



METHODOLOGY FOR SEISMIC MARGIN ASSESSMENT OF ELECTRICAL AND I&C EQUIPMENT BASED ON ELEMENTARY TESTS AND NUMERICAL SIMULATIONS.

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INTRODUCTION

The seismic qualification of electrical and Instrumentation and Control (I&C) equipment to seismic loads is routinely performed on shaking tables with excitations corresponding to a site-specific or a project specific seismic excitation. These tests give a binary result: either the equipment sustains the load, or it does not. They do not provide the amount of margin available above the tested levels. This comes as a limitation when performing seismic margin assessment as described in EPRI 2018 and when trying to use the existing tests results for another site or project.

A new qualification approach based on the joint use of tests on elementary components and numerical simulations was set in place by Framatome as part of the French SINAPS research project, see Berge Thierry et al, 2017. It allows a direct comparison between the site-independent seismic capacity of individual components and any site-specific seismic demand.

This paper describes the overall principle of this approach. It first presents the determination of the seismic demand for a given site or project and illustrates it for a typical **I&C cabinet**. It then focuses on the determination of capacity of a particular set of inner components known to be limiting when performing seismic margin assessment: **electrical relays**, whose earthquake induced chattering may induce failure of the related I&C systems. Finally, the comparison of capacity and demand is illustrated, and it is concluded on the possible generalization of the method.

DETERMINATION OF THE SEISMIC DEMAND SPECTRA

Many of the safety relevant electrical and I&C elementary components are attached into cabinets, racks, panels or other supporting structures. These supporting structures are typically anchored onto a floor of the nuclear plant, and they can both filter and/or amplify the seismic excitation from the floor to the inner components. Figure 1 a) shows a typical I&C cabinet, installed on a shaking table for its seismic qualification. This cabinet is part of a system comprising several similarly built cabinets that are hosting different possible arrangement of inner components, leading to different mass distributions and dynamic behaviour.

One possible option for the seismic qualification of the whole system is to test each and every possible arrangement of inner components in the supporting structures. Another option, more practical and cost effective, is to characterize the dynamic behaviour of the supporting structures first and to test the

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components alone or by groups in a second phase. In that case, one or several numerical models of the supporting structures are built and calibrated based on only a reduced number of actual shaking table tests. The numerical models are calibrated to best represent the actual tested structure behaviour. This calibration typically includes the damping value assigned to the numerical model and may include the representation of the anchorage stiffness (see Gupta 2019).

The numerical models allow the derivation of transfer functions between the anchorage floor and the inner components locations inside the supporting structure. The comparison of transfer functions obtained from the shaking table tests and from the numerical model allows a validation of the numerical model calibration. Figure 1 b) shows a set of calibrated transfer function corresponding to different altitudes within one configuration of cabinet. The use of transfer function implies that the supporting structure has a linear or almost linear behaviour. This can be assessed by performing sine sweep testing with various amplitudes in the amplitudes range of the expected seismic response.

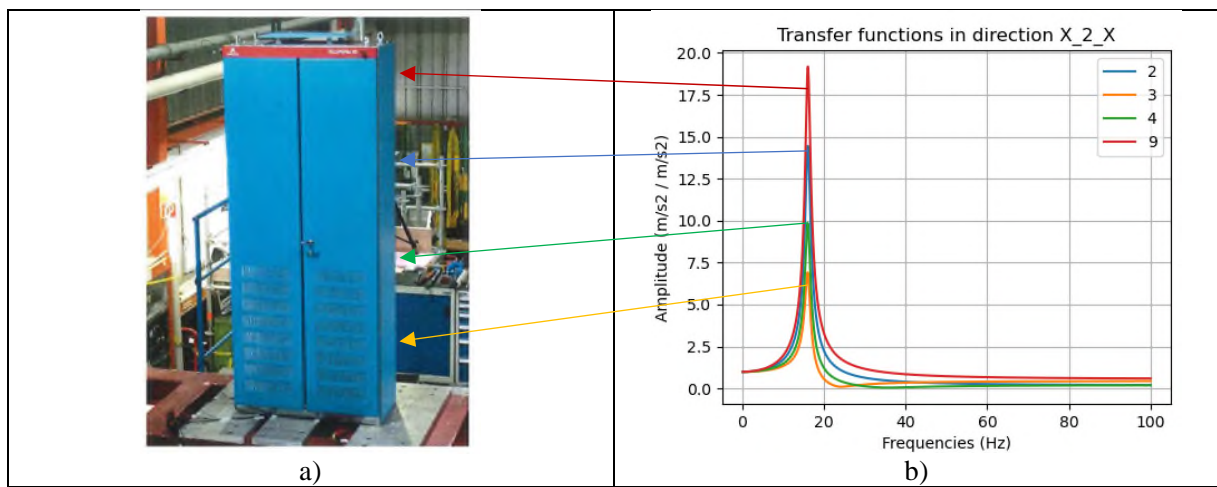


Figure 1. View of an I&C cabinet and typical transfer functions associated to different elevations

For various arrangements of the inner components within the supporting structure, the corresponding variations of the transfer functions can be calculated. Using the cabinet stiffness and masses determined by calibration and varying the distribution of internal masses, a set of transfer function reasonably covering all on-site configuration is established, as illustrated of Figure 2.

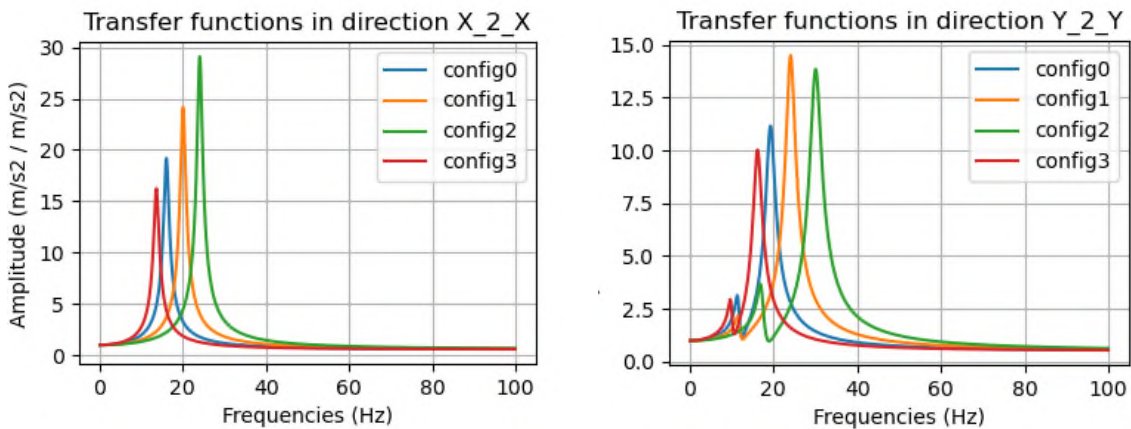


Figure 2. Transfer functions covering all possible cabinets configurations

The seismic demand to be applied to the I&C system is generally known to the designer in the form of floor response spectra (FRS). From these FRS, synthetic time histories can be generated and transferred to the different altitudes of the different configurations of cabinets, using the transfer functions of Figure 2. Figure 3 shows an example of FRS and associated floor synthetic time histories.

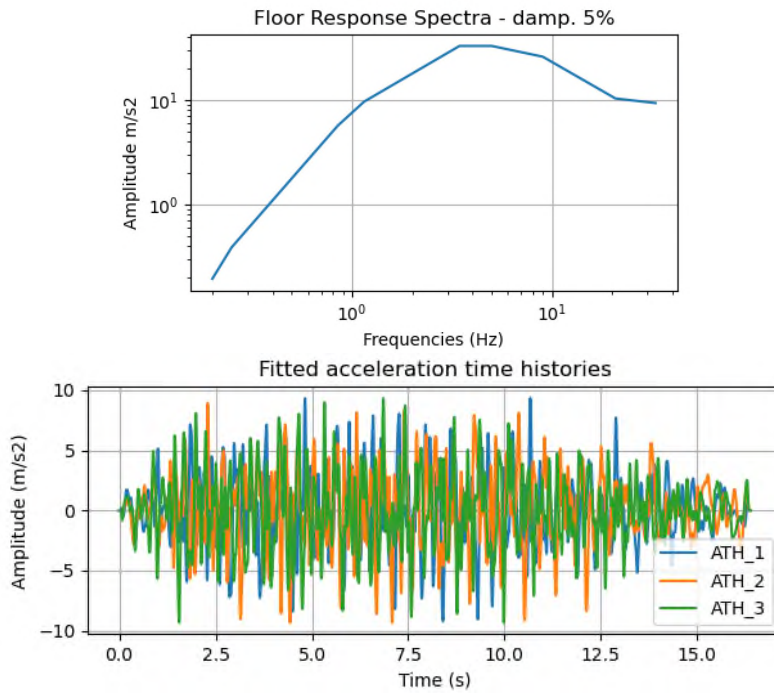


Figure 3. Floor response spectra and associated synthetic time histories

Figure 4 shows the in-cabinet response spectra (ICRS) resulting from the transfer of several time histories through several cabinet arrangement configurations. Enveloping, widening and smoothing the individual response spectra allows to cover all possible on-site cabinet configurations that would be in-between those explicitly considered. The enveloped, widened and smoothed ICRS are the seismic demand spectra applicable to the system inner components.

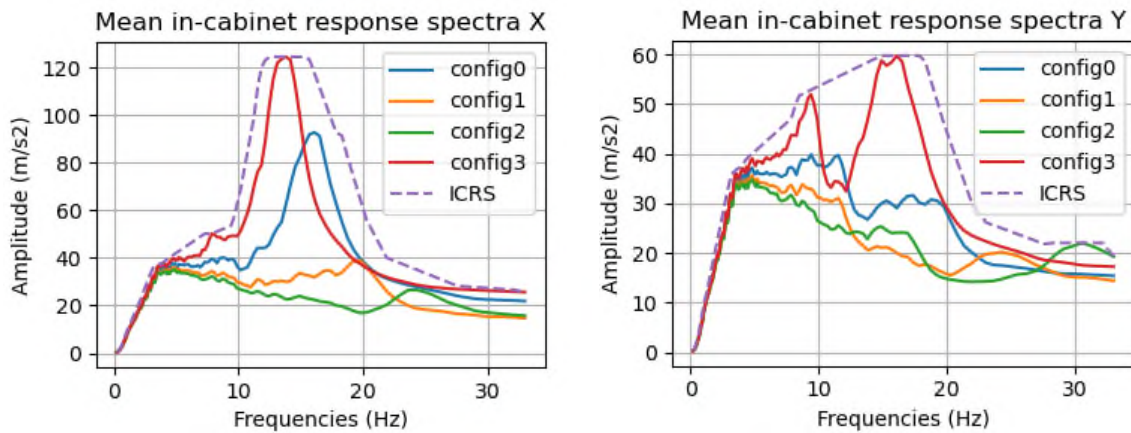


Figure 4. In-cabinet response spectra and final seismic demand spectra

DETERMINATION OF THE CAPACITY SPECTRA

Present practices and induced margins

The failure of I&C system inner components can be of different natures depending on the requirements assigned to each of them. A particular focus is generally put on components that are required to remain operational either during or after the earthquake. For these components, shaking table qualification tests are the usual industrial practice. Several kinds of excitation signals can be applied during these tests: a) Synthetic acceleration time histories representative of a project defined ICRS. This is the “best estimate” approach, but it is seldom used because the results would be too project specific and difficult to re-use in other projects. b) Synthetic time histories representative of a generic component qualification spectra that covers many possible configurations of components supports within many possible nuclear plants on different sites. As an example, such a generic spectrum is given in the RCC-E 2022 design code. These spectra are very conservative and might be challenging for some sensitive components. c) Sine sweep signals applied on a wide frequency range with an amplitude high enough to cover for several project specific seismic demand. Although this is not usual, these sine sweeps may also be represented by their response spectra.

As an example, in Figure 5, the ICRS of Figure 4 are compared to the RCC-E generic component spectrum and to a spectrum originating from a sine sweep qualification performed with an amplitude of 20 m/s² between 5 and 100 Hz with a sweep rate of 2 octaves per minute. In this figure, the large conservatism associated to the use of the generic qualification methods, either RCC-E or sine sweep, is obvious. The sine sweep excitation is much more conservative than the actual seismic demand up to 500 Hz, even though the actual maximum acceleration applied is of the same order of magnitude for both excitations.

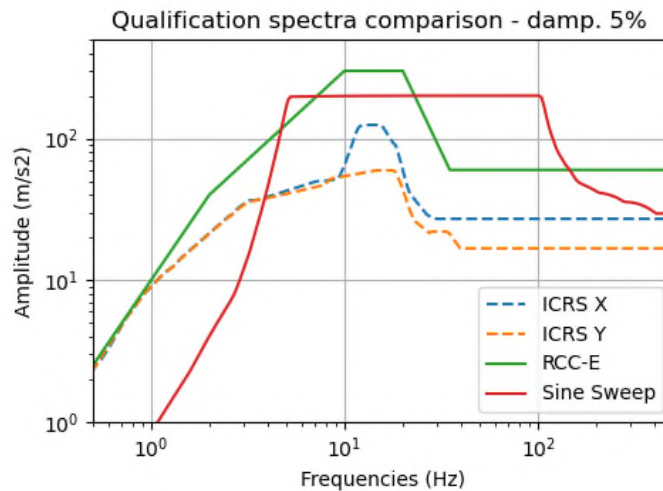


Figure 5. Comparison of the ICRS seismic demand to the generic qualification spectra

This difference between the actual seismic demand and the capacity as demonstrated by generic testing is a source of margin readily available when performing seismic margin assessments. Still, for the projects where the seismic demand is higher or where higher margins are requested, the above-mentioned qualification methodology might prove insufficient.

New methodology and example of application

The SINAPS research program was aimed at identifying and quantifying the uncertainties for the probabilistic risk assessment of nuclear power plants. One of its findings, supported by industrial studies, was that some I&C systems were limiting the complete fragility analyses, due to the lack of knowledge about their behaviour beyond the level they were submitted to during their qualification. The R&D described in the present paper was conducted as part of this program.

Within the I&C systems, electrical relays were found to be one of the weakest components, driving the fragility of the whole system. The possible seismic induced chattering of these relays may lead to switching errors in the process chain of the system, and, consequently, to a risk of operational failure. A relay chatter is a dynamically induced mechanical change of state, producing either an interruption or a spurious actuation of an electrical signal. During a seismic qualification a relay chatter is detected by continuously monitoring the electrical signals and recording any undesired change of state.

A test set up was built in Framatome lab in Erlangen to test electrical relays on unidirectional shaking tables. The set up is sufficiently rigid for the table excitation to be exactly conveyed at the relays positions, without any filtering or amplification. The test set ups of different excitation directions are illustrated in Figure 6.

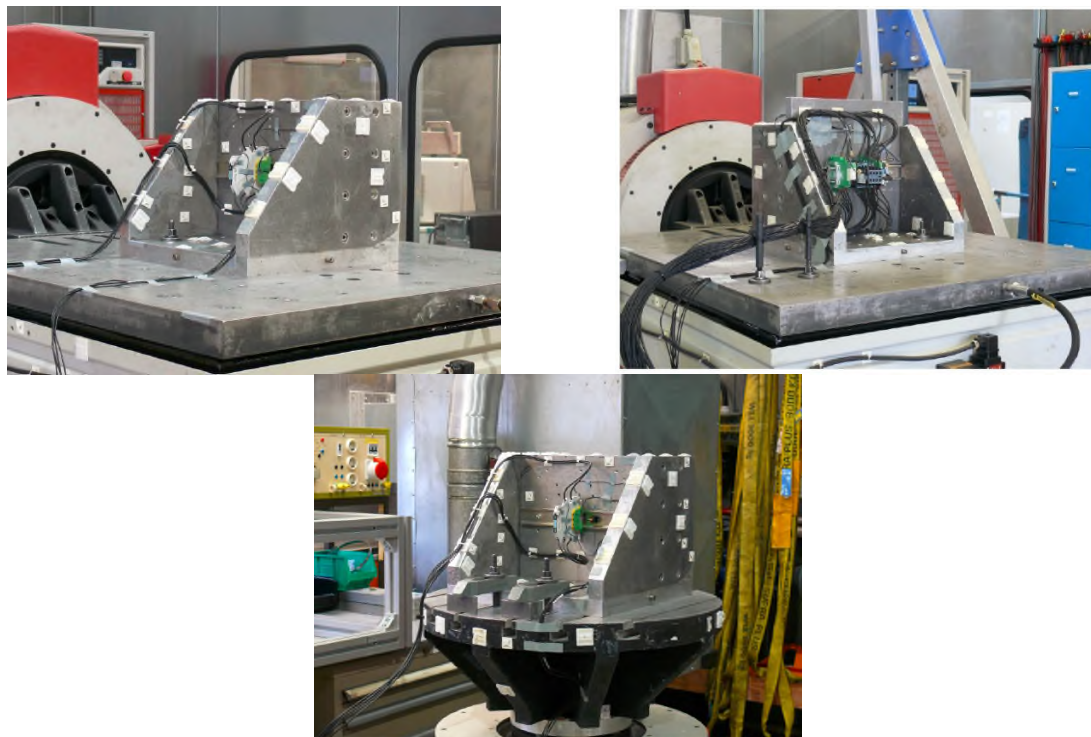


Figure 6. Test set-ups for the testing of individual components in the three directions of space

In each test, several individual components were tested at once. 4 different types of relays were tested, belonging to four different technologies by two different manufacturers. For each specimen, the tests were conducted on three identical devices to ensure a minimum statistical representativity of the results. The relays were submitted to sine sweep excitations going from 4 Hz to 100 Hz and then back to 4 Hz with a sweep rate of 1 octave per minute. During the sweep up, the specimens were switched ON, during the sweep down they were switched OFF. Each device was submitted to several sine sweeps with gradually

increasing amplitude, starting at 10 m/s² and going up to 90 m/s². All changes of state during the excitation were recorded, along with their time of occurrence, that is readily associable with the frequencies provoking these changes. The changes of states were classified according to their duration. A change lasting less than 3 ms is deemed minor whereas longer signal changes are deemed major.

As it could be expected, the tests showed that an excitation along the relay switch travel direction is always significantly more penalizing than an excitation in the two normal directions. For all tests performed in the normal directions up to 90 m/s², only minor signal changes were observed, and this not for all types of relays. In the switch travel direction, on the other side, minor signal changes were observed for all relays with excitations amplitude sometimes as low as 30 m/s² and major signal changes were observed for two relays out of the four tested. Figures 7 and 8 display some typical results obtained during the test campaign. Figure 7 compares the behaviour of the four different specimens that were tested in their lowest capacity direction. Figure 8 gives the results in the three directions for one specimen (n°2). These figures give the results obtained for the first device tested of each relay specimen. Tests on the two other devices are similar, although not identical.

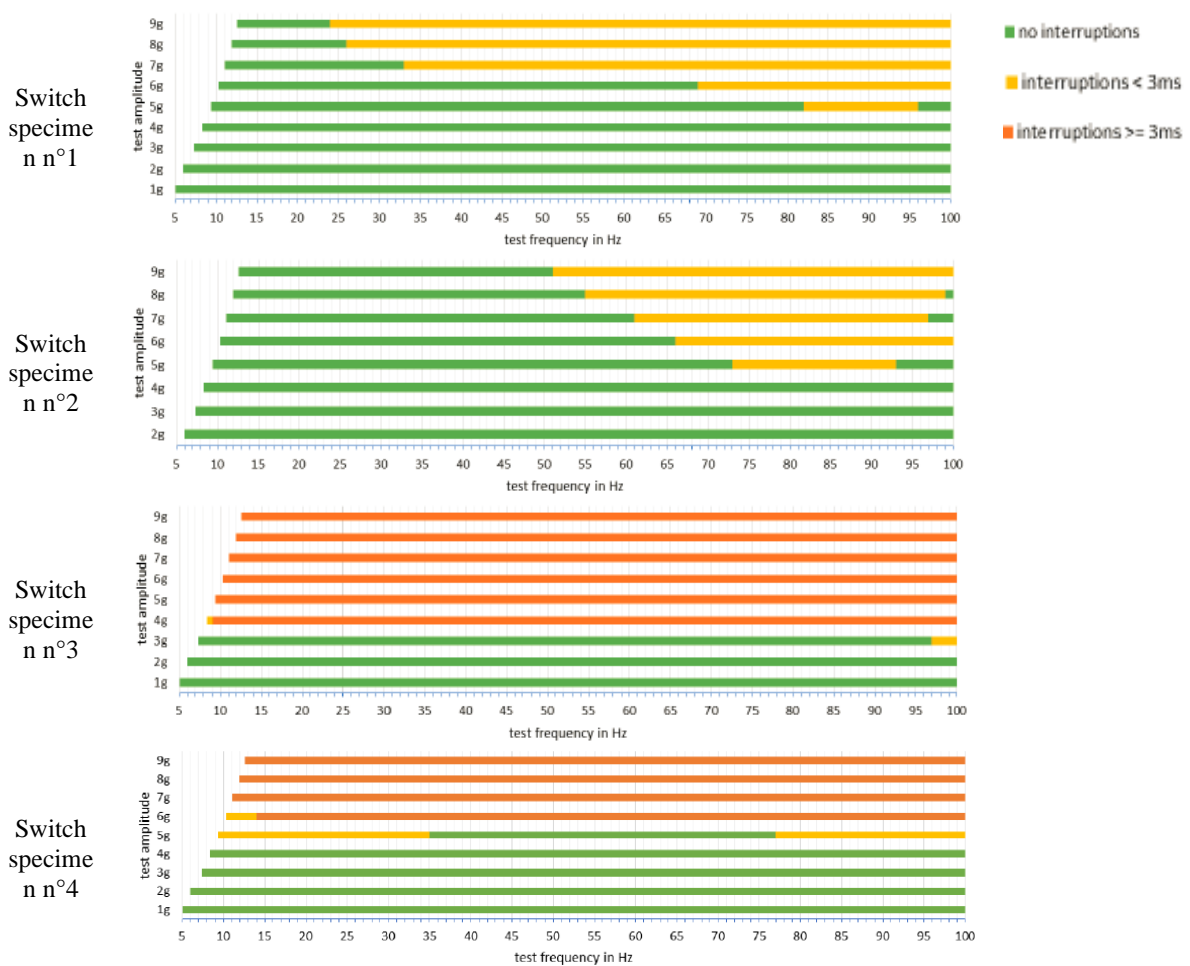


Figure 7. Results in the lowest capacity direction for the 4 types of relays tested



Figure 8. Results in the 3 test directions for the relay specimen n°2

The graphs of Figures 7 and 8 constitute a failure map for each specimen of relay tested. In the case of the specimen n°3, the failure seems to be only related to the amplitude of the applied excitation: the relay is functional for 30 m/s² and dysfunctional for 40 m/s², whatever the excitation frequency. In the cases of the specimens n°1 and 2, there is clearly a frequency range where the relay starts to chatter, and this frequency range gets wider as the excitation amplitude is increased. For the last specimen, a particular sensitivity was observed for the lower and the higher test frequencies, with a better behaviour in between. This variety of response was confirmed by the repetition of the tests on the second and third devices of each specimen.

The reverse of the failure maps of Figure 7 and 8 may be seen as the capacity map of each relay. This capacity can be represented by an equivalent synthetic composite time history excitation, aggregating the parts of the sine sweep signals for which no changes of states were observed. Figure 9 gives an example of such composite time history, corresponding to the capacity of the specimen n°2 in the direction 3. In this synthetic time history, a smooth transition between the different amplitude steps were accommodated in 5 s transition phases, as illustrated on the right lower part of Figure 9. Similar synthetic composite time histories are generated for all specimens in all directions. Response spectra can then be generated corresponding to these time histories. These spectra are the capacity spectra of the relays, per specimen and per direction.

Figure 10 gives the capacity spectra of the four tested relays along the direction 3, which is the weakest. The ratio of the capacity spectra of Figure 10 and the ICRS of Figure 5 is shown on Figure 11. The lower frequency part of the graph is not shown because, in this part, the relays were not tested but are also not expected to exhibit any resonance that could lead to chattering.

The whole physics of both cabinets and relays is encompassed into the ratio of Figure 11. In general, the minimum value of this ratio may be reached in a) the frequency ranges where the cabinets amplify the seismic excitation, b) in the frequency ranges where the inner components are sensitive to the seismic

excitation or c) at the zero period acceleration values of the spectra, which occurs when the response frequency ranges of the cabinets and inner components are well separated from each other's. In the example studied as part of the present R&D, the combination of the selected cabinets and relays would fall into the third category: the ratio is at its lowest at the zero-period acceleration. This minimum ratio can be considered as the median margin factor of the I&C system as far as seismically induced relay failures are concerned.

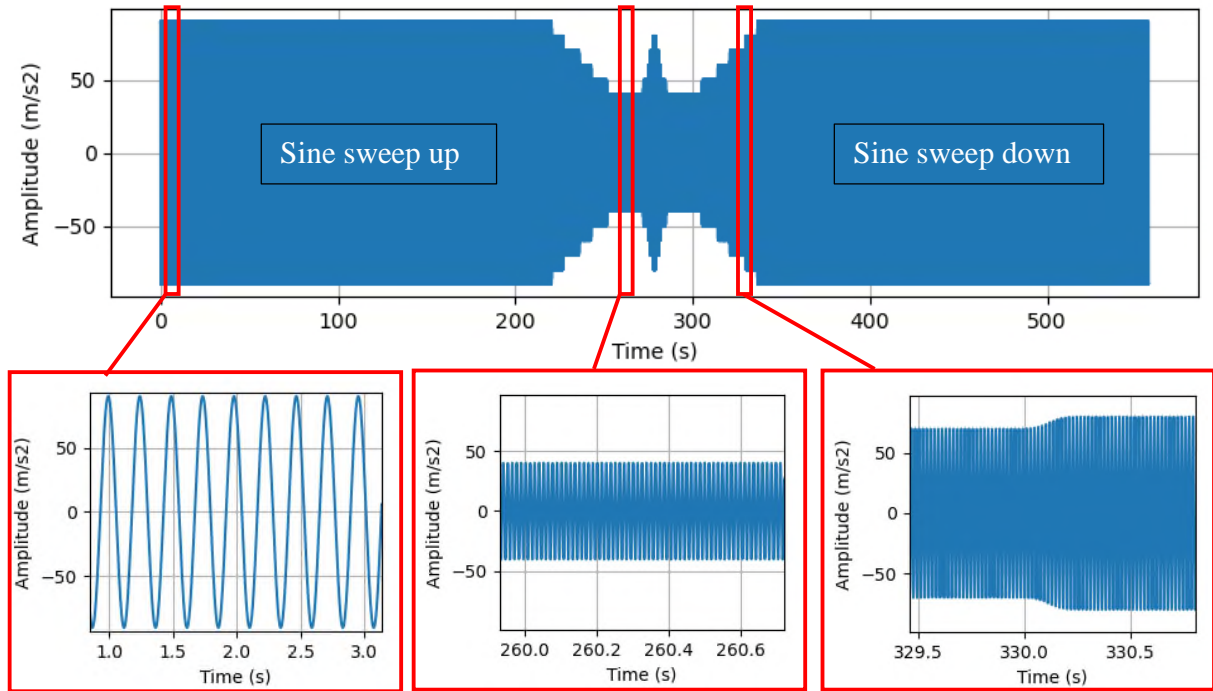


Figure 9. Composite time history for the relay specimen n°2 in the direction 3 with zoom on three different parts

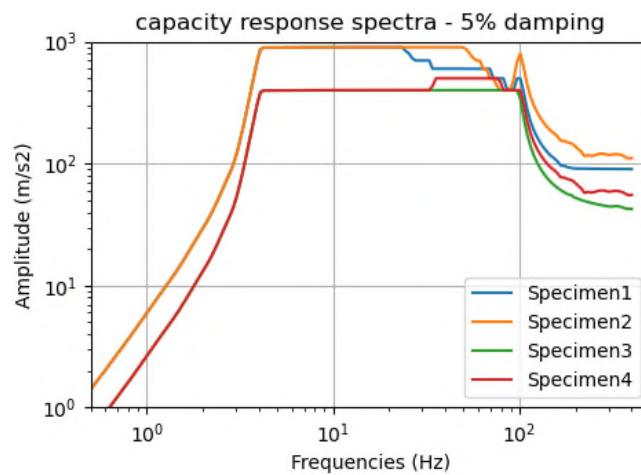


Figure 10. Capacity spectra of the four tested relays along the direction 3

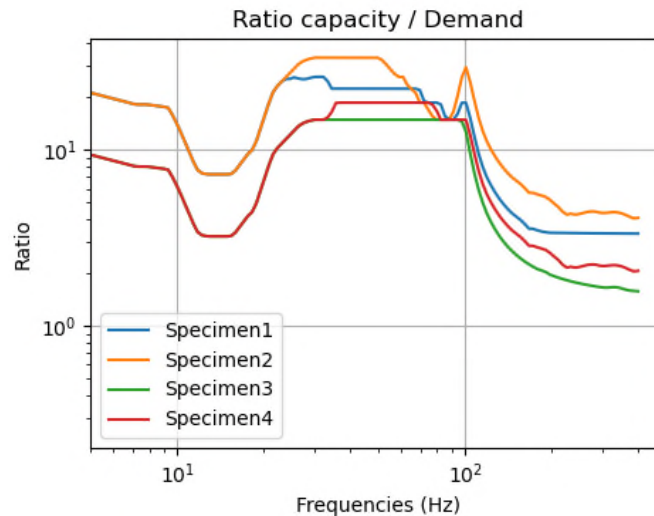


Figure 11. Ratio of capacity spectra over demand spectra

CONCLUSION

The present paper proposed a methodology to evaluate both the seismic demand within the typical I&C supporting structures such as cabinets, panels or racks and the intrinsic capacity of their inner components. Typical I&C cabinets and electrical relays, from the Framatome industrial experience, were selected to illustrate its application.

The seismic demand spectra inside the cabinets were determined by multiple frequency domain analyses, covering all possible cabinets arrangement configurations. These analyses were calibrated on a limited number of full cabinet tests on a shaking table. The seismic capacity spectra were determined by series of sine-sweep tests on the selected relays, monitoring their change of state during the excitation. Failure maps were derived from these tests and capacity spectra were generated that are fully site independent. The minimum ratio of the site-independent capacity spectra and the site-dependant demand spectra gives the best estimate margin factor for each inner components of the cabinets. The most fragile component may then be used to define the whole I&C system margin factor.

It is believed that this approach, if deployed on a large scale, may contribute to significantly increase the seismic capacity of I&C systems in seismic margin assessment or seismic probabilistic risk assessment.

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