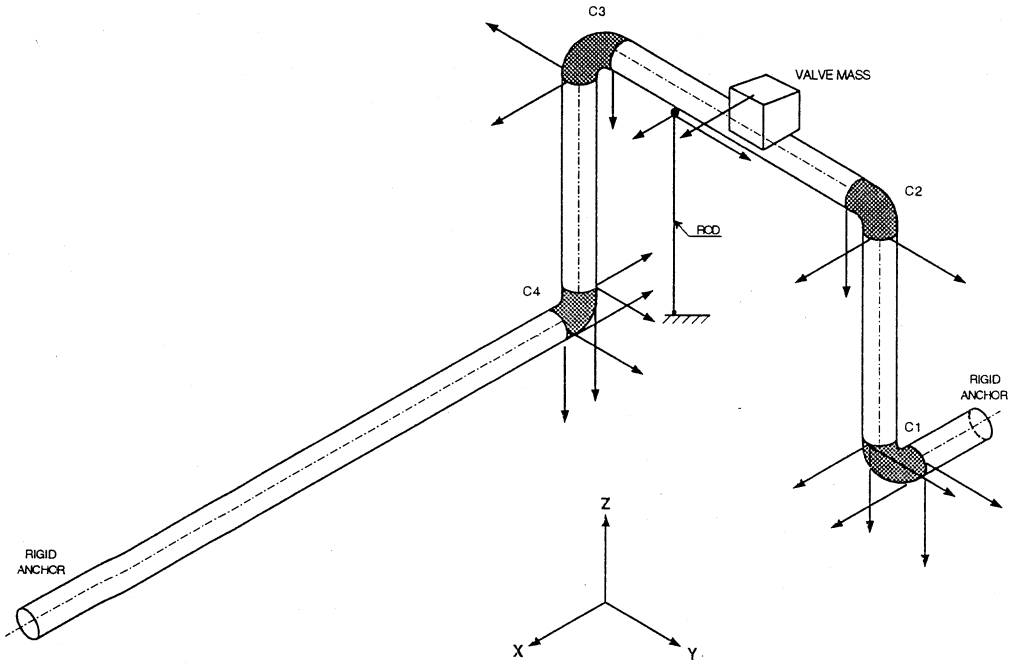


Figure 1: Tested pipework (with displacement monitors)

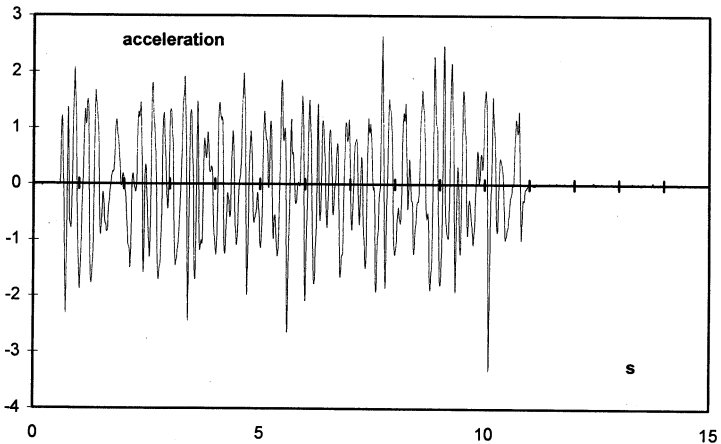


Figure 2: Shaking-table recorded accelerogram

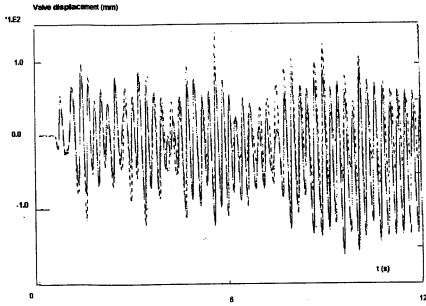


Figure 3 : Pipework seismic test (---) and non-linear time history analysis (—) isotropic hardening

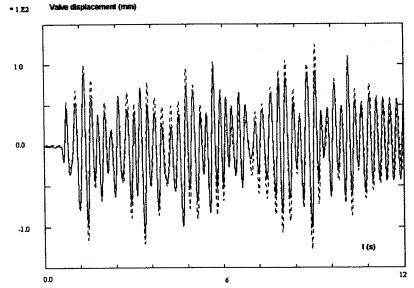


Figure 4 : Pipework seismic test (---) and non-linear time history analysis (—) Kinematic hardening

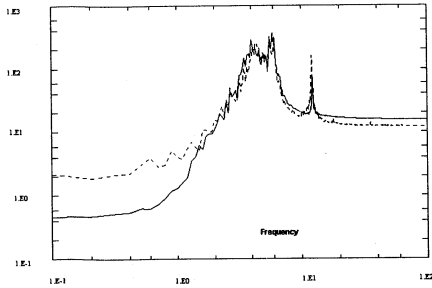


Figure 5 : linear equivalent (selective) (—) and non-linear time history (---) analyses.

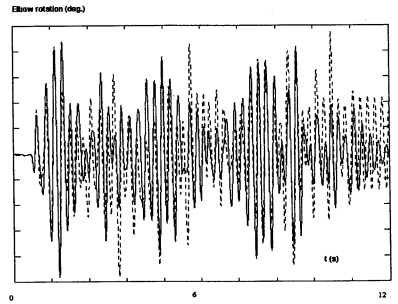


Figure 6 : linear equivalent selective (—) and non-linear time history (---) analyses