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INDUCED VIBRATIONS CALCULATION IN REINFORCED CONCRETE STRUCTURE SUBJECTED TO SOFT IMPACT WITH EUROPLEXUS CODE : VALIDATION WITH IRIS3 OECD/NEA CAPS BENCHMARK

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ABSTRACT

In order to simulate the response of Nuclear Power Plants (NPP) buildings in case of soft impacts (e.g. Air Plane Crash, APC), EDF has developed a methodology based on the use of the EUROPLEXUS fast dynamics software. The validation of the calculation procedure is presented for the OECD/NEA CAPS benchmark exercise IRIS 3 (IRIS : Improving Robustness assessment of structures Impacted by missileS) that was carried out to study the transmission of the induced vibrations. Displacements results are given, together with Floor Response Spectra (FRS) in various locations in the mock-up. High Frequency (HF) vibrations are well estimated up to approximately 100 Hz.

On the basis of this validation, various acceleration loadings calculated on NPP buildings under APC are used in a HF testing program on a sample of NPP electrical equipments. The set of loadings, along with increasing magnitudes in a test series, ensure the robustness of the analysis and a realistic assessment of HF capacities. Despite of contact chattering in some relays for the highest magnitudes, no mechanical failure is observed and all the equipments remain functional after the test series. Maximum acceleration submitted to the test table is 5.7 g on Civil Mounted equipments (like cabinets) and 20 g on Components.

INTRODUCTION

On top of the verification of buildings global behaviour and of the local resistance of the Reinforced Concrete (RC) slabs subjected to impact loading, induced vibrations propagating inside the buildings are estimated. It has to be confirmed that such vibrations are harmless for the great part of SSCs (Structures, Systems and Components) functionality. As pointed out in Singh (2017), EPRI showed that the high-frequency ground motions do not cause damage to the power plant or heavy industrial structures and equipments, see for example EPRI (1989), EPRI (2007). However, the output signal of relays is important for safe shutdown of the plant and may be influenced by high-frequency vibrations. In the industrial process, the functionality verification of SSCs under APC induced vibrations is performed from the FRS by numerical calculations or experimentally with a shaking table. As a consequence, the calculation of induced vibrations should be valid for frequencies higher than earthquake frequencies.

IRIS3 benchmark follows the IRIS 2010 and 2012 benchmarks, that were dedicated to the structure integrity. The present paper describes the validation of the EUROPLEXUS code for the FRS calculation of high frequency vibrations, based on the IRIS 3 benchmark soft impacts on a reinforced concrete structure.

IRIS 3 BENCHMARK OVERVIEW

IRIS 3 is a series of three impact tests, see Darraba, Galan and Hervé Secourgeon (2016). The same kind of missile is used in the three tests, a deformable hollow steel pipe with a pipe thickness of 2 mm and a total mass of 50 kg. In the first two tests, the target impact velocity is 90 m/s while the target velocity in the third test is 170 m/s. Actual velocities are close to these values.

Impact area on the mock-up is centered on the front wall, as illustrated on Figure 1.

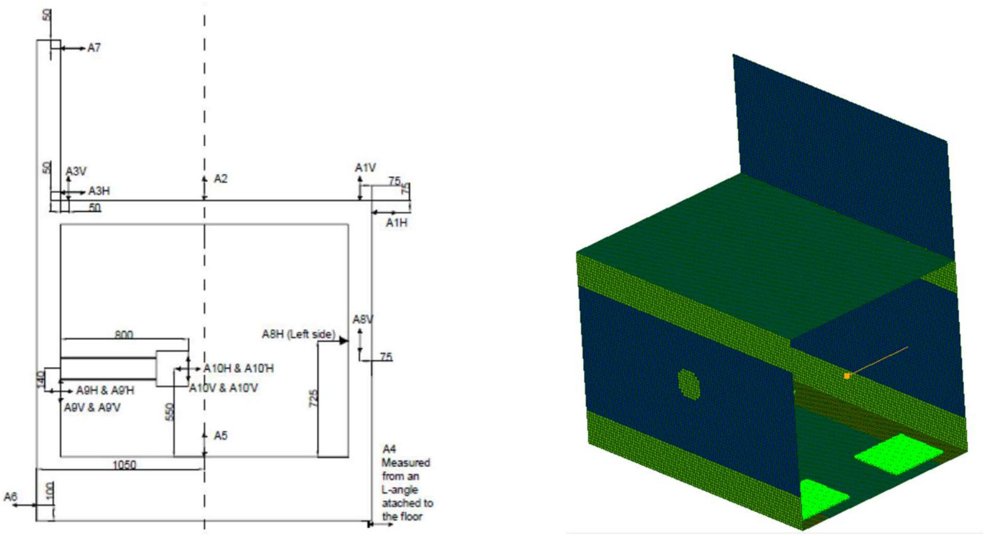


Figure 1. Acceleration sensors A1 to A10 in the mock-up symmetry plane (side view) and view of the FE mesh for numerical calculations. The circle in the figure on the right represents the impact surface

The mock-up is a structure made of reinforced concrete. It is composed of a front wall, a rear wall, a upper and a lower slabs and a cantilever wall on top of the rear wall, all of them being 15 cm thick except the lower slab which is 40 cm thick. Mock-up width is 2.5 m and its height is 2.0 m including the lower and upper slabs thicknesses.

The mock-up is made with a C40/K50 concrete. The reinforcement steel quality used in the mock-up was B500B for both the longitudinal as well as the shear bars.

In addition, two “pseudo-equipments” are anchored to the rear wall (see Figure 1, Figure 2). They are composed of a 61 kg cylinder mass located at the top of an IPE beam. The latter is fixed to the rear wall with welded connection or with bolted connection to the anchor plate.

The mock-up is vertically supported on the ground of the test hall by means of four supports. Under the laboratory slab, the soil was reinforced with concrete so that almost no displacement can be expected at the lower part of the mock-up supports.

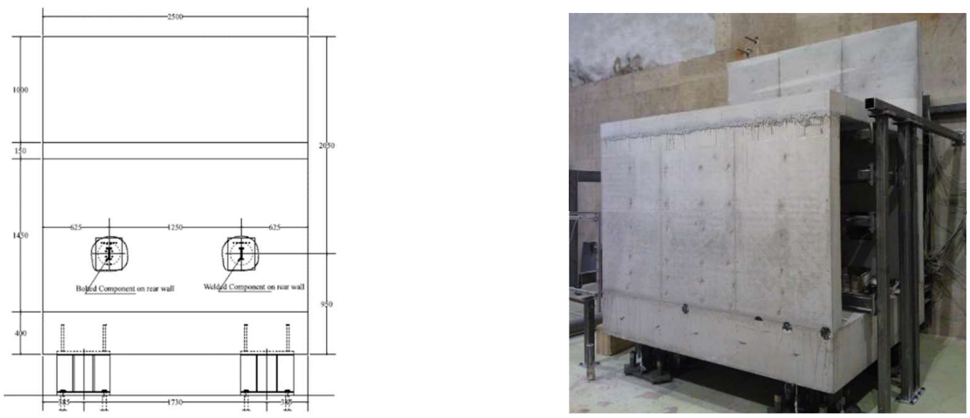


Figure 2. IRIS 3 mock-up (front view) from a drawing and a photo in the test hall

NUMERICAL MODELLING

The FE mesh, used for the modal and the impact analysis computations, can be seen in Figure 1. The structures are modelled with thick shell elements, except for the IPE140 beams (beam elements) and for Pseudo-equipments cylinder (local mass of 61 kg).

The IPE beams are connected to the rear wall by means of a common node. Therefore the IPE anchorage is simplified and is the same for both welded and bolted equipments. The anchor plate is not modelled. The mesh size is 25 mm for all the shell elements and 50 mm for the beam elements. Sensitivity analysis on the mesh size is performed to ensure robustness to this parameter.

The three impact loads are simulated in one calculation to take into account possible concrete damage at initial state of second and third impacts. The Riera method is used to compute the impact force for both 90 m/s and 170 m/s impacts, see Figure 3. The missile is not modelled. The missile buckling force is calculated according to Jones (2012), assuming a steel yield stress of 400 MPa (see Figure 4).

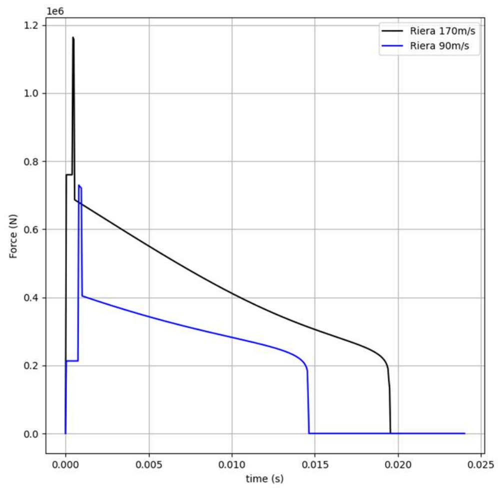
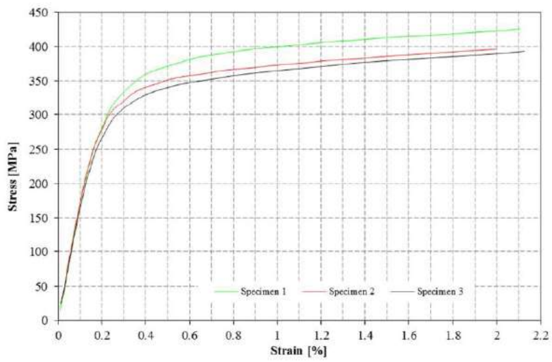


Figure 3 : Impact loading for tests Va / Vb (90 m/s) and Vc (170 m/s)

Each of the 4 supports under the mock-up is modelled through 0D elements, on a set of nodes of the mock-up lower slab. The area of this set of nodes is matching the anchor plate area of the support of 500 x 500 mm². Each set is then composed of 420 nodes.

The tension/compression and shear equivalent stiffnesses of each support are equally distributed over the 420 nodes modeling each support. These stiffnesses are computed with the help of a local model of a support. The equivalent stiffnesses considered for each support are 4,6 E+8 N/m in tension, 6,9 E+9 N/m in compression and 3,7 E+8 N/m in shear.

Material calculation properties are based on concrete class C40/K50 and on specimen static tests results given by the laboratory for concrete and rebars. The measured concrete Young's Modulus is approximately 28 GPa and the compression strength on cylinder is slightly higher than 50 MPa, with some scattering between slabs. The rebar yield stress considered is based on the test specimen curve, which is reported on Figure 4.



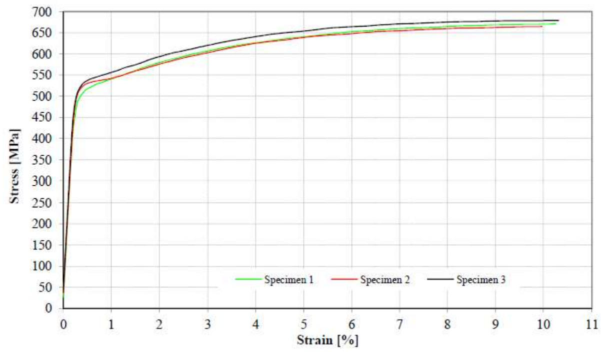


Figure 4. Tensile test results on missile specimen (on the left) and rebar specimen (on the right)

The material model is the global-type GLRC DAMA (GLobal Reinforced Concrete with DAMAge) of the EUROPLEXUS code, see Koechlin (2007), Koechlin and Potapov (2007). It is used for the reinforced concrete walls and slabs. This model is formulated in terms of generalized stresses and strains and is based on the homogenization of the non-linear behaviours of concrete and steel composing the reinforced concrete. GLRC DAMA parameters are defined from the usual calculation of the bending moment-curvature relationship of the reinforced concrete section. GLRC DAMA deals with damage and non-linear effects for both membrane and bending deformations. Strain rate effects are not taken into account in the material model. For the front wall, a strain rate coefficient of 1.1 has then been considered and applied to the concrete compression and tension strengths and for the steel yield stress.

The usual Rayleigh's damping model is used together with the material model. It is applied on the whole mock-up elements, with a 4 % damping at f1=10 Hz and f2=100 Hz. f1 is approximately the observed displacement frequency of the mock-up. It can be estimated with a preliminary calculation. In a high frequency range, the mock-up modal behaviour is not well modelled and the high frequency accelerations under impact are experimentally damped, which can be the result of numerous singularities not included in the modelling : small cracks due to concreting, construction concreting joints, etc. In NPP, the modal frequencies of the structure are usually smaller and lower value for f2 should be more appropriate due to the change in scale between the mock-up and the real buildings. The 4 % damping value is justified by numerical and experimental comparisons by EDF, showing that the non-linear material model is under dissipative because it does not take into account all the dissipative non-linear phenomena.

Results

Displacements results are given hereafter, in various locations of the mock-up (sensors D2, D3, D7 are located close to accelerometers A2, A3, A7, see Figure 1). D01 is at the centre of the impact area, so that impacted slab non-linear behavior can be assessed, particularly on the third impact. D3 is at the connection between upper slab and rear wall. It is supposed to be mainly affected by the mock-up first mode. D2 and D7 are located respectively at the upper slab centre and at the top of the cantilever wall. These two locations are at different distances from the impact point, and include the mock-up first mode and local bending modes of the slabs. Numerical results are denoted EPX on figures, they are compared to measurements referred as Test on figures.

On displacements results, permanent displacements are underestimated by approximately 1 mm, as an order of magnitude. It is more visible on the first two tests as displacement magnitudes are a few millimeters in these tests. It can be related either to material model or loading calibration, or to tests conditions, due to the construction concreting joint at the walls bottom part (cracks were visible before the first test). Apart from that, there is a good agreement on displacement magnitudes and frequencies between tests and numerical results.

Test results presented are from mechanical measurements. On locations where laser measurement was performed, at the same location, differences with mechanical results are lower than 10 %.

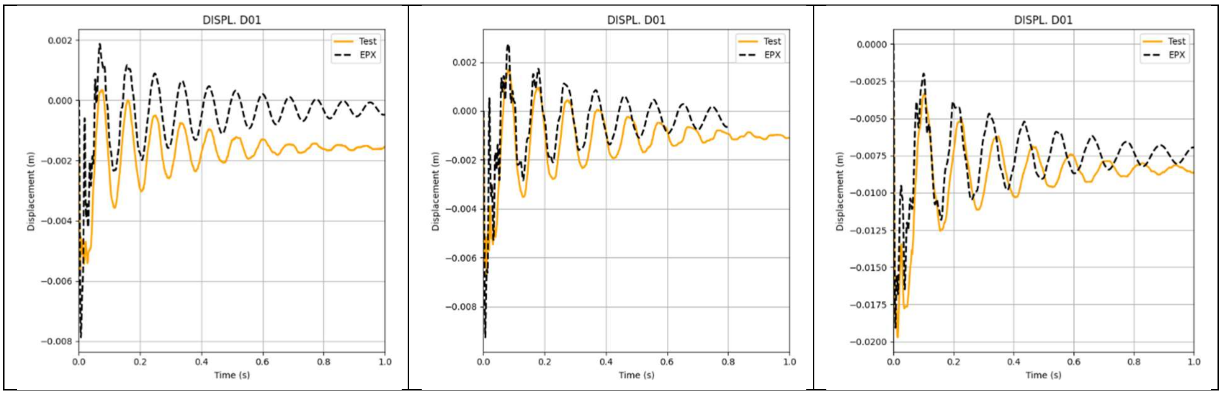


Figure 5. Displacements at sensor D01 for impact 1 (on the left) to impact 3 (on the right)

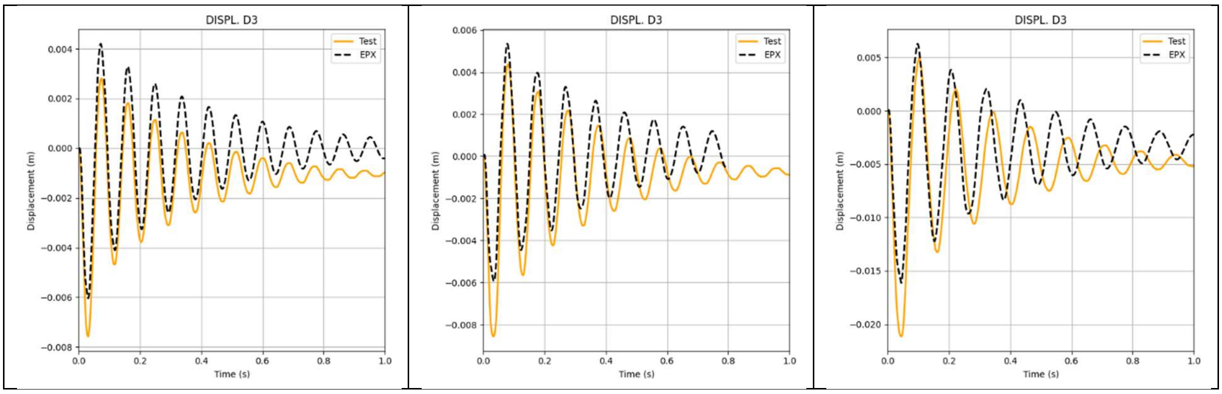


Figure 6. Displacements at sensor D3 for impact 1 (on the left) to impact 3 (on the right)

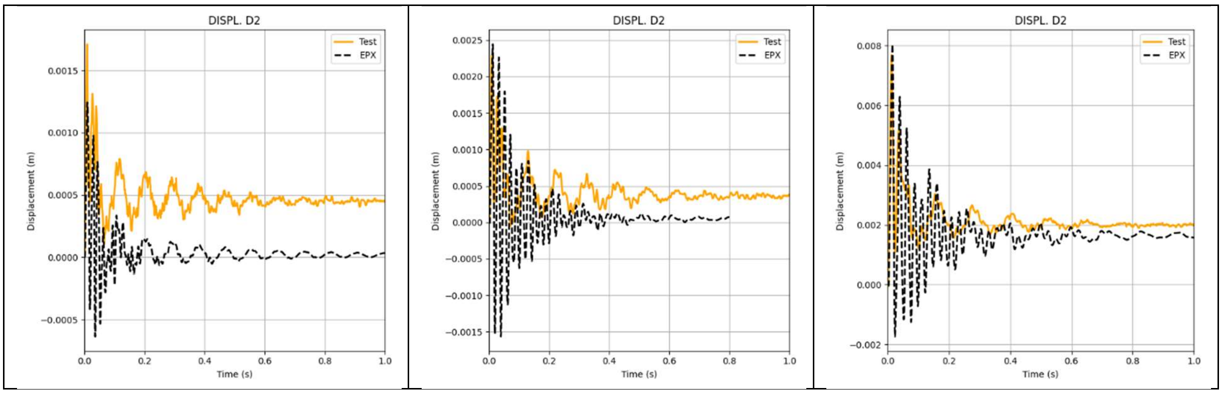


Figure 7. Displacements at sensor D2 for impact 1 (on the left) to impact 3 (on the right)

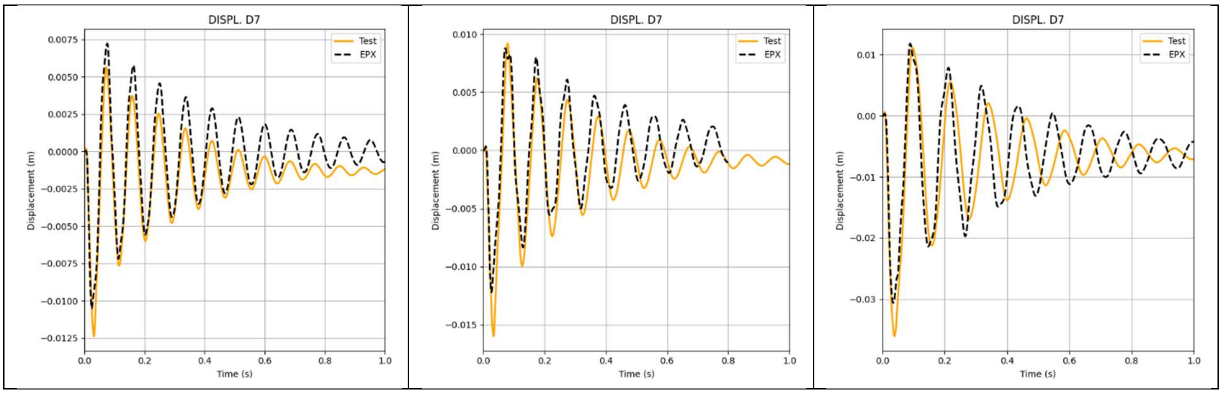


Figure 8. Displacements at sensor D7 for impact 1 (on the left) to impact 3 (on the right)

The Floor Response Spectra (FRS) at 5% damping at sensors A2, A3H, A7, A9BH and A9WH are given hereafter. A9BH is the sensor on the anchor plate of the bolted component at the rear wall and A9WH is on the welded component side.

In the first impact test, some sensors were considered unreliable by the laboratory, including A1, A2 and A3. The test and calculation FRS are presented in Figure 9 for A7, A9B and A9W.

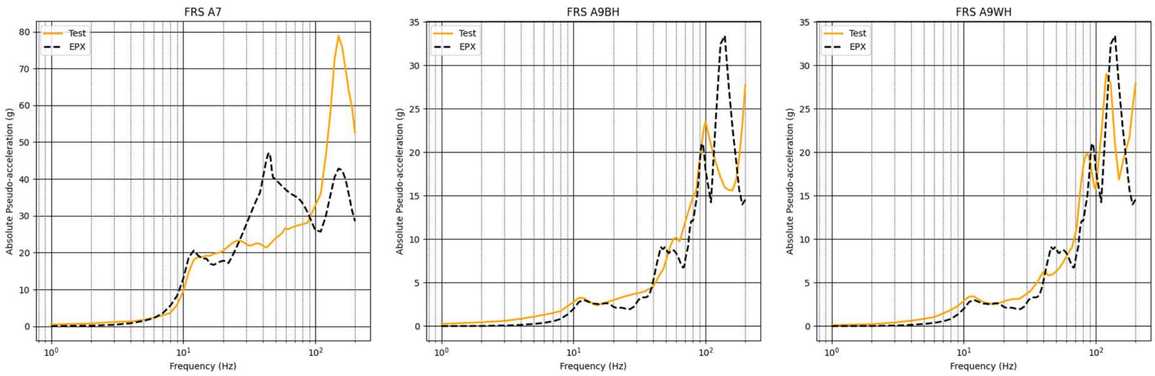
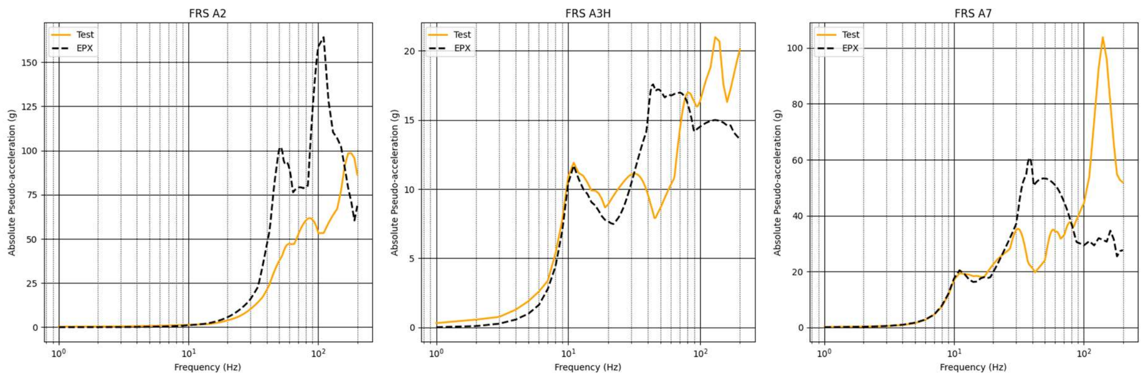


Figure 9. FRS at sensors A7, A9BH and A9WH for the first impact

The experimental FRS are well estimated for the three sensors up to approximately 100 Hz.

The test and simulated FRS for the second impact at 90 m/s are presented in Figure 10.



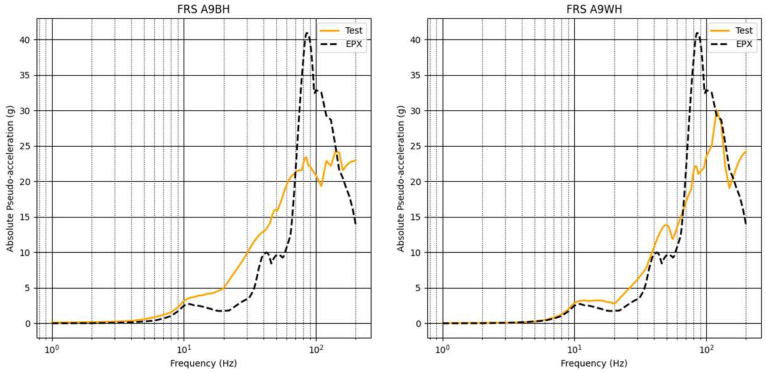


Figure 10. FRS at sensors A2, A3H, A7, A9BH and A9WH for the second impact

The experimental FRS are well estimated for the sensors A2, A3H and A7 up to approximately 100 Hz. The low frequency content at measured A3H gives reasons to doubt its correctness on this range, with non-zero value at f=0. Power spectral density of the time history signal also points out the same measurement doubt. For sensors A9WH and A9BH, the FRS are underestimated in the frequency range 20 to 60 Hz (and highly overestimated at 80-100 Hz). Results in A9 may be affected by the simplified modelling of the pseudo-equipments, linked to the rear wall at only one node close to A9. Pseudo-equipments were designed to have a bending mode at 45 Hz. However there is a good agreement in the two other tests, therefore the measurement can also be questioned in this test.

The test and simulated FRS for the third impact, at 170 m/s, are presented in Figure 11.

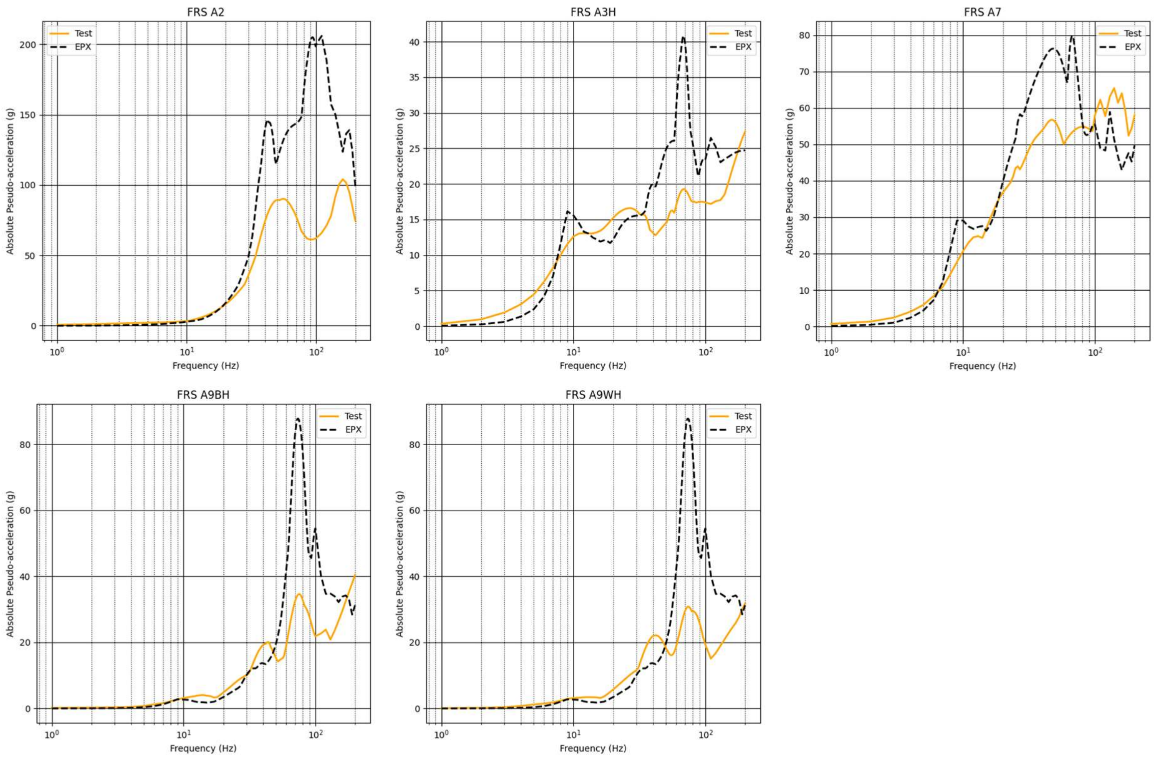


Figure 11. FRS at sensors A2, A3H, A7, A9BH and A9WH for the third impact

For this impact test with damage, the experimental FRS are well estimated or overestimated up to 100 Hz. Significant pseudo-acceleration peaks are in the numerical results and not in test results, in the approximate range of 50 Hz to 100 Hz. It was also the case of some sensors in the first two tests.

Sensitivity analysis

Sensitivity calculations are performed. One parameter is modified, one at a time, in each calculation. The reference calculation “NOMINAL” is the calculation presented previously. The results are presented in Figure 12 for the first impact. The same conclusions are drawn for the two other tests.

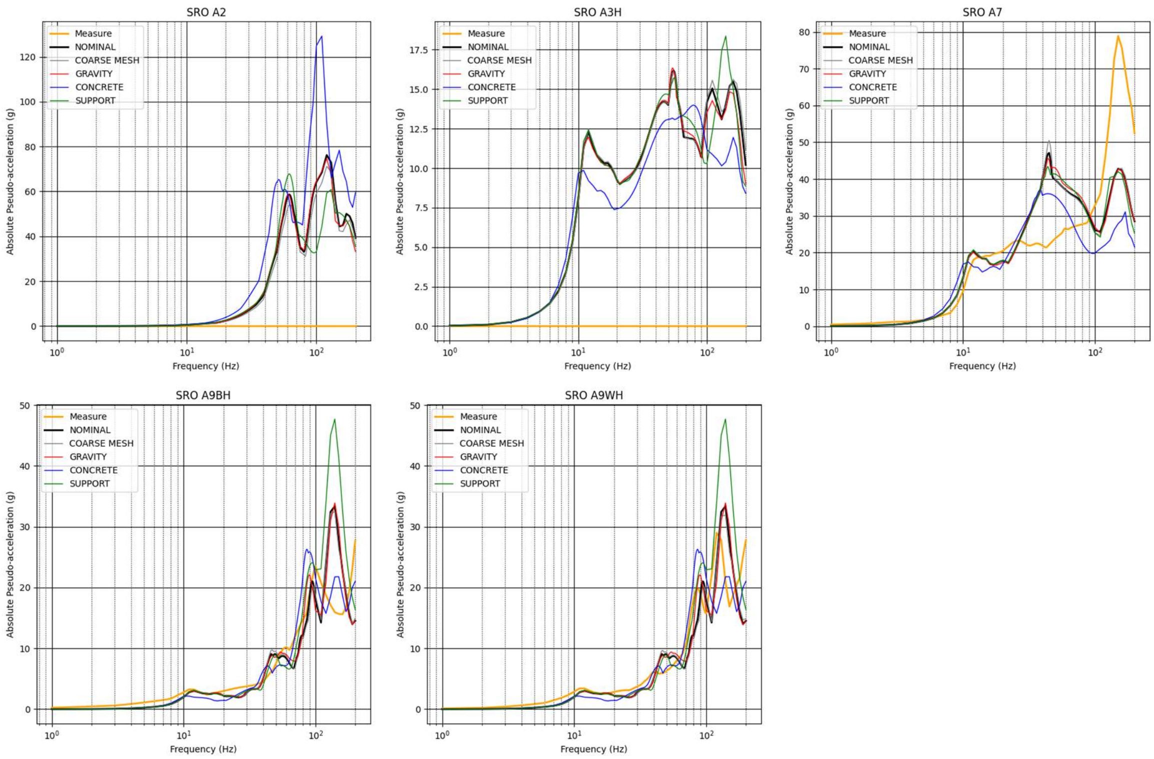


Figure 12. Sensitivity study – FRS at A2, A3H, A7, A9B and A9W for the third impact

Removing the gravity modelling (“GRAVITY”) has a negligible effect on the FRS. The use of concrete specified properties (“CONCRETE”) instead of measured ones, for the compressive strength and the Young’s modulus, has some influence on FRS without any clear trend on the whole sensor points and frequencies. The modification of support stiffness under the mock-up in the “SUPPORT” calculation ($k=10^9$ N/m both in tension and compression) sometimes modifies the FRS magnitude, generally beyond 50 Hz. Modifications in lower frequencies are considered as not significant. Finally, a coarse mesh, with twice the initial mesh size, gives negligible differences, as with finer mesh (not presented on Figure 12).

HIGH FREQUENCY (HF) TESTING PROGRAM, ON ELECTRICAL EQUIPMENTS

This EDF program was carried out from 2015 to 2018, on various electrical equipments that are installed on Nuclear Power Plants (NPP) in France. The major part is a representative sample of the equipments already installed on sites.

Equipments are from the three electrical equipments families : instrumentation, electric supply and I&C system and cabinets. Some of them previously passed a seismic qualification test.

Equipments are either civil mounted equipments or components. They are tested with increasing acceleration magnitude up to respectively 5.7 g and 20.0 g maximum value. There is a limitation due to the experimental device given the equipment mass, dimensions and frequency content of the signal. The three directions are tested, each way, for a series of accelerograms and for increasing magnitudes resulting in about 400 tests on each equipment.

Equipments have very different masses and dimensions, from a few kilograms to one ton for the heaviest cabinet, and very different dynamic properties, from small size sensors to large size cabinets, resulting in various eigenfrequencies. Critical frequencies along the three axes were tested with sine sweep for each equipment before and after the HF testing series. They have a broad range of functional properties, with various dysfunctional events checked during or after the tests.

Accelerations over time that are used in tests come from calculations on EDF NPP under APC loadings, with various configurations in terms of impact to equipment distance and civil works layout along this distance. Signals are therefore representative in terms of total duration, of duration of acceleration peaks as well as frequency ranges involved. This is consistent with previously mentioned EPRI testing conclusions, that recommended to use realistic signals as far as possible. Accelerations are neither built from PSA curves nor based on HF sine sweep testing, which turned out to be too severe without any useful information about HF sensitivity.

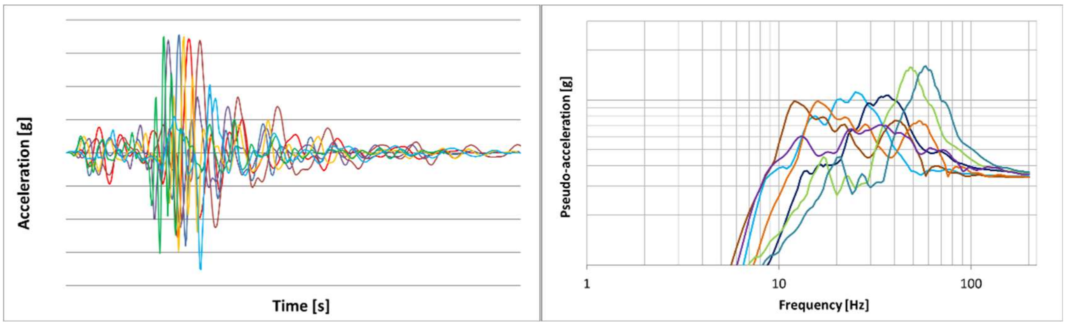


Figure 13. EDF HF testing program : time history accelerograms and associated PSA

Validation done, previously summarized for IRIS3 tests, makes it possible to assess HF functional capacity of an equipment inside NPP for induced vibrations, to compare it to seismic qualification HF capacity and to HF capacities in NEI 07-13, see ERIN (2011).

Figure 14. EDF HF testing program – Some of the tested electrical equipments (temperature sensor on the left; relay command board at the centre; LT switchboard on the right)

CONCLUSION

In the frame of OECD/NEA, IRIS3 benchmark aimed at better understanding the induced vibrations propagation in Reinforced Concrete structures subjected to soft impact. Displacements and accelerations are measured on a mock-up, at various distances from the impact point. EUROPLEXUS fast dynamics code is validated on the series of impact tests, with tests and numerical results comparison. In the first two tests, low damage and almost no plastic strains are reached. Despite the initial low damage in the second test, similar measurements in these two tests give confidence in the tests and calculation comparison. The third test provides data for a higher damage state, with moderate plastic strains in the impacted wall.

The experimental FRS are well estimated up to approximately 100 Hz. This frequency range includes the first mode of the mock-up at 8 to 12 Hz under impact. Beyond 50 Hz, numerical FRS can exhibit peaks that are not observed in tests results. They may be due to secondary modes, that are damped in the tests. It can be linked to acceleration sensitivity, that seems to increase with frequency. Although this sensitivity should be read carefully, as it deals with very low displacements and energy at high frequencies. It can then be verified whether short duration accelerations, that are harmless for most SSCs, can influence the functionality of electrical equipments such as relays.

A High Frequency (HF) testing program was carried out by EDF on electrical equipments. The main part of them are already installed on NPP sites. A series of about 400 tests was performed on each equipment, with different accelerograms from APC calculations on NPP structures. Each accelerogram was applied in all the directions, and with increasing magnitude up to the maximum acceleration of 5.7 g for civil mounted equipments (including cabinets) and of 20.0 g for components.

No mechanical damage was observed. Contact chattering occurred during the tests for some of the equipments at high magnitudes. All the equipments remain functional after the test series. The HF capacity is up to 5 times higher than what is applied in seismic qualification tests. It also confirms the NEI 07-13 capacities for the most sensitive equipments, at a 95% confidence level.

Finally, on the basis of induced vibrations validation, sensitive equipments in NPP can be verified with dedicated tests and various signals in frequency content and magnitude, to ensure that they remain functional under loadings such as APC.

EDF acknowledges VTT and IRIS3 project leader Ari Vepsä for all the work done on impact tests.

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