Asociación Argentina
de Mecánica Computacional

Mecánica Computacional Vol XXXV, págs. 1793-1808 (artículo completo)
Martín I. Idiart, Ana E. Scarabino y Mario A. Storti (Eds.)
La Plata, 7-10 Noviembre 2017

# DYNAMIC FINITE ELEMENT ANALYSES OF THE PRIMARY SYSTEM OF THE ATUCHA II NPP UNDER BEYOND DESIGN BASIS EARTHQUAKES

**Agustín Pecorari[a], José Risso[a], Alberto Cardona[a] and Adriana Politi[b]**

[a]*CIMEC, Predio CONICET "Dr A. Cassano", Col Ruta Nac 168 s/n,3000 Santa Fe, Argentina,http://www.cimec.santafe-conicet.gov.ar*

[b]*Autoridad Regulatoria Nuclear, Av. del Libertador 8250, 1429 Ciudad Autónoma de Buenos Aires, Argentina, http://www.arn.gob.ar*

**Keywords:** Dynamic Analyses, FEM, DEGB, BDBE.

**Abstract.** Atucha II Nuclear Power Plant (CNA II) is a pressurized heavy water reactor (PHWR) that started its commercial operation in May 2016. Construction began during 1980, and the design licensing base, agreed between the Responsible Entity (CNEA at that time) and the designer (KWU/Siemens), did not consider the double-ended guillotine break (DEGB) event in the primary pipe loop as a requirement of the emergency core cooling systems and reactor shutdown. Instead, a 10% loss of coolant of the cross section of the primary system, which would be equivalent to a surgeline DEGB (line connecting the primary system with the pressurizer), was considered. The Autoridad Regulatoria Nuclear (nuclear regulatory body of Argentina – ARN) entrusted the realization of an independent evaluation, to assess whether a DEGB caused by a beyond design basis event could be possible. A dynamic analysis of the Loop 2 of CNA II's primary system was performed employing the finite element method (FEM) for a beyond design basis earthquake scene, i.e. an earthquake with a mean probability of exceedance of $10^{-6}$ per year, to evaluate the possibility of occurrence of a DEGB with critical preexisting areas with circumferential through-wall cracks in the primary system. The model utilized displacement time histories as input data, applied at the supporting points of major components (reactor pressure vessel, stream generator, main coolant pump, pressurizer), obtained by numerical integration of the acceleration time histories at such points, provided by the designer.

## 1 INTRODUCTION

Atucha II NPP is a pressurized heavy water reactor (PHWR) located in Lima, Argentina, that started its commercial operation in May 2016, although the construction began during 1980. The design licensing base at that time eliminated a DEGB design requirement in the reactor coolant line, so the emergency core cooling and reactor shutdown systems were originally designed to account for the potential break of the surgeline, which has about10-percent of the cross section of the reactor coolant line. For this reason, the safety evaluation for beyond design basis earthquake of Atucha NPP was a priority for the ARN, and requested the realization of an independent evaluation to assess if a DEGB caused by a beyond design basis earthquake could be possible.

A dynamic finite element analysis of the Loop 2 of Atucha II NPP primary system was then conducted to determine the actual security margins on double-ended guillotine break (DEGB) under beyond design basis earthquake (BDBE). Typically, the frequency of occurrence for this severe kind of event is less than $10^{-5}$ per year. The BDBE used in this work is an earthquake with a mean probability of exceedance of $10^{-6}$ per year, and a peak ground acceleration (PGA) of 0.321g, according to the probabilistic seismic hazard assessment performed for Atucha site, as shown in Figure 1.

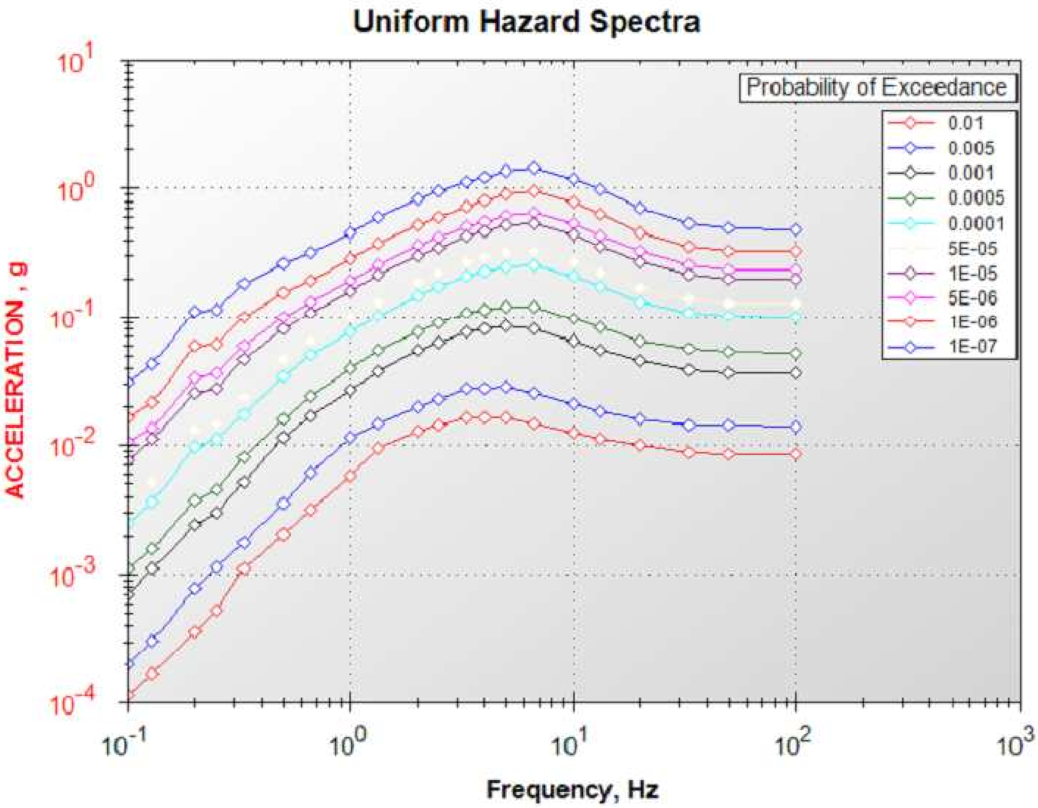


Figure 1: Probabilistic Seismic Hazard Assessment for Atucha II NPP (James J. Johnson and Associates, 2010).

The analyses were undertaken in two parts. In the first one, it was considered that there were no cracks presented at the pipes, so, the critical points could be determined from the seismic stresses. The dynamic analyses were realized applying displacement time histories in the components supports. Normal operation condition and modal analyses were also performed at this stage to evaluate the expected behaviour of the model. In the second part, the occurrence of a DEGB was assessed, but this time, circumferential through-wall cracks were assumed in critical points using a cracked pipe element.

Results from calculations were compared to the ones obtained by Engineering Mechanics Corporation of Columbus (2013).

## 2 FE MODEL

Based upon the geometry of the model for stress analysis described in TÜV Nord/Süd Nuclear Consortium Argentina (2010), an independent 3D model for dynamic analysis was generated in the software SAMCEF FIELD. It is a unifilar model, and all major components of Loop 2 were modelled (Reactor Pressure Vessel, Main Coolant Pump, Steam Generator, Pressurizer – RPV, MCP, SG, PRE; and the surgeline). See Figure 2.

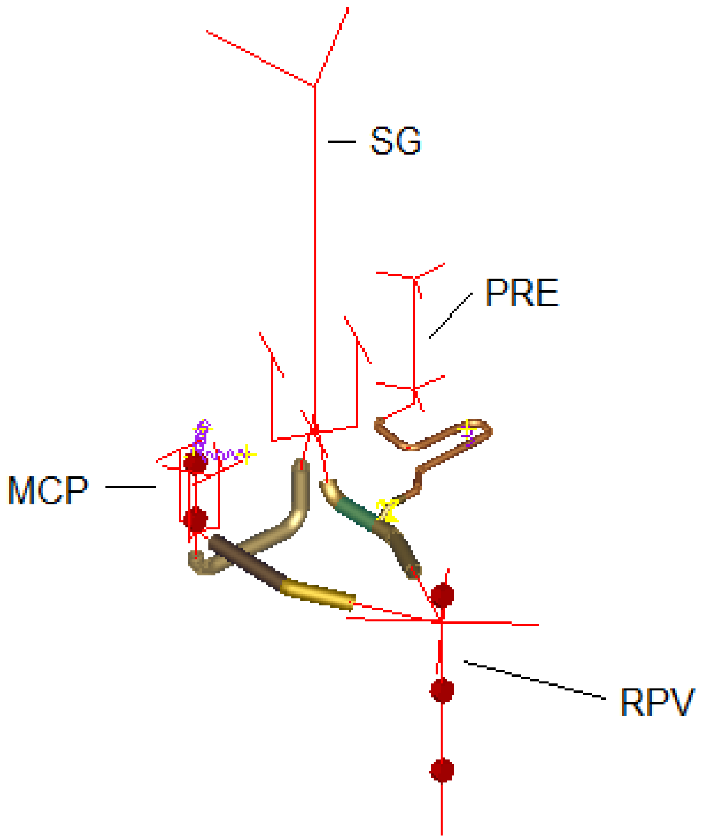


Figure 2: General view of the model.

The X direction of the model corresponds to the 90°/270° of the CNA-UII axis, while the Z direction in the model corresponds to 0°/180°. The vertical direction in the model is Y.

### 2.1 Material and behaviour

A fictitious material was considered for the reactor coolant line and surgeline, to account for heavy water weight during modal analysis.

All major components (RPV, SG, MCP and PRE) were assigned a rigid behaviour. For the PRE and SG the masses were considered to be uniformly distributed, while for the RPV and MCP the masses were defined in the corresponding centre of mass of the components. See Figure 2.

Table 1 presents the values adopted for the masses.

| | Comp. Mass [kg] | Insulation [kg] | Motor [kg] | Total [kg] | Centre of Mass [mm from +/- 0] | |
|---|---|---|---|---|---|---|
| PRE | 241000 | 5000 | - | 246000 | Distributed | |
| SG | 616000 | 9600 | - | 625600 | Distributed | |
| MCP | 71782 | 1068 | 49210 | 122060 | -2850 (casing) | 500 (motor) |
| RPV | | | | 445800 | -1678 (upper filler) | |
| | | | | 210000 | -7275 (moderator tank) | |
| | | | | 417800 | -12006 (lower filler) | |
| | | | | 1471125 | Distributed | |

Table 1: Component's masses (TÜV Nord/Süd Nuclear Consortium Argentina, 2010).

Table 2 displays the properties of the cross-sectional values assigned to the supports and bolts of the SG and MCP.

| | Area [$cm^2$] | $I_y$ [$cm^4$] | $I_z$ [$cm^4$] | $I_T$ [$cm^4$] |
|---|---|---|---|---|
| SG Bolts | 291 | 6740.5 | 6740.5 | 13481 |
| SG Upper Sup | 1864 | 1.48E+06 | 1.16E+06 | 39446.2 |
| SG Lower Sup | 4542 | 8.67E+06 | 1.54E+06 | 1.59E+06 |
| MCP Bolts | 99.4 | 786.3 | 786.3 | 1572.6 |
| MCP Beams | 1040 | 232347 | 234667 | 164527 |

Table 2: Cross-sectional values of supports (TÜV Nord/Süd Nuclear Consortium Argentina, 2010).

For the MCP snubbers, 2.1E+08 N/m was adopted as the stiffness according to TÜV Nord/Süd Nuclear Consortium Argentina (2010).

The stiffness of the surgeline support was taken from Kraftwerk Union, (1991).

## 2.2 Boundary conditions

The boundary conditions applied at the major components are presented next. See Figure 3.

*RPV*: The RPV is supported in four points which limit its vertical movement, but allow thermal expansion in the radial direction. These conditions were modelled with a bushing element, conferring large stiffnesses in vertical and circumferential directions, but low stiffness in the radial direction.

*PRE*: It is supported in two horizontal planes, with three support points in each plane. The bushing elements assigned to these points were the same as the ones applied to the RPV (large vertical and circumferential stiffnesses, but very low stiffness in the radial direction to allow for thermal expansion).

*SG*: The SG is supported in the upper part by two V-shaped struts that are attached to a concrete wall, which do not permit displacement but allows rotations of the SG. It is supported by two bolts in the lower part, which are suspended from two parallel beams, allowing the SG to move in the direction parallel to the beams to accommodate for the thermal expansion of the pipes. The beams are prevented from moving.

*MCP*: It is vertically supported by three bolts at 120° intervals, which hang from four beams. Two LISEGA shock absorbers (snubbers) are placed near the middle of the pump, allowing movement along the axes and limiting dynamic movement during an earthquake.

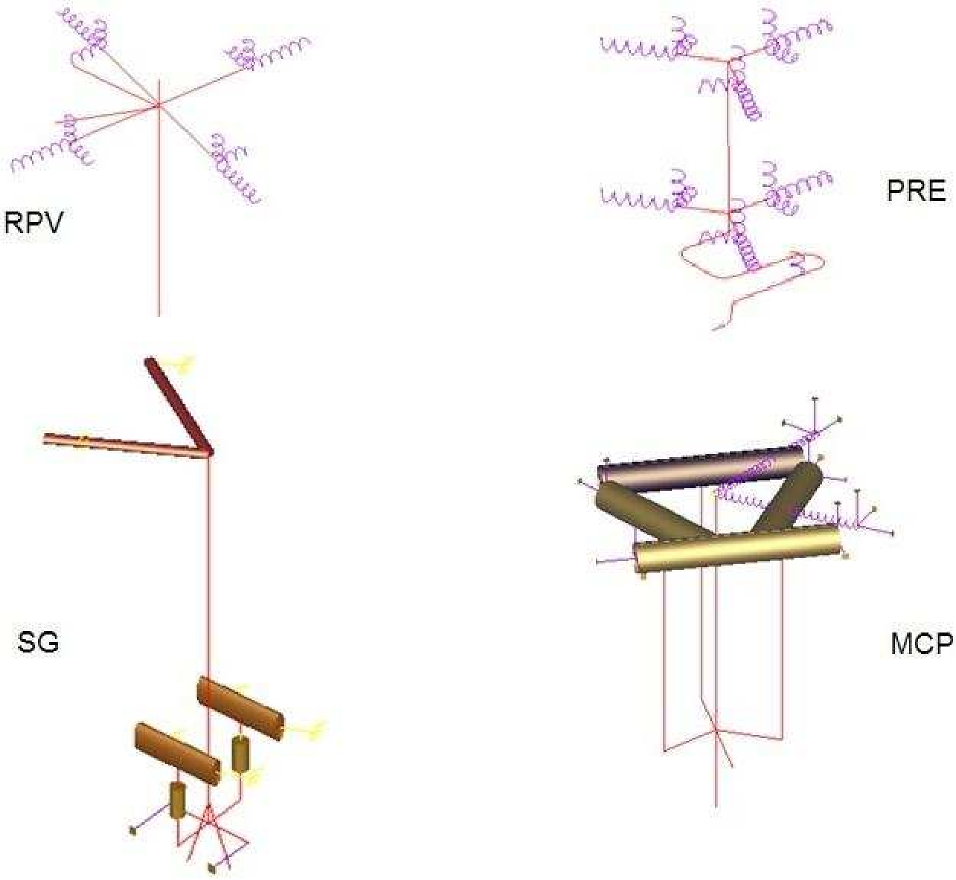


Figure 3: Boundary Conditions.

## 3 MODAL ANALYSIS

Table 3 presents the first vibration modes obtained from the modal analysis, and Figure 4 shows the first 3 modes.

| Mode | Frequency [Hz] | Motion |
|---|---|---|
| 1 | 6.048 | Surgeline – Vertical |
| 2 | 7.407 | MCP – Horizontal |
| 3 | 8.765 | MCP – Rotation around axis |
| 4 | 9.503 | SG – Vertical |
| 5 | 9.885 | SG – Horizontal |
| 6 | 10.597 | MCP – Vertical |
| 7 | 11.185 | SG, MCP and Surgeline |
| 8 | 11.939 | MCP – Horizontal |
| 9 | 13.856 | MCP and SL |
| 10 | 14.376 | Surgeline - Horizontal |

Table 3: Vibration modes.

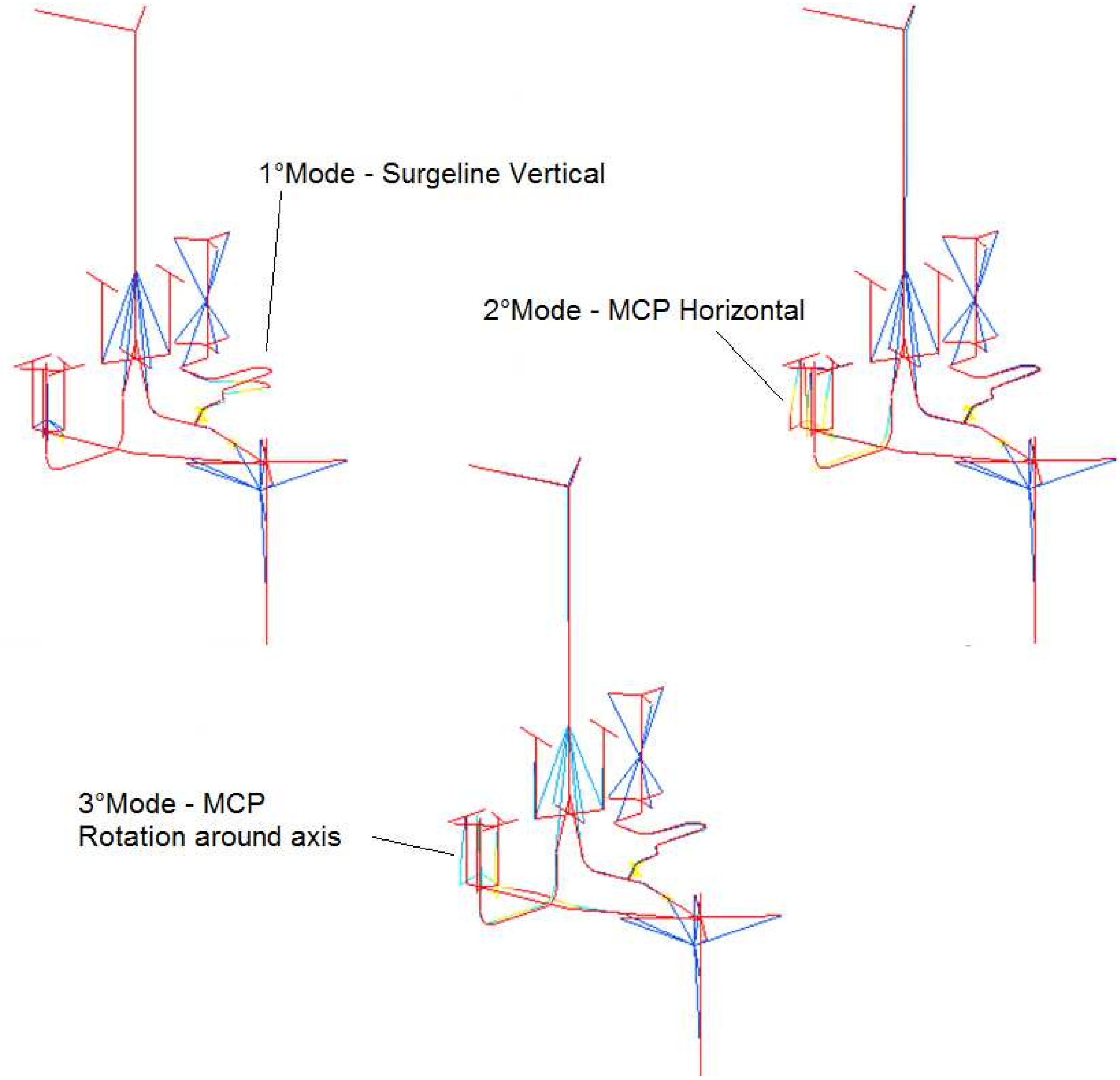


Figure 4: First vibration modes.

## 4 BDBE ANALYSIS WITHOUT CRACKS

CNA-UII is assumed in normal operation condition when the BDBE occurs, so the load combination includes dead weight of components and pipes, as well as pressure and thermal loads.

Seismic input corresponds to an event with a probability of exceedance of $10^{-6}$/year. The designer supplied the velocities time histories for that event in the supporting points of the components, which were obtained according to the best estimate parameters of the soil.

For instance, Figure 5 shows the velocity time histories in three directions for a specific point in the structure.

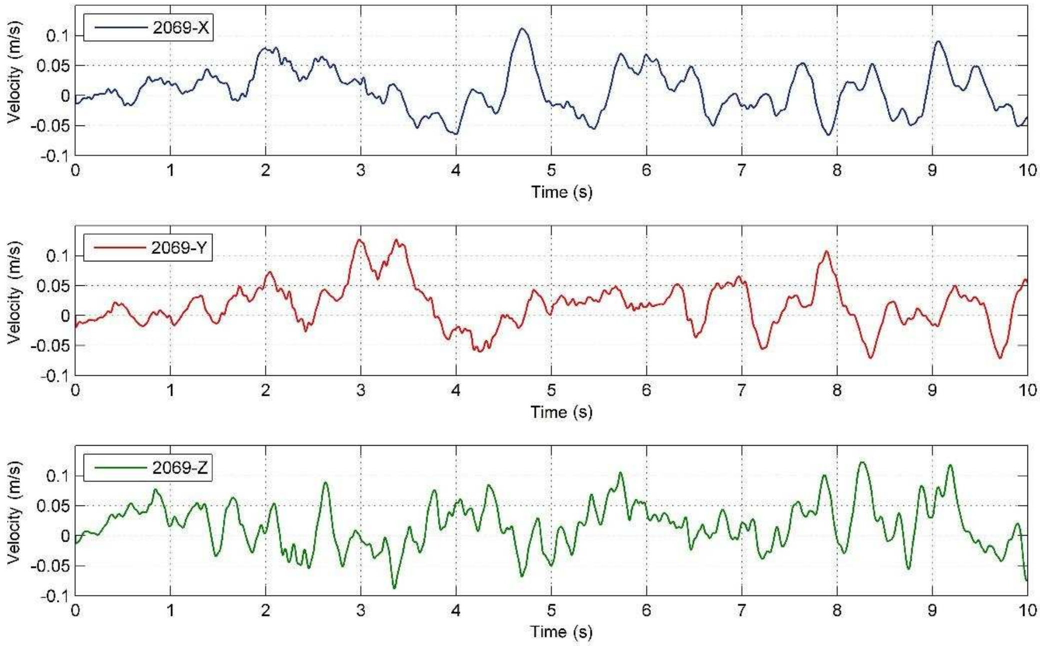


Figure 5: Velocities time history for a given point.

However, velocities time histories were not applied as seismic input in the model, and displacement time histories were used instead, which were obtained by numerical integration of the velocities time histories. A least squares baseline correction was applied in each direction. Figure 6 shows the displacement for Y direction obtained by numerical integration, with and without baseline correction.

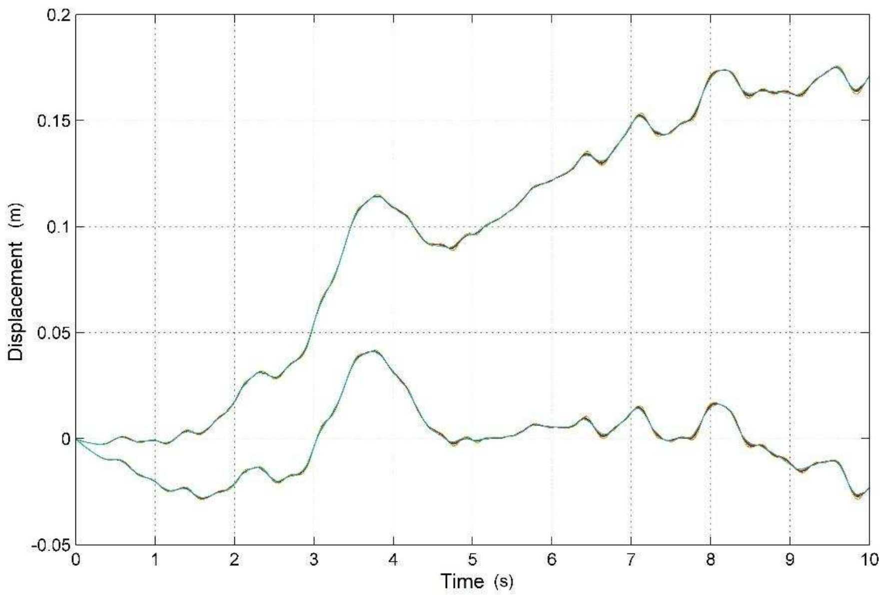


Figure 6: Displacement time histories generated, with and without baseline correction.

Displacement time histories were applied to the supporting points of the components, with the considerations made previously for the boundary conditions (Figure 7).

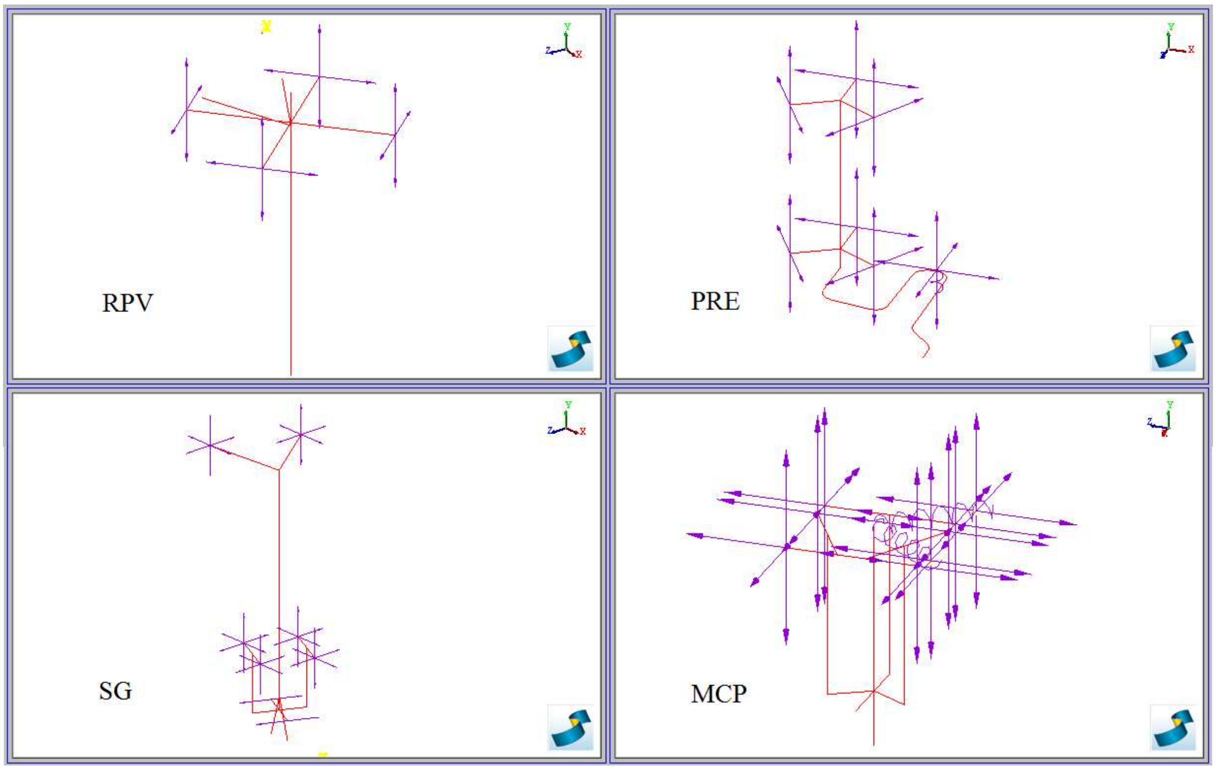


Figure 7: Application of the displacement time histories.

### 4.1 Results

Figure 8 shows equivalent stresses in the reactor coolant line for a given time. After examining the results for the whole seismic excitation, it is easily observed that the maximum stresses will be in the cold leg – MCP outlet, and in the Hot Leg – RPV outlet. Those critical points can be seen in Figure 9.

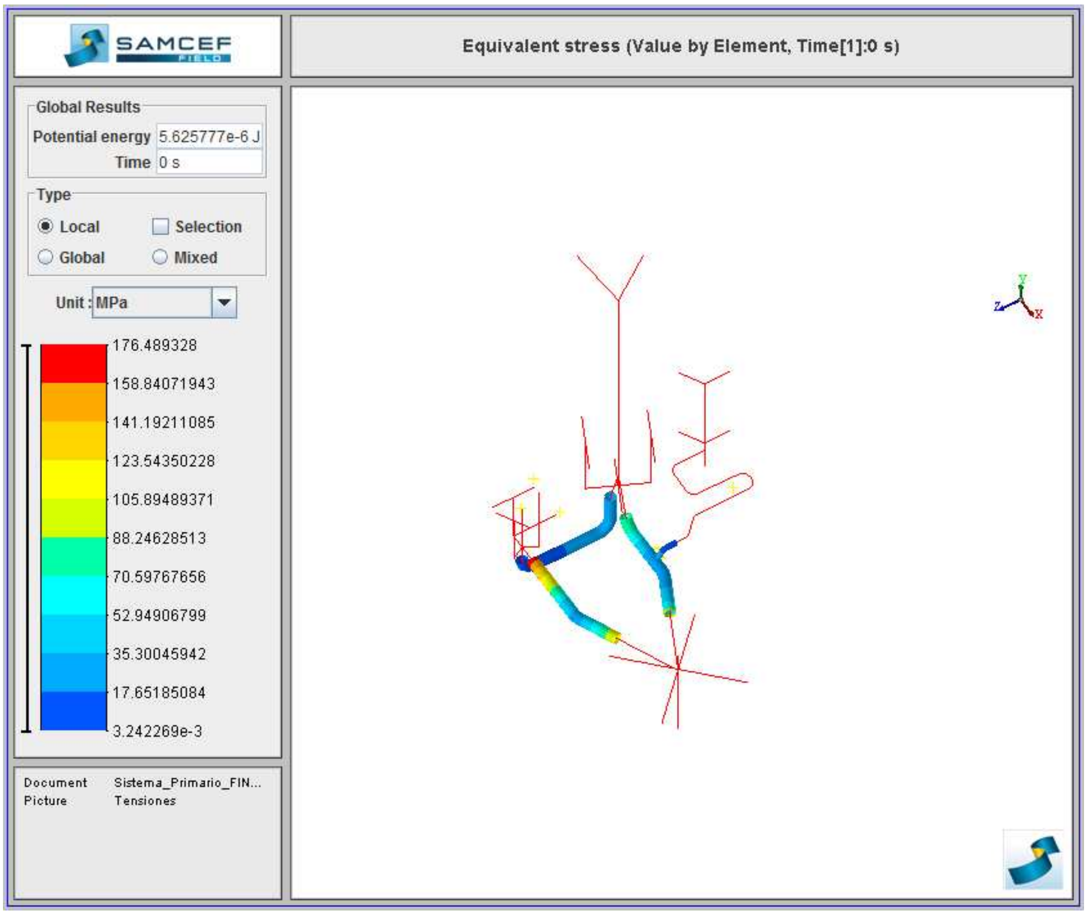


Figure 8: Equivalent stresses in reactor coolant line.

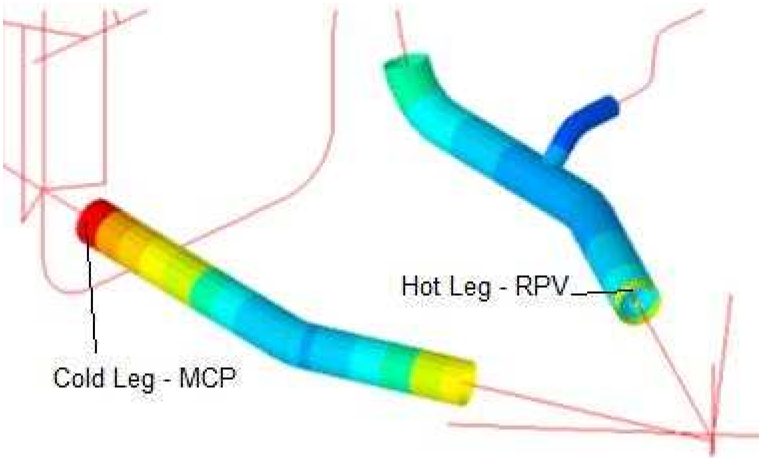


Figure 9: Critical points in Hot Leg and Cold Leg.

# 5 BDBE ANALYSIS WITH PRE-EXISTING CRACKS

## 5.1 Development of a Cracked Pipe Element

The cracked pipe element (CPE) is an element that represents the response of a cracked pipe using a Moment vs Rotation law, that evolves with the bending moments over the cracked section.

Figure 10 shows a Moment vs Rotation law of a circumferentially through-wall cracked pipe. In the first part, the pipe behaviour is elastic; then, some plastic deformations appear until the maximum load capacity is reached, to enter finally in the damage region, until failure occurs.

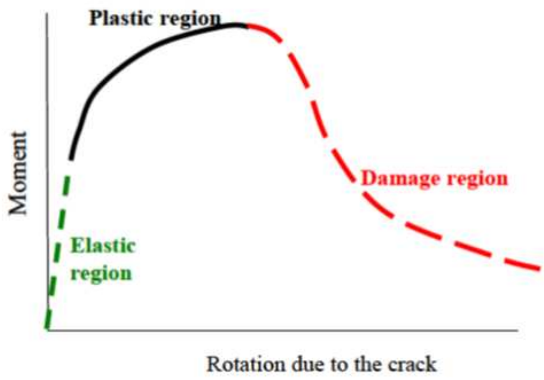


Figure 10: Moment vs Rotation due to the crack.

The CPE was employed considering the presence of a circumferential through-wall crack of a given length. To model the CPE, an element with a hysteretic rotation controller was used. The element starts in an elastic regime (with a predefined stiffness) up to the plastification load, defined with an upper limit curve, and evolves over the upper limit if the loads keep incrementing. During discharge, at first the element evolves following a linear law (with the same predefined stiffness) until reaching a lower limit curve that marks the beginning of the plastification, and then evolves over that curve if the absolute value of the load continues to increase (Figure 11).

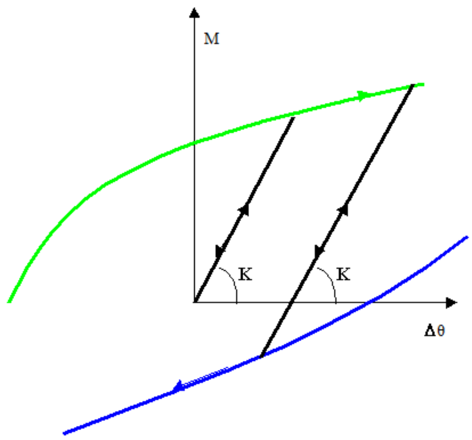


Figure 11: Controller used for the definition of the CPE.

In order to validate the CPE element, an experiment performed by the IPIRG (International Piping Integrity Research Group) was reproduced (Wilkowski, Schmidt, & Scott, 1997). The IPIRG was an international program administrated by the United States Nuclear Regulatory Commission, which had the objective to develop information to check engineering methods for the evaluation of the integrity of pipes in nuclear power plants with circumferential flaws.

The programme comprised several tasks, but the main goal was to investigate the behaviour of pipes with circumferential flaws when a cycling load was acting on them (typically from seismic events).

Experiment 1.1-3 was selected for the validation of the CPE, which consisted in applying to a circumferentially through-wall cracked pipe the dynamical inertial action generated by a vertical excitation of the pipe's supports (a similar excitation to the one produced by an earthquake). The CPE was then used to see if it could reproduce the response obtained in the experiment.

Figure 12 shows the schematics of the installation used to perform experiment 1.1-3.

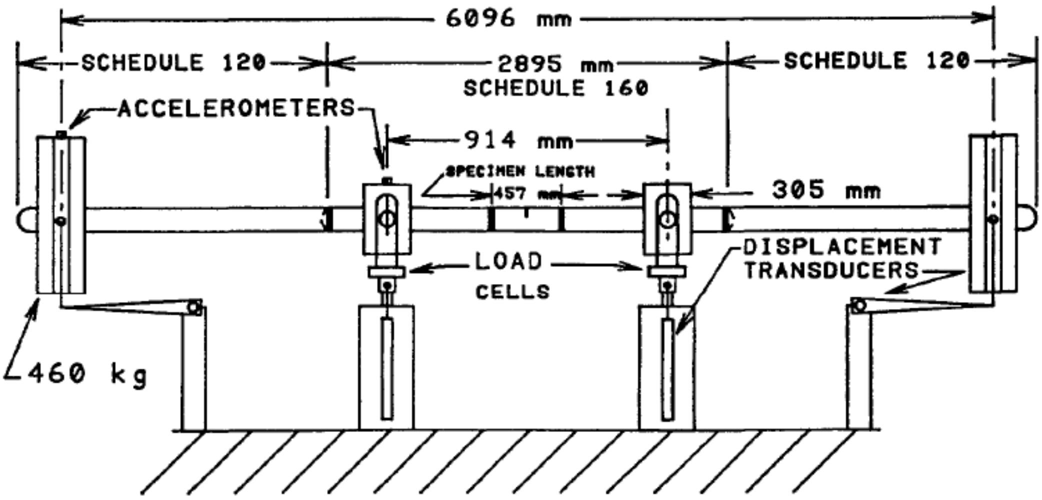


Figure 12: Schematics of the experiment 1.1-3 (Wilkowski, Schmidt, & Scott, 1997).

The result of the experiment 1.1-3 can be seen in Figure 13 (Moment vs Rotation) while Figure 14 shows the results of using the CPE in an unifilar model of FE. The result obtained by FEM reproduces adequately the experiment 1.1-3, so it is considered that the CPE is valid for reproducing a circumferential through-wall crack.

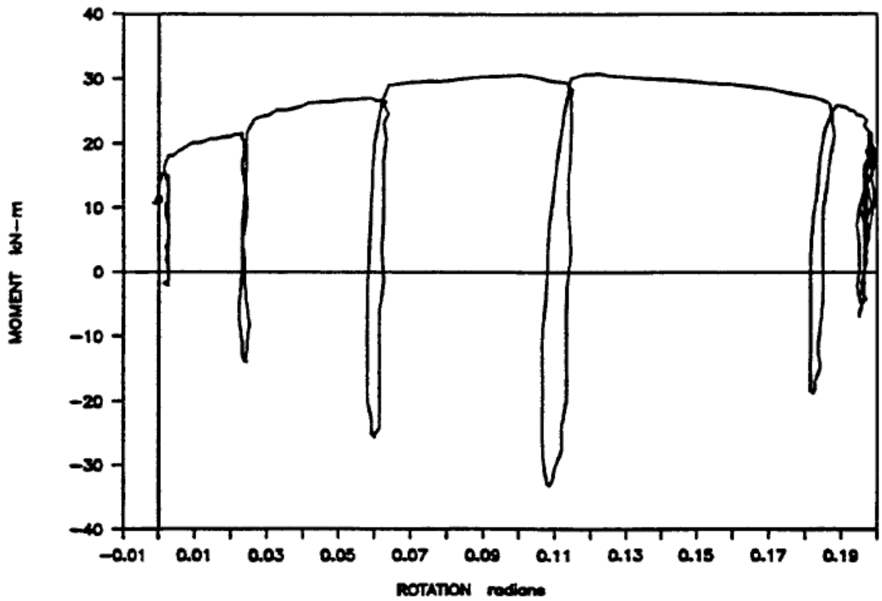


Figure 13: Moment vs Rotation. Experiment 1.1-3 IPIRG (Wilkowski, Schmidt, & Scott, 1997).

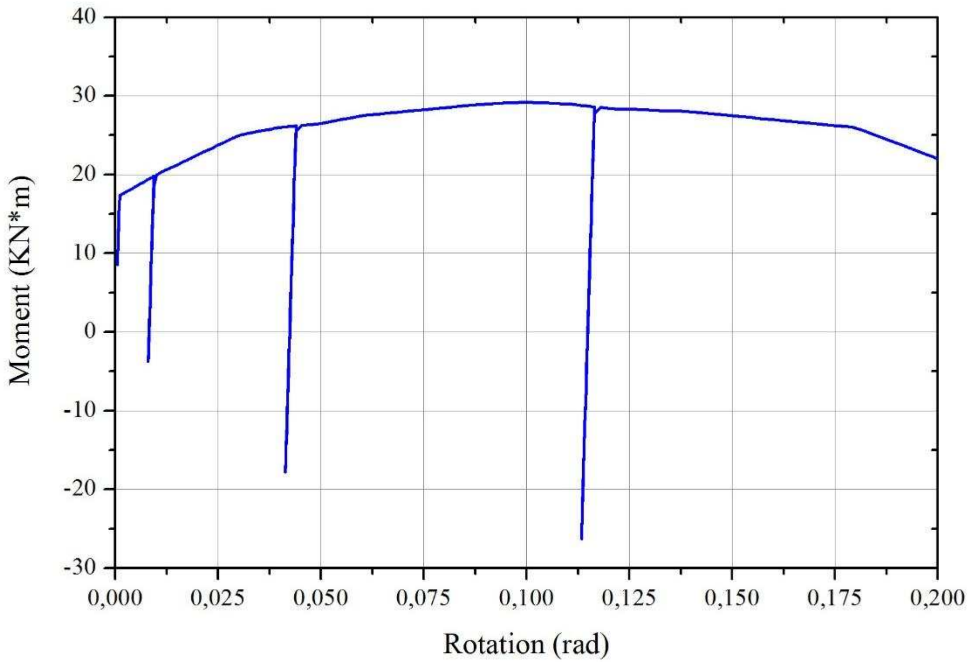


Figure 14: Moment vs Rotation, using a CPE to reproduce IPIRG experiment 1.1-3.

## 5.2 Analysis of the crack evolution in a BDBE

The same hypotheses explained in Section 4 were considered for this analysis, but now circumferential through-wall cracks at the critical points of maximum stresses were modelled using the CPE.

First, a crack of 55.5° was analysed, which corresponds to a very conservative estimation of a crack through the entire thickness that would develop in the worst-case scenario of stress corrosion cracking (maximum undetectable size according to Engineering Mechanics

Corporation of Columbus, 2013). The DEGB was not reached in the event of a BDBE with this 55.5°crack, therefore other analyses were performed with bigger circumferential cracks: 180° (i.e. half the pipe cracked) and 225° (a crack that extends beyond half of the pipe's cross section) to analyse whether a DEGB would occur or not.

### 5.3 Results

Figure 15, Figure 16 and Figure 17 show the results obtained for circumferential through-wall cracks of 55.5°, 180° and 225° respectively, at the previously identified critical points, both for the Hot Leg and Cold Leg. The Moment vs Rotation laws (M-R) that define the behaviour of the CPE were taken from Engineering Mechanics Corporation of Columbus (2013).

It is easy to see that for initial cracks of 55.5° and 180°, the crack would not propagate because the response of the CPE is inside the elastic zone. For the case of a 225° crack, the response of the CPE goes into the plastic zone, but without reaching the damage region. There is still a considerable reserve of energy under the fracture curve, so a DEGB would not occur in any case.

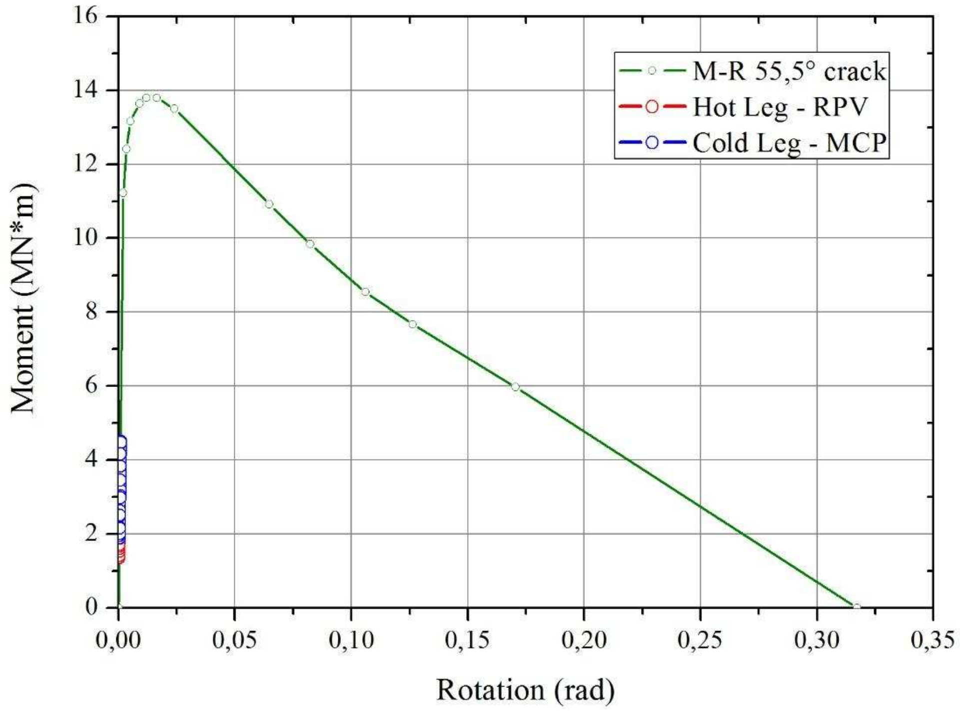


Figure 15: Moment vs Rotations for a 55.5° crack.

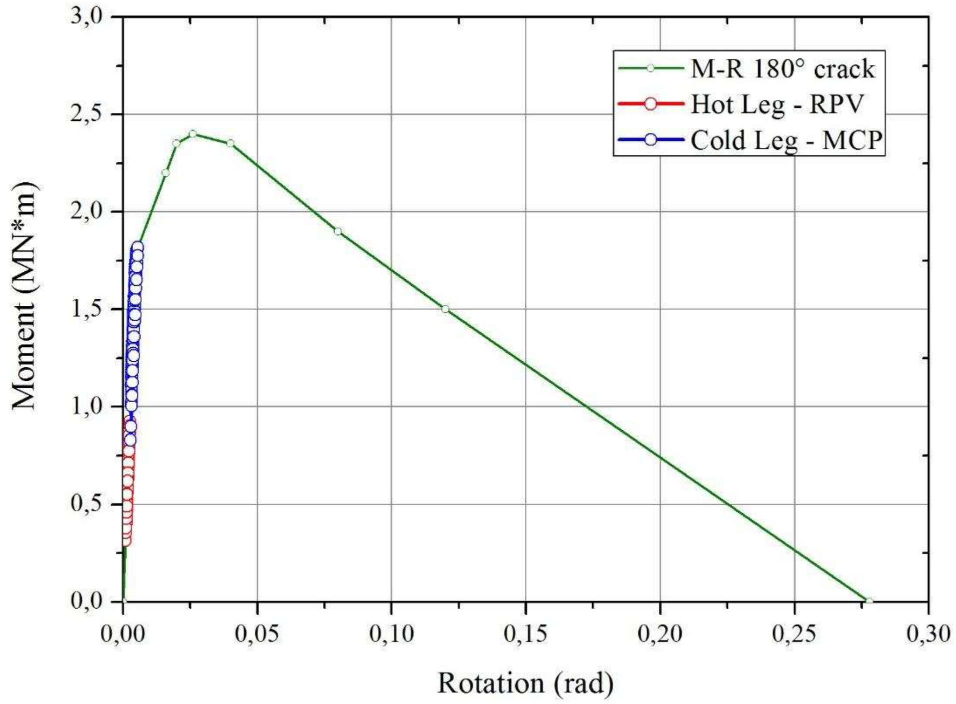


Figure 16: Moment vs Rotation curve for a 180° crack.

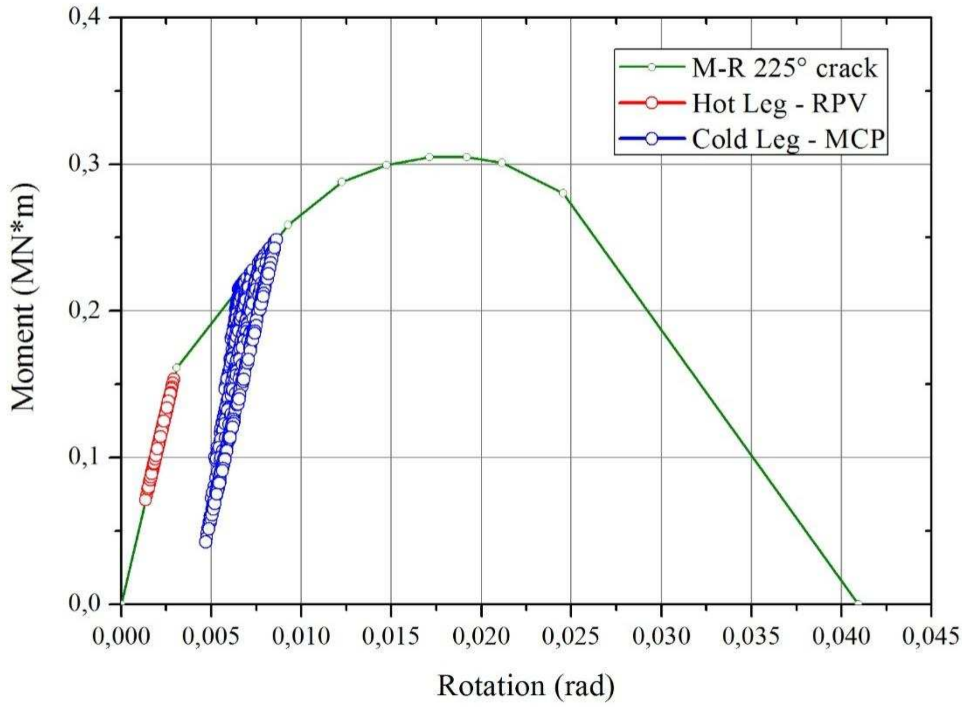


Figure 17: Moment vs Rotation for a 225° crack.

Figure 18, Figure 19 and Figure 20 show the results obtained by EMC2 in Engineering Mechanics Corporation of Columbus (2013). It is important to mention that the rotation value for the input curve in these figures had been divided by a factor of 2.

In every case (considering the observation of the smaller value in rotations) the results obtained in the present paper match the ones reported by EMC2 in Engineering Mechanics

Corporation of Columbus (2013) when the same parameters of Moment vs Rotations are used. The introduction of the CPE in the union of the MCP and RPV with the reactor coolant line, being the CPE of less stiffness than the part connected by it, dominates the system's response, so a similar behaviour is expected for the different models.

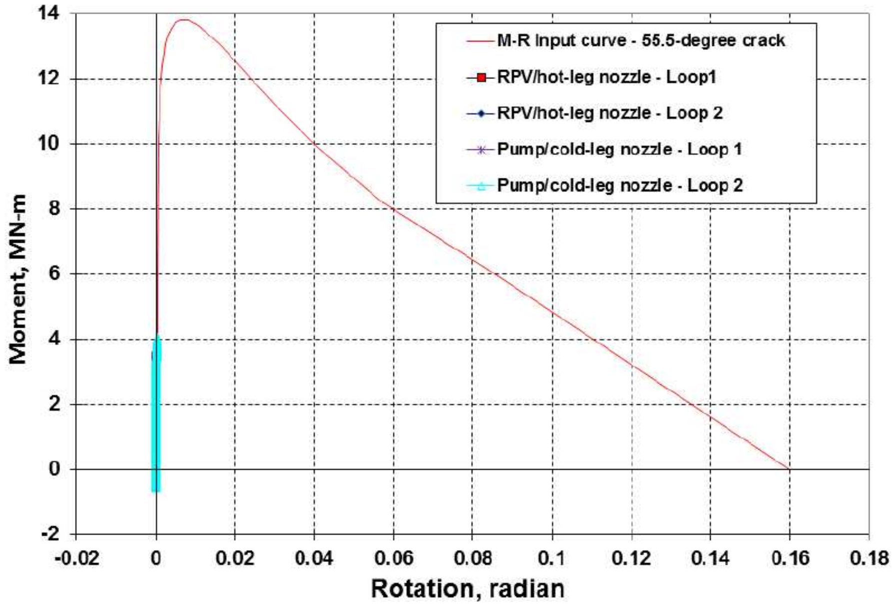


Figure 18: Moment vs Rotation for a 55.5° crack. Engineering Mechanics Corporation of Columbus (2013).

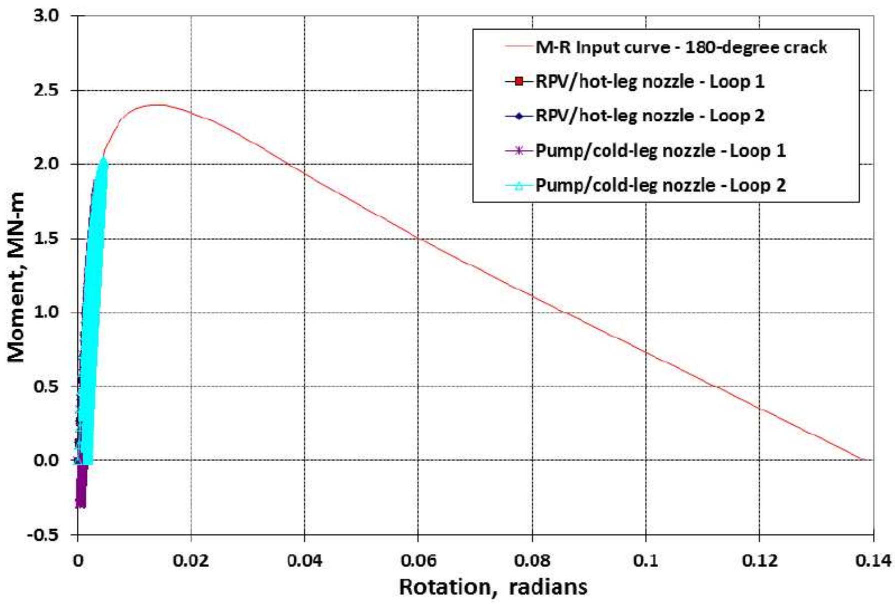


Figure 19: Moment vs Rotation for a 180° crack. Engineering Mechanics Corporation of Columbus (2013).

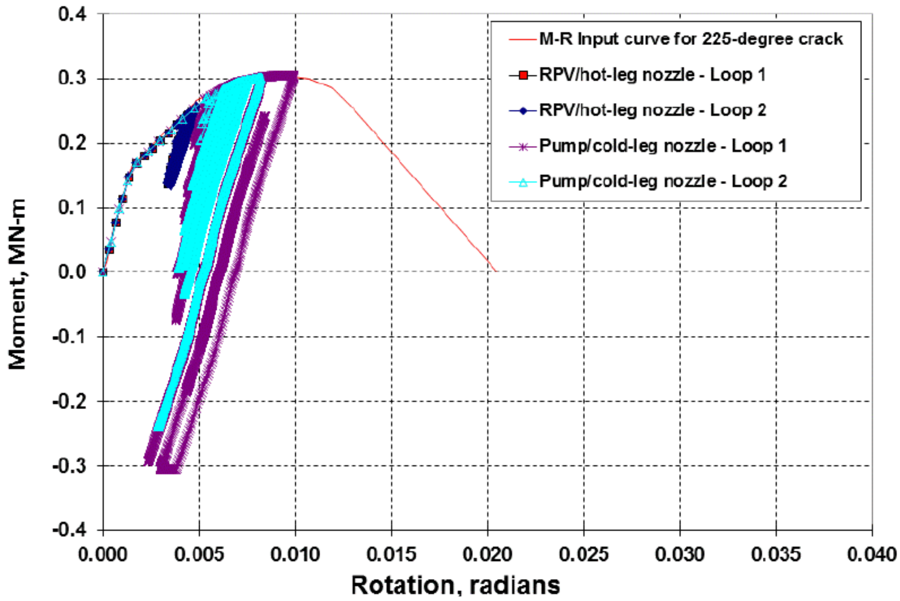


Figure 20: Moment vs Rotation for a 225° crack. Engineering Mechanics Corporation of Columbus (2013).

## 6 CONCLUSION

A dynamic analysis of the Loop 2 of Atucha II NPP primary system was carried out using SAMCEF FIELD, for a BDBE at the site, to assess whether a DEGB would be possible with pre-existing circumferential through-wall cracks in the reactor coolant line.

The BDBE is an earthquake with an annual probability of exceedance of $10^{-6}$. The plant is considered to be in normal operation conditions at the time the seismic event occurs. Displacement time histories were applied in all the major components supports according to the boundary conditions. The location of the maximum stresses was determined in this way.

A CPE, which consists in a cracked pipe finite element with a hysteretic rotation controller, was introduced into the model at those critical points to model the circumferential through-wall crack. The CPE was validated by reproducing the experiment 1.1-3 of the IPIRG.

The analysis performed using an independent finite element model to the one described in Engineering Mechanics Corporation of Columbus (2013), confirms that in the case of a beyond design basis earthquake a DEGB would not occur, even if the pipe was degraded with the maximum undetectable crack between inspections. Moreover, even if the crack exceeds several times the maximum undetectable size, a DEGB is neither expected for a seismic event of a magnitude equal to the BDBE.

## 7 REFERENCES

Engineering Mechanics Corporation of Columbus, *Development of Dynamic Break Opening Analyses for Atucha II Primary Piping System*. Volume 1 – Summary Report, 2013.

James J. Johnson and Associates, *Development of Dynamic Break Opening Analyses for Atucha II Primary Piping System*, *Conduct Detailed Seismic Analysis and Seismic and Seismic Hazard Curve Development*. 2010.

Kraftwerk Union, *S611E - 11 - 98628 Reactor Building Working Isometric – Surgeline*. 1991.

TÜV Nord/Süd Nuclear Consortium Argentina, *Final Report as per Annex A (2009/4c) – Part 2 of 2: Stress Analyses for the RCL and the SL*. 2010.

Wilkowski, G., Schmidt, R., & Scott, P. and others, *International Piping Integrity Research Group (IPIRG) Program. Final Report*. NUREG/CR--6233-Vol.4, 1997.