

Influence of Gaps on Seismic Behaviour of the Primary System of a PWR

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This paper deals with the influence of gaps on the dynamic behaviour of the Reactor Coolant System (RCS) of the french PWR when subjected to an earthquake event.

One of the basic rule of the french RCS design is that primary components and coolant pipes should not be constrained during the thermal motions of the RCS and of Civil Works.

This purpose can be ensured by using, for the RCS lateral support, snubbers which can accomodate without constraints any slow motion. But this solution is not always possible due to mechanical limits, space constraints, or even costs.

An other solution, which is used in the french plants for the lateral support of the steam generators, is to use stops with adequate gaps. These gaps, which are adjusted with shims during the hot functional testing, change during lifetime, particularly because of temperature transients.

In a first step, the paper gives insight on the reality of these geometrical gaps ; the measures of the size of the gaps on site are in good agreement with calculation results.

In a second step the paper shows the mechanical analysis process, taking into account the gaps, using a seismic non linear time history analysis of a RCS-building coupled model subjected to base motions (translations and rotations) ; the time history analysis uses a very performant modal superposition method in a relative coordinates system.

The special effects of the gaps on the RCS seismic behaviour are pointed out : frequency shift, impact loads, excitation of high frequency modes of components and pipes...

In the last step, the paper presents the difficulties in such kind of analyses. Some are solved by parametric studies that allow the low computer cost of the non-linear time history analyses. But the most important, such as the adjustment of the impact damping, require experimental tests conducted on shake tables with simplified scaled model.

1. Introduction

The Reactor Coolant System (RCS) support of the french PWR is designed in order to induce no additional stress during any thermal motion (expansion or contraction) in the loops and in the civil works.

For example, the vertical support of Steam Generators (SG) or Reactor Coolant Pumps(RCP) is ensured by support legs with twin ball bushing joints which allow horizontal displacements. The lateral support of components often uses snubbers which can accomodate any slow motion. But this solution is not always possible due to snubbers mechanical limits or space constraints.

Therefore the lateral support of steam generator is ensured by stops with adequate gaps. These gaps are adjusted with shims during the hot functional tests in such a way that the steam generator is never stressed by its stops.

Particularly the adjustment gaps take into account the temperature transients which can occur and the thermal inertia differences between metallic loops and concrete.

As consequence the gaps during power operation are not closed but can be a few millimeters wide (3 to 6 mm). This range of values could appear very small in comparison with the size of the components (a SG is about 20 meters high). But, as it is shown in this paper, these gaps have a great influence on the dynamic behaviour of the primary system in an earthquake event and cannot be neglected.

2. Reality of gaps

2.1. Example of SG lateral support design

The steam generators of the french PWR are laterally supported at two levels. The SG lower lateral supports are located at the steam generator base (close to the top of the support legs). The stops which are efficient during an earthquake are located perpendicularly to the hot leg. An other stop parallel to the hot leg is only impinged upon during LOCA due to the existence of large gaps.

The SG upper lateral supports are located at about SG mid-height. Figure 1 shows a design example ; the steam generator is surrounded by a welded ring. Perpendicularly to the hot leg the support is ensured by 2 stops with gaps against which the SG slides during thermal motions. The 4 snubbers located parallel to the hot leg can follow these slow motions but are locked for seismic motions.

Shims are used for adjusting gaps ; they are screwed on the plates which recover the second phase concrete. The adjustment is such that, during normal operation, the steam generator bears upon the stop on the reactor pump side.

2.2. Calculation of gaps

The calculation of gaps is based on simplified assumptions about the temperature distributions in the supports and the concrete and about the thermal motion of civil works. The adjustment gaps are evaluated in order to prevent strong contacts between the steam generator and its stops during any situation of the reactor. The calculation takes into account the most unfavorable situations which tend to close the gaps : loop temperature transients and differential thermal expansion due to the difference of expansion coefficients and thermal inertia between steel and concrete. For example, at the end of the reactor temperature ascension, the concrete is still cold because of its high thermal inertia. On the other hand the calculation of the seismic mathematical model gaps considers generally

the most unfavorable situations which tend to open the gaps during power operation .

2.3. Verifications on site

For all plants, after the measurement of gaps during the hot functional testing for determination of the shim size, more work can be done to verify the real gaps. This verification is mandatory during the precritical testing but only compulsory during hot standby. A good agreement between these measures and the adjustment gaps is generally found. It should be noted that no gap measurement is made during normal operation. But the good experimental results prove that the gap calculation assumptions, particularly on civil works motions, are justified.

3. RCS seismic non linear time history analysis

3.1. Mathematical model

3.1.1. Impact model

Figure 2 shows the very classical impact model used in this kind of analyses. A spring and a dashpot in parallel are coupled in line with a gap. The force developed in this element when the gap is closed is (with the figure notations)

$$F = k (X_1 - X_2 - j) + c (\dot{X}_1 - \dot{X}_2) \quad (1)$$

This simplified formulation is related to the actual lack of knowledge about impact parameters.

3.1.2. RCS mathematical model

Figure 3 schematizes the non linear coupled building and RCS model which is used in the analyses. A vertical beam, representing internal structures of reactor building, supports the primary system model.

This is for two reasons. The first one is obviously mechanical. Because of mass ratio ($M/m \approx 6$), a dynamic coupling between the internal structures of building and the RCS cannot be neglected. The second one is mathematical. By including a part of building in the RCS model, the resulting structure is only excited by a single point, the base of internal structures which corresponds to the top of the raft : it eases the mathematical treatment. The excitation consists of 6 DOF accelerations time histories which are calculated by the Architect Engineer through soil-structure interaction analysis.

The RCS model includes all loops. Internal structures of reactor building and primary equipments (Reactor Pressure Vessel - RPV -, SG, RCP, pressurizer) are represented by single beam lines. This modeling technique is mainly justified by the analysis purpose which is only to determine general seismic RCS behaviours. Furthermore this way cancels computer limit problems such as storage capacity or calculation cost.

A good space distribution of primary components masses is obtained, in the one hand, by a rather large number of nodes (a S.G. includes about 10 nodes) and, in the other hand, by the use of consistent mass matrices.

Besides the stops, impact elements are also used for modeling supports whose behaviour is geometrically non-linear : RPV vertical pads, snubbers and vertical support legs of primary components. In this case non-linear elements model the difference in tensile-compressive stiffness values.

RCS mathematical models comprise about 250 nodes, 350 elements including 60 non-linear.

3.2. Method

The RCS time history analysis is performed with a non-linear modal superposition method. In a first step the modes of the structure without stops (called reference structure) are determined. In a second step these modes are superposed for calculating the time history response of the structure, with stops, subjected to base motions.

The equations of motion are solved in the relative coordinates system fixed to the base of the structure.

When the gaps are closed, the forces which are developed in the non-linear elements (eq. 1) are applied as external forces on the reference structure (ref. 1 : pseudo-force method). The base excitation is changed into equivalent inertia forces applied on the whole structure (ref. 2). In this very classical process the terms of Coriolis acceleration due to base rotations are neglected. But considering the other acceleration terms values, this is without any significant effect on results.

In the current non-linear process, modes used for response calculation partly lose their physical significance because they do not correspond to vibration modes of the structure when gaps are closed. They must be understood as mathematical base vectors only useful for solution calculation.

It is one of the reasons for which a good response accuracy requires a greater number of modes than in the linear cases. Nevertheless it should be noted that to solve the equations of motion in the relative coordinates system needs a lower number of modes than to solve the equations in an absolute coordinates system because the rigid body motion of the structure has not to be represented (ref. 2).

The time step size, which is imposed by the non-linearities, lies between 1 and 2 milliseconds for RCS seismic analyses.

A verification of non-linear mathematical process is easily provided by closing the gaps of two opposite stops with similar stiffness. The obtained results are in perfect agreement with results of linear analyses in which the two stops are represented by a single spring.

With respect to direct integration, non-linear modal superposition reduces drastically computer costs. This efficiency allows long seismic time history analyses (higher than 10 seconds ; the calculation comprises between 5000 and 10000 steps).

3.3. Main results

The purpose of this paper is obviously not to present the results of a particular analysis but only to point out the special effects of the gaps on the RCS seismic behaviour, especially with comparisons between results of non-linear (open gaps) and linear (closed gaps) analyses.

3.3.1. Frequency shift

It is obvious that the modes frequencies decrease if the structure is less supported. So the frequencies of the reference structure (without stops) are lower than the frequencies of the structure with stops linearized by closing gaps. The frequency of the fundamental mode of french design steam generators decreases from about 7 Hertz (closed gaps in upper and lower supports) to about 2 Hertz (open gaps).

With gaps a few millimeters wide, a relatively steady state SG motion is created between 4 and 5 Hertz. Roughly it can be decomposed in two phases : during contacts the SG embeds an upper stop according the 7 Hz half sinusoidal movement ; then this stop rejects and

"projects" the SG on the opposite stop according the 2 Hz movement. Thus the response frequencies of the structure significantly change considering gaps. They do not correspond any longer to single modal frequencies but to modal frequencies combinations.

3.3.2. Impact loads

As a general rule, the existence of gaps increases the loads in the stops. This is due to impacts which are not taken into account in linear analyses. Between its stops the velocity of the SG can be relatively increased which in turn increases its kinetic energy and consequently produces a larger stop deformation.

It is difficult to provide amplification factors due to gaps because the dynamic responses are always very complicated. For example, by opening gaps the amplification process could be reduced by the frequency shift if a resonance condition was obtained between internal structures of building and closed-gaps steam generators.

The choosen impact damping (c value of eq. (1)) has also a great influence on results (see § 4.2.).

Nevertheless it should be present in mind that a load amplification of 2 in the stops can be found by opening gaps.

Excluding stops, a general load increase in the whole loops is found when gaps are considered. This overload, which reduces when distance to SG is increased, is only due to larger movements of the structure. A good approximation of this phenomenon can be obtained by statically forcing displacements at SG stops levels.

3.3.3. High frequency modes excitations

This important phenomenon is shown by RCS response spectra determination.

Figure 4 shows a mathematical model which can be considered as a very large approximation of a steam generator (vertical pipe) and a hot leg (horizontal pipe) ; the SG upper and lower stops are modelled by the non-linear elements. This simplified model, which is obviously not used for RCS seismic analyses, corresponds just to a possible experimental test to be performed on shaking table to validate some parameters (see details § 4.3.) Results obtained with this model subjected to Y translational accelerations (corresponding to NRC spectra) are only given to illustrate the high frequency modes excitations due to impacts. Figures 7 and 8 present respectively structure response spectra at the middle of the hot leg (node 50) and at the SG top (node 200). The difference between closed gaps results and open gaps results (2 mm for each stop) is quite obvious.

In the linear analysis, only the first modes of the structure (< 20 Hertz) are excited and give peaks on spectra. The zero period acceleration (ZPA) is obtained directly after 30 Hz. In the non-linear analysis, spectra present, in the one hand, a higher general level and, in the other hand, important peaks up to 100 Hz. The first peak corresponds to global structure motion (see the previous frequency shift (7 → 4.5 Hz) on figure 8). The other peaks correspond to modes which are greatly excited by impacts. For example, the 2 peaks at about 35 Hz on figure 8 and 80 Hz on figure 7 correspond respectively to 2nd SG mode (fig. 5) and to 1st hot leg mode (fig. 6). Consequently to these peaks the ZPA is very high and is obtained only after 100 Hz.

3.3.4. Non-linear aspect

This last point is self evident. With linear analyses, the results are proportional to the excitation (if all the other parameters are unchanged). Obviously it is not the case of

non-linear analyses. The interesting fact for RCS seismic analyses is that the significant results are not proportional to the excitation but are lower. (It should be also noted the light frequency shift to the right of the fundamental SG motion, when the excitation increases due to the reduction of the SG excursion time between stops).

4. Difficulties in RCS non-linear seismic analyses

4.1. Parametric studies

The RCS non-linear time history seismic analyses can give relatively scattered results. Consequently parametric studies are required even more than for linear analyses. The low computer costs make possible all kind of parametric studies such as excitations influence or gaps size influence. The results are not always easy to predict because of the complexity of involved dynamic phenomena.

4.2. Validity of results

It should be very present in mind that the non-linear found effects are only results of calculations. It is essential to know if predicted effects correspond to physical reality, i.e, if the mathematical model (with a large sense including method) is valid. The comparison between real support design (fig. 1) and modelization (fig. 2) shows the problem ; a kind of tank, whose sides impinge stops, is modeled by a beam line which is directly subjected to impact forces. The use of such models is surely justified to represent, with a satisfying agreement, the general structure motions. But in order to generate structure response spectra, some ill-known parameters such as impact damping (c value of eq. (1)) must be adjusted.

Figures 9 and 10 compare the previous non-linear structure spectra obtained with a 2% critical damping value for dashpots (fig. 7-8) to spectra with a 10% damping value (the modal damping in the whole structure (2%) is unchanged ; the c values of dashpots are determined with simplified methods to correspond to a given critical damping percentage ; after time history calculations, an energetic approach verification is performed to prove the real agreement). A great difference appears on figures, particularly at the SG top (see that the 80 Hz peak on the hot leg does not relatively change). The loads in the stops are reduced from 25%. The 10% damping value may seem too large, but it corresponds to a coefficient of restitution of about 53% (against 88% for a 2% critical damping). That means that a SG, released from a H height, should rebound on its stops up to a 0.53 H height. This is not necessarily unrealistic considering that the c values of single dashpots must represent all the dissipations of energy which occur during impacts : local plasticity of stops and concrete, structural damping of stops, civil works and SG shell, SG rotation motion around its stops, radiation damping ...

Parametric studies about impact damping are obviously not sufficient because they cannot say what results are correct. Experimental tests must be performed.

4.3. Experimental tests

The basic idea of these experimental tests is only to qualify the used non-linear analysis process. For this purpose it is sufficient to work with simplified models which widely approximate real components. Figure 4 shows a mathematical representation of such model. The vertical and horizontal constant section pipes correspond respectively to a steam generator and a hot leg. The real masses and stiffnesses are kept as possible to preserve the

SG dynamic behaviour. The scale which is chosen in order to put the model on a shake table should be about 1/5. So the scaled model should be 4 meters high for a 5 tons mass. A seismic excitation should be applied along the direction of non-linearities. The experimental results should allow the qualification of predicted non-linear effects through the adjustment of internal parameters such as impact damping. The range of obtained values should be then transposed to RCS seismic analyses.

5. Conclusion

Gaps are real in the steam generators stops design of the french PWR. Although small, they cannot be ignored because they drastically change the dynamic behaviour of primary system in an earthquake event.

Using a modal superposition method, non-linear seismic time history analyses can be performed at low computer costs. But some non-linear predicted effects may be overevaluated because of the present lack of knowledge on impact parameters especially impact damping.

A great experimental effort must be done in order to validate the non-linear seismic analysis process, if possible, through the adjustment of internal parameters.

If impact damping is found to be relatively high, it may appear that a design with stops and gaps is favourable for high seismic areas.

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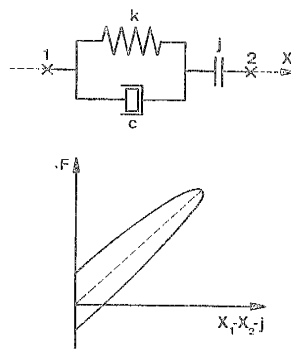
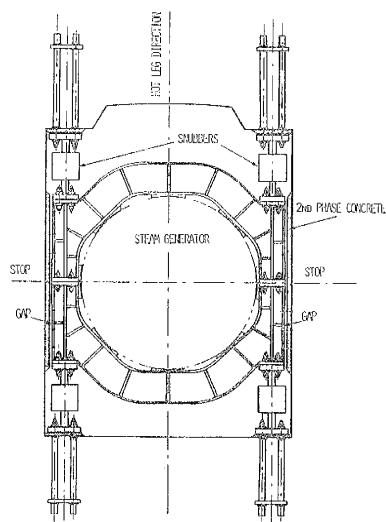


Fig. 1 : SG upper lateral support example

Figure 2 : Impact model

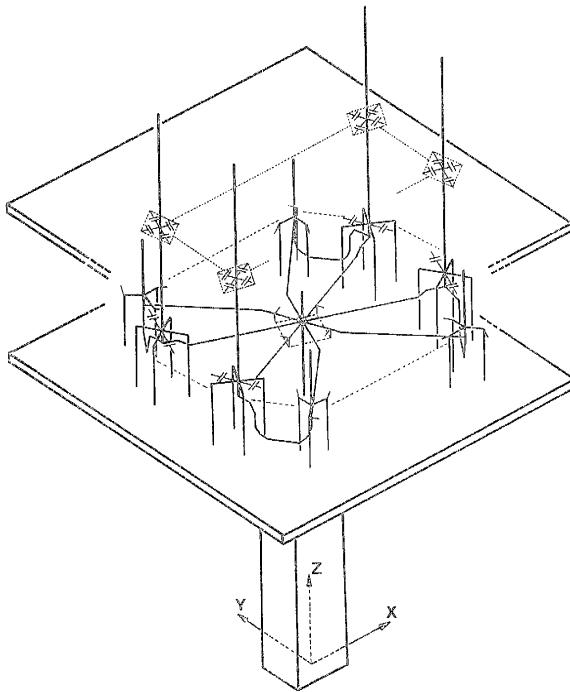


Fig. 3 : Schematic coupled primary system and building model

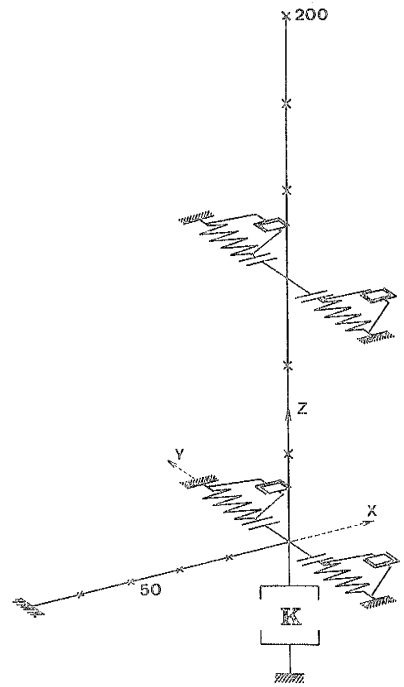


Fig. 4 : Mathematical model of a possible experimental test

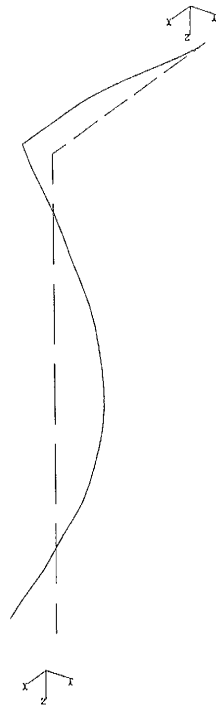


Fig. 5 : Second steam generator mode ($f \approx 35$ Hertz)

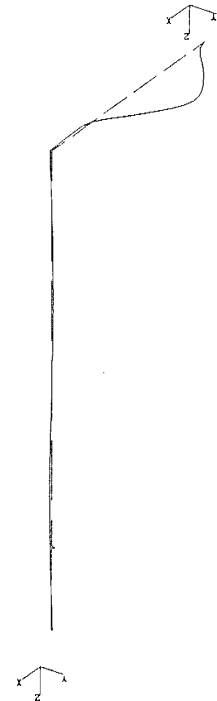


Fig. 6 : First hot leg mode ($f \approx 80$ Hertz)

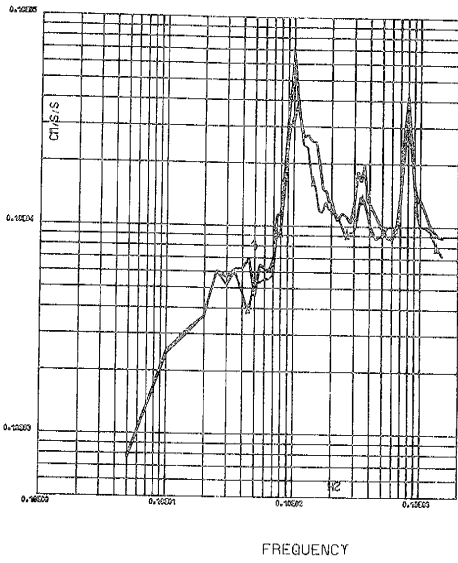


Fig. 7 : Response spectra at node 50
(hot leg middle)
— open gaps
-▲- closed gaps

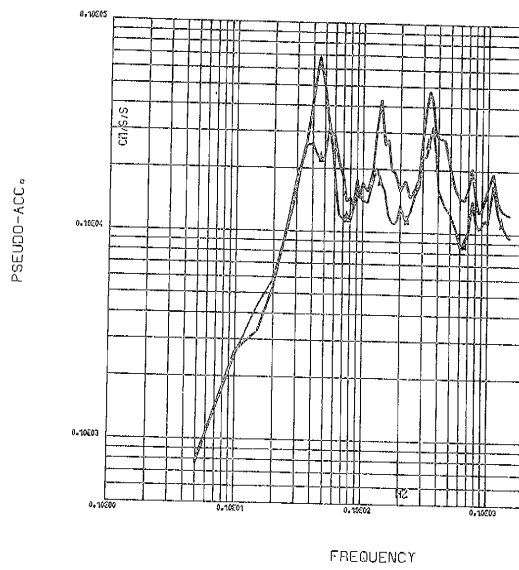


Fig. 8 : Response spectra at node 200 (SG top)
— open gaps
-▲- closed gaps

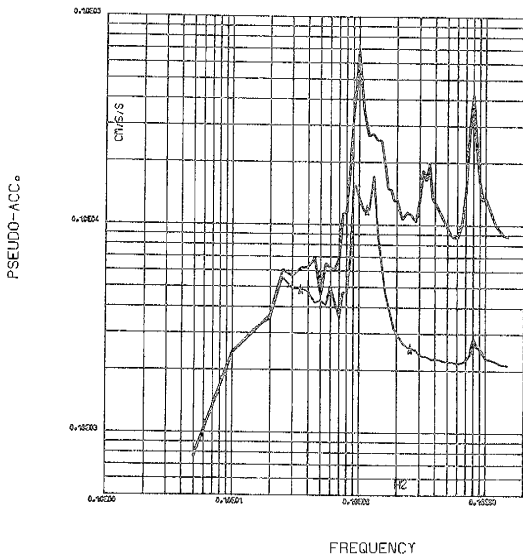


Fig. 9 : Response spectra at node at node 50
(hot leg middle)
— 2 % impact damping
-▲- 10 % impact damping

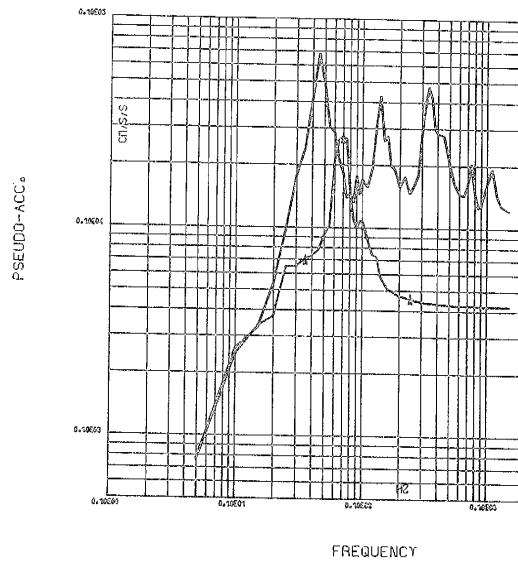


Fig. 10 : Response spectra at node 200 (SG top)
— 2 % impact damping
-▲- 10 % impact damping