NEW ADVANCES IN THE SEISMIC ANALYSIS OF NUCLEAR STRUCTURES AND EQUIPMENT FROM THE SINAPS@ PROJECT

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Abstract

In this contribution, an overview of the enhancements of analysis methods devoted to the calculation of structural and equipment responses and seismic margin assessment which have been elaborated within the SINAPS@ project is presented. We first underline several improvements of the current engineering practice, based upon the conventional linear assumptions. Then, we highlight the advanced methodologies based upon nonlinear constitutive models for reinforced concrete structures and equipment, which are needed for best-estimate analyses and uncertainties propagation. Both approaches take profit of enhanced definition of the seismic motion and associated intensity measure parameters. On one hand, we present the computational capabilities implemented in integrated seismic equivalent linear analyses, including soil column modelling (defining the seismic motion transfer from bedrock to the free-field and the foundation), (structure-) soil-structure dynamic interaction, structural response and transfer functions to equipment-floor anchorages. In particular, we compare the usual response spectrum method and random vibration theory results, producing mean values and confidence intervals. On the other hand, we present advanced reinforced concrete structural elements to model the nonlinear behavior of representative wall-slab structure of nuclear facilities buildings, accounting for stiffness degradation, associated energy dissipation, and internal forces redistribution. We compare floor response spectra and robustness calculations based on assumptions in terms of reinforced concrete member effective stiffness (accounting for degraded structural elements in bending) and viscous damping, as provided by usual standards and guidelines, and results obtained from refined nonlinear transient modelling, on some iconic case-studies. We emphasize the support by experimental campaigns and numerical contests to strengthen the verification and validation process of used methodologies and simulation tools for practitioners.

Key Words: Seismic analysis, Floor response spectra, Robustness, Seismic Margin, Best-estimate, SMART, Nonlinear structural behaviour, Nuclear Facilities, safety.

1. Introduction: advanced methods for designing and modelling structures and equipment for seismic safety demonstration

Context and findings

Recent evolutions of seismic risk requirements and standards in the nuclear industry in many countries around the world have increased the levels of ground motions intensity measures to be accounted for. Especially, a "Hard Core Seismic Level" (HCSL) has been defined in the French nuclear Complementary Safety Studies context after the major Tohoku earthquake and tsunami which have led to the Fukushima Daiichi power plant accident on the 11th of March 2011 [2], [4]. Other nuclear safety Authorities, such as NRC or ONR have also decided to increase former provisions against extreme seismic hazard, especially by the strengthening of the safety reassessment against the seismic risk. In the meantime, IAEA and OECD/NEA published specific recommendations and guidelines in that field: safety standard and review services, both at design stage and for periodic reassessment review [8], [15], [20]. In order to share with the academics and industrials, dedicated workshops were organized [6], [16].

In France, nuclear buildings housing safety-related equipment have to be assessed according two types of performance objectives: (1) robustness of structural elements against seismic loads, (i.e. assessment of the structural capacity, especially steel rebar quantities, accounting for ductility and internal forces redistribution) and (2) limitation of the dynamic amplification on floors supporting safety-related equipment and systems. Conventional practices in seismic analysis of nuclear power plants require to assess (1) the structural responses using a set of linear behavior assumptions and to ensure the fulfillment of (2) performance criteria expressed in terms of force variables, for robustness analyses.

However, lessons learned after some salient seismic events combined with economic stakes have led experts to investigate more realistic seismic assessment methods, see for instance [2], [14], [36], [37], in particular in order to make progress towards justification of available safety margins for existing plants. This trend began before the Fukushima Daiichi NPP accident, and was accompanied by several research and development (R & D) programs. The feedback shared by the international community after the Kashiwazaki-Kariwa seismic event in 2007 [14], was a crucial step in that way, with respect to the examination of usual design criteria and methods. Many operators decided to contribute in sharing data about equipment capacities, for instance within the Seismic Qualification Utility Group (SQUG) database, established under the auspices of EPRI [33]. Meanwhile, probabilistic approaches applied on the estimation of seismic hazards and the system fragility are more and more widespread. These data and methods allowed to implement a Seismic Margin Assessment (SMA) procedure, used for periodic safety review, resulting in optimisation of engineering work and plant strengthening [38].

For instance, it is now recognised and admitted that conventional engineering methods lead to large values of reinforcement ratios for new reinforced concrete building design and over-estimated floor response amplifications affecting equipment assessment. So the chain of safety margins and the propagation of uncertainties under seismic loading are problematic when more realistic approaches are sought: we need to assess the conservatism at each stage of the process and to master the epistemic uncertainties brought all along the computational chain by assessment methodologies.

Even though the use of advanced assessment methodologies requires specific assumptions, they are needed in order to assess accurately not only the robustness of a given structural system (equipment and structure) but also the floor dynamic amplification accounting for localized dissipative phenomena.

Design and reassessment methods, and their optimisation and evolutions

The design methods devoted to conventional constructions are nowadays mostly performance-based, namely they incorporate criteria assuming several levels of limited structural degradations to ensure up to certain extent the robustness of the structures, for instance ASCE standard SEI/43-05. Best-estimate approaches are allowed, and sometimes required, to perform beyond-design analyses. Uncertainty treatment (on the loading conditions, the material characteristics data…) makes achievable seismic probabilistic reassessment approach (SPRA) of a NPP, leading to estimate the residual probability of radiological release in the environment.

Four main features can be highlighted for best-estimate seismic assessment analyses:

1. physical-based ground motion definition and accelerograms selection,
2. nonlinear structural behaviour integration in order to determine the capacity, the ductility of structural components and the needed reinforcement ratio,
3. uncertainties propagation techniques, and :
4. higher model realism (geometry, interfaces, boundary conditions, etc.), in particular to better describe the dynamic interactions (site-structure, soil-structure, fluid-structure) and junctions between components and building in establishing floor spectra [42], [20], [39], [40]. The SINAPS@ research project has led to several advances in the states of art and recommendations in such topics in the context of earthquake engineering practices within the nuclear industry [2], [4].

2. The two ways taken by the nuclear seismic engineering studies

The major improvement of the engineering practices can take two forms, according to safety and economic issues:

1. preserve the usual practice based on conventional design methods and assumptions but with a refined methodology;
2. introduce best-estimate analyses taking profit from R&D works, including nonlinearities and uncertainties modelling.

Both can be invoked by engineering practitioners, depending on the context.

Practices based on conventional design methods and assumptions

The following improvements to conventional methods and assumptions can be highlighted:

- improvement in the floor areas geometrical description in order to avoid unwanted over-conservatism in the floor spectra calculations, as loading requirements for Structures, Systems and Components (SSCs) and safety-related equipment;
- improvement in the boundary condition modelling: dynamic (Structure)-Soil-Structure Interaction and shallow foundations (see Figure 1~~Figure 1~~) and one-dimensional site effect with equivalent linearized behaviour of the soil column from the actual soil profile, fitted to the actual seismic ground motion intensity. The ground motion signal is then defined by deconvolution in depth from the free field. High performance computing capacities are successfully used for that purpose [1]. These implementations

in engineering studies lead to more accurate calculations of differential displacements between adjacent buildings for a comparable computing burden;

- coupled dynamic interaction between equipment and reinforced concrete (RC) building within an integrated approach. It is important to notice this is required when dealing with heavy equipment;
- implementation of an integrated analysis, avoiding the inherent conservatisms lying in splitting up the seismic motion characterisation at interfaces of the whole system: site response + dynamic soil-structure interaction + RC building response + equipment/component. One specific type of integrated analysis is presented in the next paragraph :
- frequency response function fields calculations on the floors, to compute easily and anywhere in the structure floor response accelerograms and spectra. Floor response spectra can be computed by linear Random Vibration Theory, by means of power spectrum densities (PSD) determination [8], [25], using a reduced modal basis modelling of the building and a usual Site-Soil-Structure Interaction approach in the frequency domain. This methodology allows accounting for a probabilistic modelling of the seismic ground motion and the correlative dynamic response of the structural system, providing the whole floor response spectra, that challenges the traditional response spectrum analysis generating a mean expected maximal dynamic response;

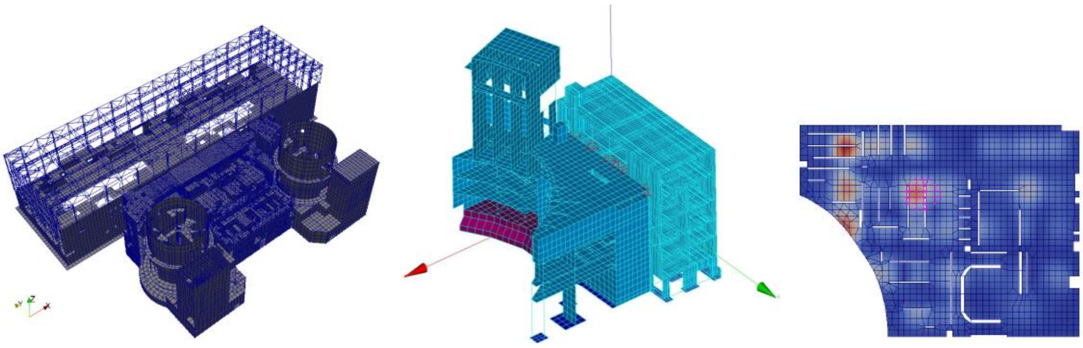

Figure 1. Left: Structure-Soil-Structure Interaction analysis. Middle: auxiliary building refined FE models of a NPP. Right: floor spectra zonation and iso-contours of vertical acceleration amplification.

- refined modelling of the supports, especially in case of differential motion of piping systems within the combination rules in the response spectrum analysis;
- specific modelling of embedded building with deep foundation in reinforced soil layer, by “full FEM” approach and equivalent linearized soil behaviour [2];
- Linear equivalent methods, relying on iterative elastic calculations with updated material properties depending on adimensional damage indicators enable to increase the the representativity of conventional analysis for structures loaded beyond their design values [23],[12];
- implementation of a SMA method to assess the seismic ruggedness of safety-related equipment and systems, from methodology established in [33], to application [38].

Advanced methodologies

As far as the advanced methodologies are required, they are founded on previous R&D works, either experimental or computational, in order to identify phenomena and parameters, then to characterise quantities of interest to validate simulation models and methods, and also from advanced nonlinear and probabilistic models. Up-to-date state of the art reviews have been recently published [34], [39], [40], [41]. Regarding the case of reinforced concrete structures, they can be applied to improve the quantification of the floor spectra and the structural robustness.

Several benchmarks and contests organised under the auspices of IAEA or OECD/NEA and supported by several R&D bodies can be mentioned. In the French nuclear industry, CEA, and nuclear operator EDF, have decided common R&D programs to better understand some beyond-design behaviours of RC structures. To illustrate these research programs, the ten year SMART project is a perfect example [27]. Two large-scale experimental programs performed on asymmetric large-scale RC structures and including shaking table tests were realized (see figure 2). The experimental data produced have been used in two international benchmarks gathering more than 40 teams coming from all over the world. The main objective was to better understand the out-of-plane effects due to bending coupled with torsion in the beyond design regime. The whole SMART program confirmed that the design provisions to be implemented according to the French nuclear guidelines allow the RC structure to sustain a seismic loading for which the intensity measure is 4 to 5 times higher than the intensity measure of the design loading. In addition, the international benchmarks allowed to make consensus on best modelling practices emerge among the scientific community. They were also interesting opportunities to test the range of application of best-estimate methods. Especially, the seismic margin factors were evaluated numerically under a blind condition and then compared with the experimental evidences. A satisfactory agreement was obtained with a moderate scattering.

Figure 2. SMART 2013 experimental campaign and numerical contest, see [25]. Left: representative RC mock-up (scale factor ¼), prone to coupled torsion-bending dynamic behaviour; right: damage field calculated by nonlinear RC plate FE method for the design level seismic motion, corroborated by concrete cracking zonation on the tested mock-up.

This program took profits from former experimental campaigns such as CAMUS (reduced scaled RC beam-column system under horizontal seismic motion [5]), NUPEC-JNES tests in Japan (RC structural systems under seismic motion [16], [35]), or SAFE (in-plane cyclically loaded RC shear walls) carried out at JRC [20]. Going along the same path as the one followed by the aforementioned R&D works, the SINAPS@ project has investigated and brought answers to several issues belonging to the overall advanced seismic analysis chain [4]:

- definition of seismic ground motions at the bedrock or outcropping rock instead of the free-field motion, to reduce uncertainty in the signal deconvolution procedure trough the soil-column;
- methodology to model the spatial variability and incoherency of ground motions within dynamic soil-structure interaction calculations [1];
- contributions to the modelling of energy dissipation and stiffness degradation of RC structural members and buildings under increasing seismic loading levels [24].

However, the state of practice in French regulatory guides limits presently the use and valorisation of non-linear calculations (larger number of accelerograms and additional variability to take into account, limitations on the use of additional damping even though experimental results show that the dissipative behavior included in most of the available models is not sufficient). In addition, the determination of the applicability range, required by the French regulators in the nuclear industry, is not always easy to show. It is important to notice that a multi-level working strategy has been followed, starting from the 1D nonlinear models up to the full 3D nonlinear models. Among this panel of advances approaches, a specific attention has been paid to enhanced simplified models accounting for warping due to torsion in cross-section of RC beams or localized failure due to plastic hinges formation. In addition, 2D nonlinear models have been developed in order to be able to quantify local features, related to cracking, such as crack openings which are of primary importance when dealing with the assessment of safety functions of the third barrier of a core building of a NPP [27], [16], [18]. To analyze the building response, homogenized nonlinear constitutive models of RC plates have been developed and validated, allowing for damage (stiffness degradation) and steel-concrete slip (tension stiffening effect): [21], [6].

- identification tools to better set up the parameters related to the damping phenomenon. In particular, these research works allowed to split up the effects coming from the material dissipation and the structural ductility on the evolution of the damping ratio along with the developments of nonlinearities. In addition, numerical developments applied to uniaxial one-degree-of freedom model allowed to show the benefits which could be taken from an updating strategy of the viscous damping model to take into account the effects coming from material nonlinearities, [10], [11];

These features are necessary bricks in the construction of an integrated analysis, avoiding the inherent conservatisms lying in splitting up the seismic motion characterisation at interfaces of the whole system: site response + dynamic soil-structure interaction + RC building response + equipment/component and the fragility curves calculations, which are key features for the PRA.

In addition, some nonlinear advanced methodologies have been developed by EDF for specific uses:

- nonlinear viscous damping device model, used for seismic differential motion mitigation of adjacent RC building;
- nonlinear frictional colliding model applied to the wheel-rail contact condition for crane bridges seismic behaviour, validated on an experimental campaign carried out by CEA [8]. It appears that accounting for these nonlinear boundary conditions reduce the overall dynamical response of the system, and helps to identify the available safety margins, according to recognised feedback of actual seismic events experienced by similar plants.

Finally, several expertise studies can be implemented using in-situ measurements, specifically for equipment being difficult to be characterised by analysis: electrical cabinets, specific anchor systems, cable trays, etc, a minima in order to calibrate their boundary conditions and modal and damping characteristics in the linear range.

3. Data and parameters

Advanced methodologies can be seen as more sensitive to poor quality in available data and parameters than usual engineering analysis methods; this can affect negatively the confidence in the obtained results. The first key point for a practical use and dissemination of advanced methodologies is the availability of:

- validation of the results acquired on representative case studies, with respect to experimental campaigns (SMART, etc.) or instrumented test sites (Volvi site, Argonet in Greece, etc.), allowing to ensure the domain of applicability of advanced models;
- contest numerical results obtained on representative and documented case studies (e.g. Karisma IAEA-benchmark, 2010, [16]);
- methodological guides implementing the flowchart of the studies and detailing the key-assumptions, aiming at reducing the risk related to a human mistake and increasing the sharing of experience between practitioners and experts.

Another key-point is the availability of referenced data and robust updating techniques for input parameters concerning the specific case:

- detailed drawings and checked on site data;
- construction provisions;
- dedicated identification of soil material properties, of mechanical constitutive parameters, of boundary conditions, of damping properties, even though in case of this last item significant progress have been made within the framework of the SINAPS@ project for uniaxial structural members;
- parameters validity domain according to the expected loading range;
- verification step of the effect of parameter set and validation of the constitutive model on a canonical case (for instance to check the overall response of a RC cross-section computed from individual contribution of steel rebar and concrete phase constitutive models, within the expected loading range);
- spatial variability of parameters, in particular for probabilistic studies.

Finally, we have also to focus on:

- the intensity measure of the seismic ground motion selection, that have to be fitted to the structural and material behaviour, in order to reduce the epistemic variability during the ground motion selection procedure. For instance some intensity measure parameters can be more appropriate for ductile elastic-plastic structures, others are more appropriate for RC structures. We can refer for instance to the SMART campaign [27] for a discussion;
- the definition of performance objectives and associated criteria, that have to be appropriate to assumptions made and to manageable outputs of the simulations (and of course to safety requirements);
- the way to combine seismic results with other loading conditions (stationary states, etc…).
- another issue that has limited the implementation of such advanced methodologies in the recent past is the considerable increase they bring to computation time. Nevertheless, HPC solutions combined when necessary with reduction model strategies are now considerably reducing this drawback.

4. An example

As mentioned before, one topic of interest for the safety-related equipment refers to the dynamic amplification due to the RC floor behaviour in auxiliary buildings when subjected to a seismic loading. In the conventional engineering analysis, the assumption is made that the RC floor behaviour remains elastic but it is allowed, according to many standards, to reduce the Young' modulus of structural elements that are in bending, while keeping a certain value of equivalent viscous damping. This simplified approach leads to a rough estimate the possible redistribution of the efforts due to the ductility, the precise localisation of dissipation sources in the structure remaining unknown, but assumes a rough reduction of the natural frequency of the floor vertical eigenmodes. These hypotheses contribute to the epistemic uncertainty that has to be enclosed by safety coefficients to be applied to parameters and criteria. This point constitutes a drawback when performing a probabilistic approach.

An earlier experimental campaign was performed in 2002 within the joint R&D framework CEA-EDF [21]. Its aim was to determine the amplification behaviour, under an increasing sequence of vertical seismic motions, of a reduced-scale mock-up, representative of an auxiliary building RC slab of a French NPP. The vertical seismic motions considered range was beyond the design value (up to ten times this value). Nevertheless, we will limit our present analysis to the range of seismic motions remaining moderately superior to the design value, due to the lack of knowledge on the precise contribution of a phenomenon of dynamic interaction to higher seismic motion response. The corresponding response spectra encompassed a plateau covering the first frequency peak of the RC slab. The acquired results (accelerations, residual displacements) were recently compared anew with several numerical simulations, ranging from the conventional engineering analysis to advanced nonlinear modelling, [21], [6], [40], accounting for the behavioral specificities of materials: stiffness degradation and energy dissipation. This comparison is reported as a test-case of Code_Aster [1]. In terms of vertical acceleration on the RC floor, a reduction to the amplification compared to the reference linear computation has been obtained both experimentally and computationally, due to the nonlinear phenomena arising in the reinforced sections. This amplification reduction is more pronounced as the seismic motion intensity is increased, from the first cracking threshold crossing. Nonlinear calculations, for which parameters were identified on the usual concrete material data, have been proved to be able to catch the frequency peak shift along the increasing seismic motion sequence, in a pretty good correspondence with experimental values. On the opposite, the conventional engineering analysis with equivalent reduced Young's modulus predicts a dynamic response which is no sufficiently stiff for these moderate solicitation levels, with a peak shifted in too low frequency range. Even though this frequency shift is overestimated for the seismic motion analysed, the resultant peak amplification computed is considerably overestimated, when compared to experimental results. The use of non-linear models shows a much closer fit to the experimental peak amplification, even though it confirms the need for additional damping in computations, even though some of the concrete dissipative behavior sources are included in the constitutive model. This example clearly highlights the interest of non-linear approaches when best-estimate methods are sought.

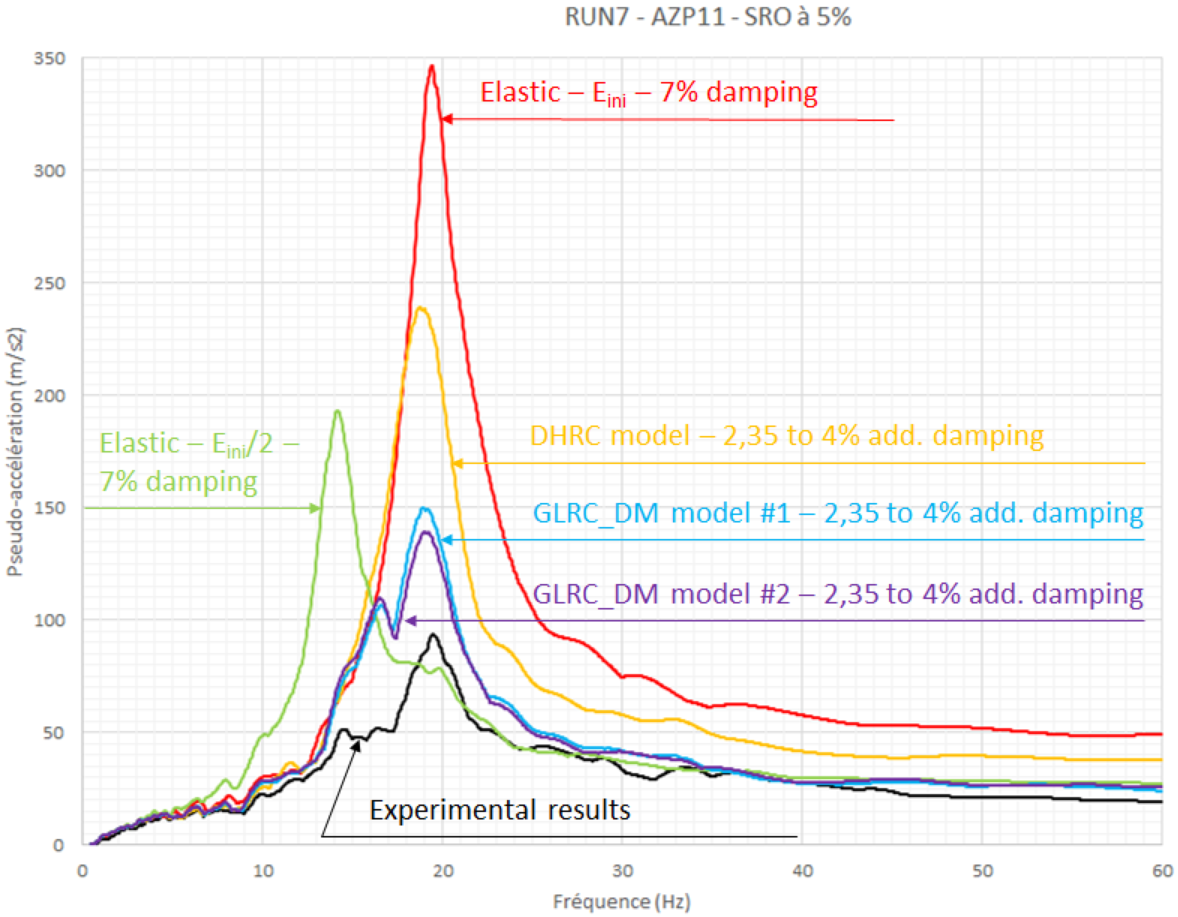

Figure 3. SDOF Response spectra with 5% damping, at the centre of the floor, for run #7 (ZPA 0,59g).

Despite these promising results from advanced nonlinear models, the topic of the damping modelling remains open, because nonlinear dissipative RC constitutive relations, used by these calculations, are not able to describe all the dissipation observed during the experimental campaign [10]. Therefore, the computed peak acceleration values are still significantly larger than experimentally measured ones, though much closer than the conventional computed ones. Another issue would be the modelling of the actual nonlinear behaviour at the wall-slab RC junction, which participates to the redistribution of efforts in the whole system.

5. Conclusion

It is now recognized and admitted that the updated state of the art, both in the usual engineering practice range and in the advanced best-estimate methodologies take profit of a better understanding of the actual behaviour of a NPP under seismic loading conditions, in particular for severe earthquakes under consideration in the new regulations and safety requirements. With the increasing capacities of simulation solutions, this helps to produce more reliable justifications of safety criteria and available margins, both in a deterministic and a probabilistic contexts. The trend to perform probabilistic analyses requires to ensure the validation of nonlinear best-estimate models, inside the whole chain from the site response to the dynamic loading transferred to the equipment or component.

To increase their dissemination, the view is now to contribute to new methodological guides, based on R&D shared programs and recommendations from IAEA and OECD/NEA, including a hierarchisation between conventional approaches, simplified methods and best-estimate ones, in view to reduce the epistemic uncertainty, the contribution of on field data acquisition.

Recommendations for best-estimate analyses should include validation tasks of constitutive models, methods and simulation tools, in sense of regulation requirements (e.g. Art.3.8, arrêté INB-2012 in France[1]), and wide dissemination of simulation platforms [1] among practitioners that include the necessary ingredients of the whole chain of seismic risk analysis.

Perspectives of enhancements go on in the development of numerically robust nonlinear models, in the increase of their physical representativeness for a better acceptability and validation. Specific topics need further R&D actions, like damping in RC structural elements or efficient reduced models devoted to uncertainty propagation in structural dynamics complex models. One can notice this latter point is crucial when dealing with PRAs.

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