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Interpretation of the IPIRG2 seismic tests

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ABSTRACT

As part of the second International Piping Integrity Research Group (IPIRG2) program, five cracked-pipe system experiments were conducted under seismic loading. One of the main objectives of these experiments was to generate experimental data to assess non linear analysis methodologies for characterizing the fracture behaviour of circumferentially surface and throughwall cracked pipe in a representative piping system subjected to combined inertial and displacement controlled stresses.

NOMENCLATURE

D	Outside diameter	σ_b	Bending stress
t	Thickness	σ_t	Pressure induced axial tensile stress
d	Crack depth	σ_y	Yield stress
2c	Crack length	σ_u	Ultimate stress
R_i	Inside pipe radius	σ_f	Flow stress, $\sigma_f = (\sigma_y+\sigma_u) / 2$
R_m	Mean pipe radius	J_i	J at crack initiation
R_o	Outside pipe radius	S_{ad}	Available RCCM code stress in level D
I	Area moment of inertia	P	Pressure

1. INTRODUCTION

Seismic tests were performed by BATTELLE on a pipe loop containing a circumferential crack; it was loaded by pressure and temperature at PWR conditions and by a displacement time-history [1].

In parallel to this IPIRG2 program, CEA has conducted different analyses to predict and evaluate the system response and the fracture behaviour of the pipe in which the crack is located in a straight specimen. This work was performed in the framework of co-operation between CEA, EDF and FRAMATOME.

Elastic and elasto-plastic calculations were performed with uncracked and cracked models for the pipe loop [2]. The analyses presented in this paper include comparisons of :

- maximum linear stresses (σ) for uncracked pipe to yield stress (σ_y), to RCCM code criteria and to experimental total stresses.
- experimental total stresses, corresponding to moment at crack initiation and maximum moment, to predicted total stresses by Net Section Collapse (NSC), Dimensionless Plastic-Zone Parameter (DPZP) and JSIN [3] [4] methods.
- tests time-histories response to linear and non linear calculation results.

2. PIPE LOOP CHARACTERISTICS

The pipe loop is shown in figure 1; its main features are :

- Four current straight parts in carbon steel ASTM A710, grade A, class 3. The nominal dimensions are : D = 406 mm, t = 26.2 mm. The Young's Modulus, E_D, is equal to 195.39 GPa.
- Five long elbows in carbon steel WPHY-65. The nominal dimensions are : D = 406 mm, t = 26.2 mm (for elbows 1, 2, 3 and 5) or t = 40.4 mm (for elbow 4). The Young's Modulus, E_C, is equal to 193.05 GPa.
- Straight test specimen in stainless or carbon steel with circumferential surface or throughwall crack located in base metal or weld. The length of the test specimen is equal to 305 mm.

A 1950 kg mass, which simulated a valve is located in leg 2 of the pipe loop. The mass of the double ended guillotine break restraint system incorporated into the specimen is equal to 320 kg.

The detailed real average thicknesses of current straight parts and elbows as the boundary conditions for the pipe loop are described in reference [2].

3. TEST DESCRIPTION

The test conditions for each seismic experiment were pressurized water reactor (PWR) conditions : i.e temperature equal to 288°C and pressure equal to 15.5 MPa.

The displacement time-history applied by the actuator to the pipe system was either a simulated seismic excitation or a sinusoïdal excitation.

In the simulated seismic experiments, two levels of excitation were applied to the pipe. For the low level named "N + SSE", it was expected that the excitation would not cause the crack to extend. The high level named "TEST" was an increased amplitude of the "N +SSE" load history, designed to achieve surface-crack penetration during the load history. If the surface-crack penetration was not obtained during the level "TEST", the same excitation named "DECISION TREE" was applied after the level "TEST".

During the experiments, the carbon steel materials of straight pipes and elbows remained elastic as designed. The matrix of seismic experiments with straight test specimen is shown in table 1.

Table 1 : Matrix of seismic experiments with straight test specimen

Test	Forcing Function	Material	Crack Type
1-1	Seismic	SSBM	Long surface crack
1-2	Seismic	CSBM	Long surface crack
1-5	Sinusoïdal	SSW	Short surface crack
1-7	Seismic	CSBM	Throughwall crack

SSBM = Stainless Steel Base Metal CSBM = Carbon Steel Base Metal
SSW = Stainless Steel Weld

4. TEST RESULTS

The main test results measured by BATTELLE during the seismic experiments are given hereafter in order to compare the calculated values to the test results.

Before the seismic tests an uncracked pipe experiment without "restraint" was conducted to determine the system damping and the first natural frequencies. The damping was estimated to be approximatively 0.5% and the first frequency was measured equal to 4.5 Hz.

During the high level seismic experiments, the crack penetration was obtained for all the tests with an initial surface crack.

A double-ended-guillotine-break (DEGB) occured at the maximal moment in the carbon steel experiment 1-2.

For each test, the table 2 presents the experimental results obtained for crack initiation and maximum moments. The main geometrical characteristics of the test specimen and crack are also given in table 2.

Table 2 : Experimental results for crack initiation and maximum moments.

Test	D mm	t mm	Max d/t	$2c/\pi D^{(a)}$	Moments (KN.m) initiation	maximum
1-1	417.1	25.53	0.628	0.383	594	598
1-2	405.1	24.8	0.719	0.412	[350-476]	476
1-5	415.3	25.8(b)	0.495(c)	0.228	[481-557]	776
1-7	399.8	26.4	1	0.12	611	852(d)

(a) Based on the equivalent crack length and inside pipe diameter
(b) Without weld crown (c) d with counterbore and t without weld crown (see figure 2)
(d) Decision Tree (not TEST)

5. ANALYSES DESCRIPTION

5.1. Linear and non linear calculations.

The calculations are made with a global model including a throughwall crack pipe finite element [5]. For all the calculations, the outside diameter of the current straight parts and elbows was taken equal to 406 mm and the real average thicknesses are used. With these geometrical features and Young's Modulus E_D and E_C, the first frequency calculated for the uncracked pipe without "restraint" is equal to 4.72 Hz. This first frequency is 5% higher than experimental result. For the experiment 1-1, the first comparisons of the response spectrum and time evolutions of the measured and calculated moment at the crack location has shown the first mode predominance and discrepancies due to the first frequency shift between calculation and test (see référence [2]). In order to improve these test 1-1 results, the Young's Modulus was modified to adjust the first frequency. These modified values given by

$E_C^* = E_D^* \times \frac{E_C}{E_D}$ so, $E_D^* = 172.75$ GPa and $E_C^* = 170.68$ GPa are taken for all calculations.

For the surface crack experiments, an equivalent throughwall crack to the surface crack is defined such that its corresponding limit load is identical to the limit moment of the surface crack given by Zahoor formulae [6]. For the dynamic calculations, the damping is taken equal to 0.5% and the crack propagation is not taken into account.

All the calculations were performed using the CEA CASTEM 2000 FEM code and a dynamic time-history implicit algorithm.

5.2. Elastic stresses comparisons to yield stress, RCCM code criteria and total experimental stresses.

The maximum linear stresses σ are calculated for the uncracked pipe under pressure, thermal expansion and "TEST" seismic loading for each experiment. The linear stresses σ are defined by :

$$\sigma = S_P + S_T + S_I + S_D$$

with

S_P : Membrane pressure stress ($S_P = \frac{PD}{4t}$)

S_T : Thermal stress

S_I : Inertial seismic stress

S_D : Differential displacement seismic stress or Seismic Anchor Motion stress.

S_T, S_I, and S_D are bending stresses calculated from the corresponding moment named M by $\frac{MR_o}{I}$ with $I = \frac{\pi}{4}\left(R_o^4 - R_i^4\right)$

5.3. Comparisons of fracture prediction analyses to experimental results.

The comparisons are made on the total experimental stresses named σ_{exp} and the total predicted stresses named σ_{pred}. These total stresses are defined by :

$$\sigma_{exp} = \sigma_t + \sigma_{b,exp}$$
$$\sigma_{pred} = \sigma_t + \sigma_{b,pred}$$

with

σ_t : Pressure axial stress ($\sigma_t = \frac{PR_i^2}{2R_m t}$)

$\sigma_{b,exp}$: Experimental bending stress ($\sigma_{b,exp} = \frac{M_{exp} R_o}{I}$)

$\sigma_{b,pred}$: Predicted bending stress ($\sigma_{b,pred} = \frac{M_{pred} R_o}{I}$)

The predictions have been performed using :

- The geometrical characteristics given in table 2 except for the d/t value of the experiment 1-5. For this experiment where the crack is located in a weld, the d/t parameter is defined by the "specified" crack depth and wall thickness of pipe and is equal to d_2/t_2 (see figure 2).
- The quasi-static material characteristics given in table 3 for the NSC, DPZP and JSIN methods and with the C statistical parameter used in the DPZP method.

Table 3 : Quasi-static material characteristics and C parameter for DPZP method

Test	σ_y MPa	σ_u MPa	σ_f MPa	J_i KJ/m^2	E GPa	C
1-1	180	461	320.5	854	140.5	34
1-2	234	601	417.5	149	217	34
1-5	180(a)	461(a)	320.5(a)	55(b)	140.5(a)	34
1-7	222.7	514.4	368.55	69.3	161.2	18.3

(a) Base metal
(b) Weld metal

6. TESTS AND ANALYSES COMPARISONS

6.1. Elastic stresses comparisons to yield stress, RCCM code criteria and total experimental stresses.

For each experiment the ratios of the maximum linear stress σ and of the RCCM code available stress in level D, S_{ad} to the yield stress are given in table 4. In this table the elastic stress ratios calculated for the total elastic stresses σ and for the total elastic stresses minus Seismic Anchor Motion (SAM) stresses are compared with the total experimental stresses.

Table 4 : Comparisons of maximum linear stress and RCCM code available stress to the yield strength. Elastic stress ratios with and without SAM stresses (S_D).

Test	σ/σ_y	S_{ad}/σ_y	σ/σ_{exp}	$(\sigma - S_D)/\sigma_{exp}$
1-1	2.28	2.7	1.59	1.12
1-2	1.96	1.6	1.98	1.4
1-5	2.34	2.7	1.32	0.99
1-7	2.47	1.6	1.52	1.07

For the both carbon steel experiments (1-2 and 1-7) the RCCM code available stress is exceeded respectively by 22% and 54%. The linear elastic stress ratios or "margins" divided by total experimental stresses are small as they are lower than 2. These "margins" decrease considerably if the Seismic Anchor Motion stresses are not taken into account in the calculated elastic stresses.

6.2. Comparisons of fracture prediction analyses to experimental results.

The ratios of the maximum total experimental stresses to the maximum total predicted stresses for NSC, DPZP and JSIN prediction methods are given in table 5. For the JSIN method the predictions are made also for crack initiation. A prediction method is said "conservative" if the ratio is greater than 1.

Table 5 : Comparisons of fracture predictions analyses to experimental results.

Experiment / Prediction				
Test	NSC (σ_f)	DPZP	JSIN initiation	JSIN maximum
1-1	0.94	0.94	1.2	1.15
1-2	0.77	0.78	1.16	1.24
1-5	0.82	0.96	1.12	1.3
1-7	0.87	1.17	1.78	1.34

The table 5 shows that in comparison to experimental results :

- The NSC method with σ_f is non "conservative" of 6% to 23%.
- The DPZP method is more "conservative" than the NSC method for the low toughness materials.
- The JSIN method gives "conservative" results for the initiation and maximum results.

6.3. Experimental, linear and non linear calculated results.

The comparisons of the experimental and non linear calculated time evolutions have been made for the moment at crack location, the main displacements of the pipe and the rotation of specimen. In addition some frequency domain analyses of these results have been performed. The non linear calculations for cracked pipe loop give generally good correlations with experimental results for the moment at crack location and displacements of the pipe. An example of this correlation is shown on the figure 3 by the comparison of the measured and calculated moment time evolutions for the experiment 1-7. The correlations are less good for the rotation of specimen. The experimental and calculated maximum moments at crack location are given in table 6.

Table 6 : Experimental and calculated results.

Maximum Moment at crack location (KN.m)				
Test	Experiment	Linear uncracked	Non linear uncracked	Non linear cracked
1-1	598	816	769 690$^{(*)}$	553 514$^{(*)}$
1-2	476	913	773 536$^{(*)}$	633 435$^{(*)}$
1-5	776	1032	881 738$^{(*)}$	805 701$^{(*)}$
1-7$^{(**)}$	801	1058	935	860

(*) : until surface crack penetration
(**) : level TEST (not DECISION TREE)

7. CONCLUSIONS

The main conclusions obtained for the analyses of the IPIRG2 seismic experiments with crack in straight specimens are :

- The NSC method with σ_f is non "conservative" of 6% to 23% in comparison with experimental results
- The elastic stress ratios or "margins" on total stresses are lower than 2. These "margins" decrease considerably if the Seismic Anchor Motion stresses are not taken into account in the calculated elastic stresses.
- The non linear calculations for uncracked pipe loop reduce the moment at crack location by less than 15% due to the plasticity but overestimate the experimental results.
- The non linear calculations for cracked pipe loop give good correlations with experimental results. The calculated non linear moment at crack location is decreased for the cracked pipe in comparison to the uncracked pipe by 18% to 28% for the large surface cracks and by less than 9% for the two small cracks (small surface and throughwall cracks).

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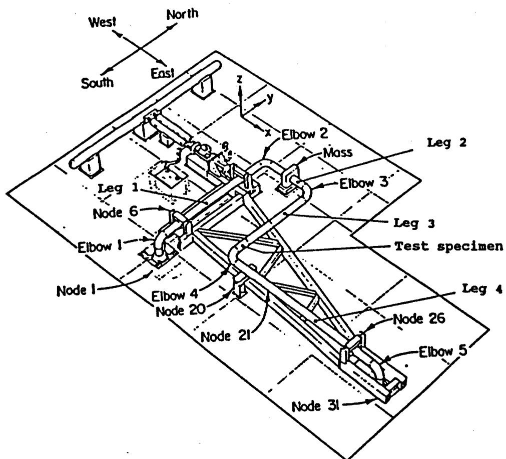

FIG. 1 - ARTIST'S CONCEPTION OF THE TEST CONFIGURATION

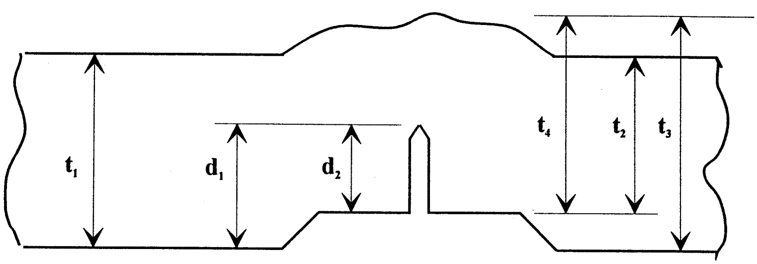

Figure 2 : Schematic of the weld geometry used for the 1-5 experiment

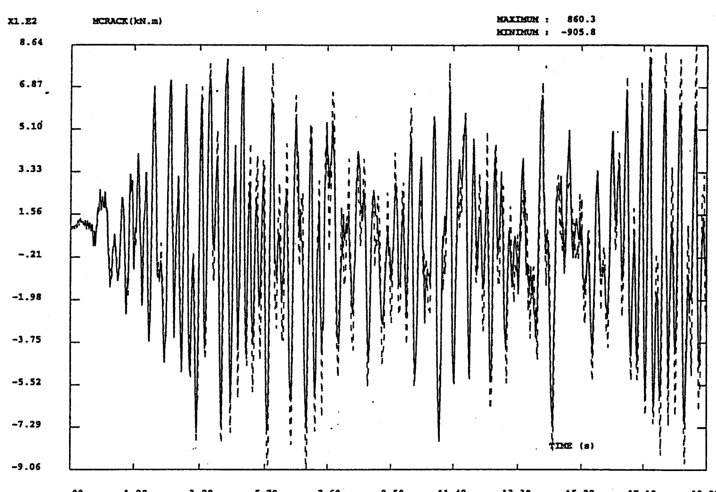

Figure 3 : Moment at crack location EXP 1-7 (Level TEST)