MUTI-LEVEL MODELLING APPROACH OF RC STRUCTURES UNDER EARTHQUAKE LOADING: CONTRIBUTIONS FROM THE SINAPS@ PROJECT

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Abstract

In order to transmit seismic signals (in terms of frequency content and amplification) from the soil and foundation to structural elements and equipment, models for structural analysis may allow taking into account the different mechanisms prevailing in material and structural responses. However, such models should permit to evaluate the robustness of the overall structure and seismic motion transfer on specific floors thanks to seismic margins assessment (SMA) regarding the design. One should note that model means the geometrical and the kinematic description of the structural members as well as the refine modeling of involved materials response. The seismic ground motion is clearly non-deterministic, regarding the acceleration level as well as the frequency and time features of the seismic waves reaching the building. The vulnerability assessment of the structure and its equipment is part of the integrated safety assessment studies. Accounting for uncertainties has to be achieved at the structural level. Such studies imply refinement levels, which should be in accordance with the engineering computing practice. The concern of SINAPS@ WP3 consists in developing or increasing the robustness of several types of modelling (from simplified ones to the more complex ones, devoted to any kind of structural elements of reinforced concrete building), to address their identification regarding available data and at last, to appreciate their sensitivity to uncertain data for vulnerability analysis. Models being able to handle this former feature are the elementary bricks allowing seismic safety assessment analysis. Such qualities are emphasized thanks to a specific application: evaluate the models ability to propagate uncertainties with respect to their refinement or simplicity level. Three types of modelling are addressed in this contribution: 1D simplified models, 2D plates and shells elements and at last full 3D description of the structure implying reduced order models numerical strategies to handle nonlinear computations.

Key Words: Seismic safety analysis, Non-linear behaviour, reinforced concrete, Structure computation, Nuclear Facilities, Seismic margin assessment, Uncertainties propagation.

1. Introduction

The seismic ground motion is clearly non-deterministic, regarding the acceleration level as well as the frequency and time features of the acceleration waves reaching the building. The vulnerability assessment of the structure and its equipment is part of a general approach for criticality studies. Accounting for uncertainties has to be achieved at the structural level. Such studies imply refinement levels which should be in accordance with the engineering computing usual practice. The concern of SINAPS@ WP3 consists in developing or increasing the robustness of several types of modelling (from simplest ones to more complex ones), to address their identification regarding available data and at last to appreciate their usefulness in the framework of vulnerability analysis. Models able to handle this former feature are the elementary bricks allowing seismic hazard assessment analysis. Within the development of numerical models adapted to perform reinforced concrete (RC) structures computations, two main issues need to be tackled: the development properly-said of mechanical models incorporating different nonlinear mechanisms likely to occur and the ability for existing tools to account for variability inherent in structures and materials allowing the interaction of the different sources of uncertainty.

To ensure good representations of models regarding the failure criteria (frequency decrease due to stiffness degradation, inter-storey drift, crack openings), different kind of approaches are developed. The first section is dedicated to the enhancement of the mechanical response of structural elements subject to seismic loads. For such purpose, two different options have been proposed:

- Kinematics enhancement of structural elements or homogenization of the RC section constitutive behaviour, decreasing the total amount of degrees of freedom.
- Keeping the 3D description of the structural behaviour but reducing the CPU time consuming by several techniques (model reduction or structural zooms on regions of interest).

The second section is focused on 3D approach regarding structural analysis allowing accounting for all dimensions and complexity of the seismic input whose use in earthquake engineering is to be now allowed thanks to reduced order models approaches developed in the project.

2. Structures modelling

This first section exposes the different tasks linked to the enhancement of the mechanical response of structural elements subject to seismic loads. Two methodologies have been developed based on kinematics elements (beam, shell or plate) enrichment or reduced order models.

2.1 Enriched kinematics or homogenised models

Different kinds of models have been developed or enhanced allowing to sum up their complex behaviour to their 1D (beam) or 2D (plates) responses thanks to adequate enriched kinematics.

1D beam modelling

The study of the vulnerability of reinforced concrete structures requires powerful numerical tools. For nonlinear dynamic calculations, finite element analyses of beam type structural element present a good compromise between calculation time and precision of the results. Numerous finite element beam models based on the Timoshenko kinematics have been developed in recent years, including elements adopting a force or a displacement formulation. The Timoshenko beam finite element model proposed by [Caillerie et al., 2015] for example, makes possible to obtain the exact solution at the nodes for complex solicitations using a single element [Bitar et al., 2016]. Ecole Centrale de Nantes (ECN), Grenoble INP and INSA de Lyon have developed three enriched finite element beam models for the calculation of reinforced concrete beams. These three finite elements adopt a displacement formulation, have enriched kinematics at the fiber or the section scale and allow to take into account respectively: Concrete cracking, section warping, under shear loading, and the confinement effect of transverse reinforcement occurring when concrete expands.

The SINAPS@ project allowed to separately develop three distinct beam formulations ([Ibrahim Bitar 2017] (ECN), [Sophie Capdevielle 2016] and [Natalia Khoder (in progress)] (Grenoble INP and INSA Lyon) within a Matlab framework. The common objectives and characteristics of these three models are described hereafter. They allow calculating damage, plasticity, cracking and warping in a finite element framework using an implicit integration while keeping the advantages of the beam formulation which is easy to use

The key idea consists in adding to the classical beam strain obtained from beam theory an enriched kinematics allowing accounting for additional mechanisms such as displacement discontinuities due to cracking (Figure 1) or cross section warping due to shear or torsion (Figure 2) and concrete confinement due to the stirrups.

$$\boldsymbol{\epsilon} = \boldsymbol{\epsilon}^r\left(\boldsymbol{u}^r\right) + \boldsymbol{\epsilon}^w\left(\boldsymbol{u}^w\right)$$

$$\boldsymbol{a_s}(y)\boldsymbol{N}(x)\begin{bmatrix}\boldsymbol{u}_1\\ \boldsymbol{u}_2\end{bmatrix} + \boldsymbol{N}^{\boldsymbol{en}}(y)\begin{bmatrix}u_1^w\\ u_2^w\\ \vdots\\ u_n^w\end{bmatrix} = \boldsymbol{u}(x,y) \quad \Rightarrow n_r + n_{en} \text{ parameters}$$

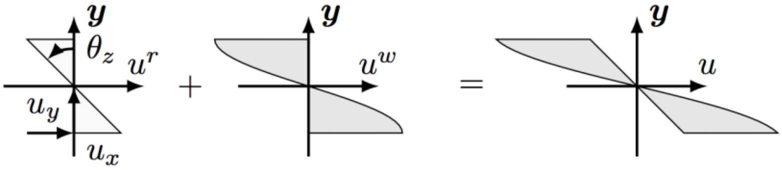


Figure 1: Beam kinematics enrichment used to simulate cracking, warping and confinement of the cross sections

The beam element that takes into account cracking has been validated with numerical and experimental results on a RC beam submitted to bending and a reinforced concrete frame directly applicable for quasi-static tests (pushover analysis in the context of seismic studies). A campaign to validate the beam that considers warping on torsion beam tests has been also carried out for cyclic and transient dynamic problems. The validation of the transverse confinement model has been done for the moment only in elasticity (PhD in progress).

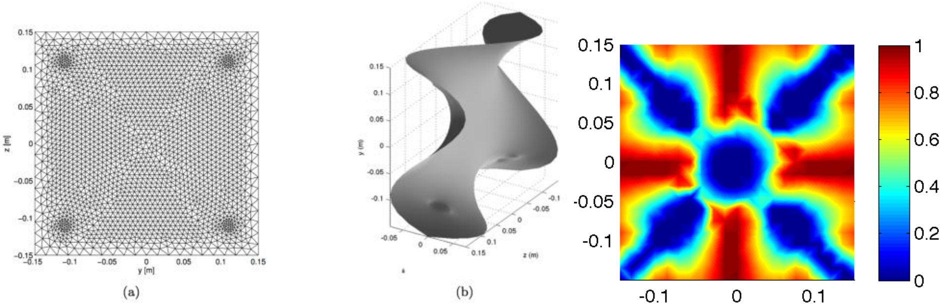


Figure 2: Cross section deformation due to torsion warping. Effect on the damage computation (Capdevielle et al. 2017)

2D RC plate Modelling

EGIS, ECN and EDF have developed and implemented in the finite element Code Aster a stress resultant non-linear constitutive model for cracked reinforced concrete panels. The GLRC-HEGIS model (Huguet *et al.* 2017) takes into account concrete damage, cracking, steel-concrete debonding and yielding of the reinforcement bars. While the work has started prior to the SINAPS@ project, the SINAPS@ project made possible to finalize and consolidate different aspects: identification of the model parameters: validation and numerical implementation robustness. The main features of the GLRC-HEGIS model, based on a simplified reinforced concrete representative volume element concept, are: Constitutive law for the cyclic behaviour of homogenized reinforced concrete panels (Figure 3), flexural-membrane coupling, generalized Standard Formulation (associate flow rule), implicit time integration, stiffness degradation of concrete sections considering damage, tension-compression dissymmetry, explicit crack modelling, bridging and interlock effects, yielding of reinforcement bars, tension stiffening, bond slip.

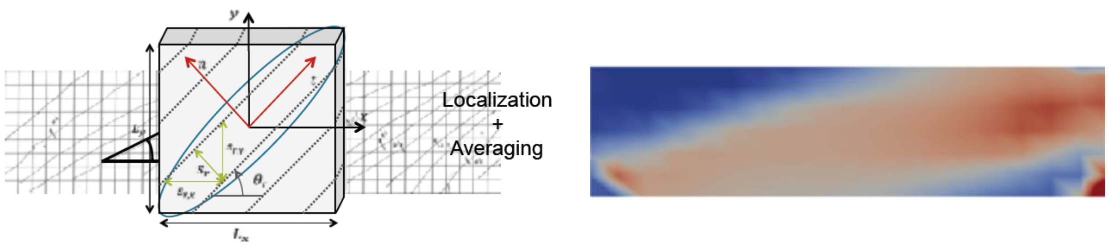


Figure 3: 2D homogenized RC Model. Prediction of crack field in a reinforced concrete shear wall test (Huguet et al. 2017)

The model is suitable for quasi-static (e.g. pushover analysis, alternating cycles...) and non-linear transient dynamic problems, for vulnerability analyses and floor spectra calculations. It can be combined in a finite element model that uses other type of structural elements: 3D, beams, multifiber non-linear beams. The model is suitable for moderate and strong earthquakes that cause degradation in reinforced concrete structures and steel yielding without reaching ruin (no softening phase at the global level). It does not take into account the dowel effect.

EDF, for its part, confirmed its practice of 2D-plate models and assessed the capabilities of the homogenized RC constitutive models previously developed in Code_Aster. These are homogenized models of reinforced concrete plate, based on a reinforced concrete representative volume element: GLRC_DM (Markovic *et al.* 2007) and DHRC (Combescure *et al.*, 2013; Voldoire, 2015) with damage and irreversible strains and tension stiffening effect (associated to the steel-concrete debonding). Although these models were developed prior to the start of the SINAPS @ project, we consolidated many aspects: implementation of identification tools to help the engineer, validation, robustness enhancement. The common objectives and characteristics of these two constitutive models are:

- homogenized reinforced concrete plates cyclic constitutive models avoiding the multi-layer approach;
- dissipative phenomena in reinforced concrete, post-elastic phase in order to evaluate the safety design margins, for moderate seismic event far from the building collapse;
- stiffness degradation of the sections by damaging the concrete, neglecting the softening phase; tension-compression dissymmetry;
- no modeling of the plasticity of the steel bars;
- tools for identifying homogenized parameters from engineer data: geometry of the section (section and position of the steel rebar), material parameters (elasticity, tensile and compression thresholds), including according to design codes;
- generalized standard formulation (normal flow laws) and direct implicit time integration;
- field of application: quasi-statics and transient dynamics (e.g. progressive pushover, alternate cycles, etc.); targeted vulnerability analyzes: calculation of floor response spectra for equipment safety analysis; robustness of building. Compatibility with any type of modeling of other structural elements: 3D, beams, nonlinear multi-fiber beams, extra offset reinforcement layers...
- modeling of the damping by global viscous models: Rayleigh type or modal damping.
- calculation of engineering parameters: flexural-elastic updated stiffness due to concrete damage; maxima reached for the principal strains in the concrete wall to verify the validity of the concrete tensile state.
- limitation of use: moderate earthquakes producing "moderate" degradations of the reinforced concrete structure, without going as far as ruin (steels remaining in the elastic range).

The specific objectives of the DHRC constitutive model are:

- flexural-membrane coupling and representation of any reinforced concrete sections, starting from the distribution of the steels in the reference volume element,
- modeling of damage and stiffness reduction, associated energy dissipation,
- modeling of steel-concrete slip and irreversible deformation, tension-stiffening associated dissipation.

The differences between these two models are summarized below:

GLRC_DM	DHRC

Maturity of use	Industrialization to finish
Heuristic homogenization, non-extensible	Numerical periodic homogenization, extensible
Identical steel layers x-y, sup-inf	Any kind of steel layers
Initial isotropy, induced anisotropy	Native anisotropy
No steel-concrete debonding	Steel-concrete slip consecutive to damage □ dissipation and tension-stiffening effect
no flexure-membrane coupling	couplage flexion-membrane natif
–	CPU time : more expensive than GLRC_DM: 30 to 100%
Parameters to be provided in Code_Aster from "engineer" data and assumptions on the post-elastic strain range. Number of parameters: steel: 3, concrete: 8, geometry: 5, method: 2	Salomé_Méca automated identification tool by FEM numerical homogenization of parameters from engineer data. Number of parameters: steel: 3, concrete: 10, steel-concrete sliding: 1, geometry: 11

A validation campaign has been carried out and is maintained and distributed via Code_Aster, for engineering purpose at EDF and subcontractors, on structural elements and then on quasi-industrial reinforced concrete structures, with different representative reinforcement rates, typical of the industrial applications targeted in nuclear civil engineering. Their use has thus been facilitated for the engineering studies on the nuclear power plants fleet. The sensitivity of the responses is noticeable according to the choice of the threshold parameters of the concrete, as well as post-peak behaviour parameters. Required tests are part of the family of standard tests of the profession; however it is noted that pathways of progress are expected on the characterization tests of the steel-concrete bond. Finally, the advantage of performing a flexural-membrane cyclic response analysis of a reinforced concrete representative volume element before launching the study of the reinforced concrete building in order to verify the suitability of the chosen parameters has been emphasized. In particular, comparisons with experimental campaigns, performed on mockups, which are representative of nuclear buildings designed according to French standard, have shown that floor response spectra for moderate seismic levels obtained with these constitutive models are closer to the experimental values than those obtained by simplified assumptions with reduced Young's modulus of flexural structural members, commonly used in engineering practice (Banci *et al.*, 2018).

CEA and ENS Paris-Saclay have developed modelling strategy dedicated to the physical description of cracking in reinforced concrete structural elements. This approach is based on the following pillars:

- an *enriched kinematic* integrating explicitly the discontinuous nature of the displacement field in a media crossed by a crack. This crack can work in mode I, mode II and mixed opening;
- the integration of *an anisotropic cohesive law working for cyclic response*. The law describes the link between stress vector versus displacement jump allowing to drive the specific effects of three type of cracking (tension, directional shear and anti-directional shear) (Figure 4);
- a strategy for *cracks tracking* in order to reduce stress locking phenomena observed numerically.

The additional kinematic field used to describe the crack opening has been discretized thanks to kinematic operators with zero average. It leads to the possibility to condense the additional degrees of freedom and to avoid the modification of the global stiffness matrix.

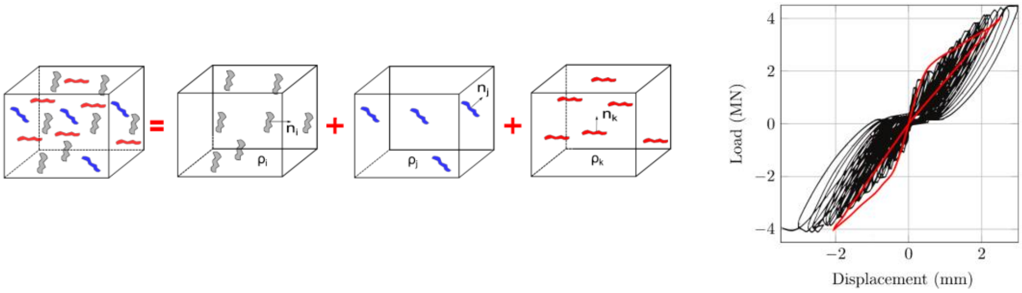


Figure 4: 2D Kinematics enrichment for plain concrete allowing for crack modelling. Global response of the numerical model compared to the experimental one of a RC shear wall subject to cyclic loading.

This approach has been implemented in Cast3M, the finite element code developed by CEA. Furthermore, commented samples are also provided. The developed approach can be considered to determine the response of reinforced concrete structures under quasi-static as well as dynamic loading (seismic loading). It has been implemented for finite element of “CST” type (Constant Strain Triangle). For sake of simplicity, it has been implemented for 2-dimensionnal problems under plane stress hypothesis.

The main limitations of the proposed approach are due to two main reasons: (i) the simplifying assumptions and (ii) some numerical prerequisites.

In particular, one can quote:

- no hysteretic dissipation and residual strains;
- the necessity to use a crack tracking method in order to reduce the locking phenomena;
- no coupling between membrane and flexural behavior.

2.2 3D Models

Keeping a 3D approach for kinematics regarding structural analysis allows accounting for all dimensions and complexity of the consequences at the local scale of the material associated to the seismic input loading. The computing clock wall time ever prevents one from including such analysis into a RC building reliability analysis framework. Nowadays, recent and important breakthroughs concerning reduced order models make their use feasible.

The PhD thesis of Matthieu Vitse focused on the mechanical response of reinforced concrete structures subjected to cyclic loading conditions, which is based on a 3D approach of the kinematics for structural elements. For that purpose, preserving a 3D approach of the kinematics allows to take into account all the complexity of the seismic load in the analysis of the structure. However, the very high computational cost prevents from integrating these approaches directly into a reliability framework. However, the recent and important progress in the field of model reductions provides a glimpse of their possible use for industrial simulations. It is thus the object of the carried out works.

The PhD thesis was dedicated to the development of an algorithm for the resolution of nonlinear problems for which there is variability on some of the model parameters or on the loading conditions, which are only described by their intervals of variation. The aim was to evaluate the uncertainties in civil engineering structures and to quantify their influence on the global mechanical response of a structure to a seismic hazard. Unlike statistical or probabilistic approaches, we relied here on a deterministic approach. However, in order to reduce the computation cost of such problems, a PGD-based reduced-order (Figure 5) modeling approach was implemented, for which the uncertain parameters were considered as additional variables of the problem. These solutions lead to what is called a "virtual chart" which once post-processed at an extremely low cost, makes it possible to draw conclusions about the influence of uncertainties on the response of the structure.

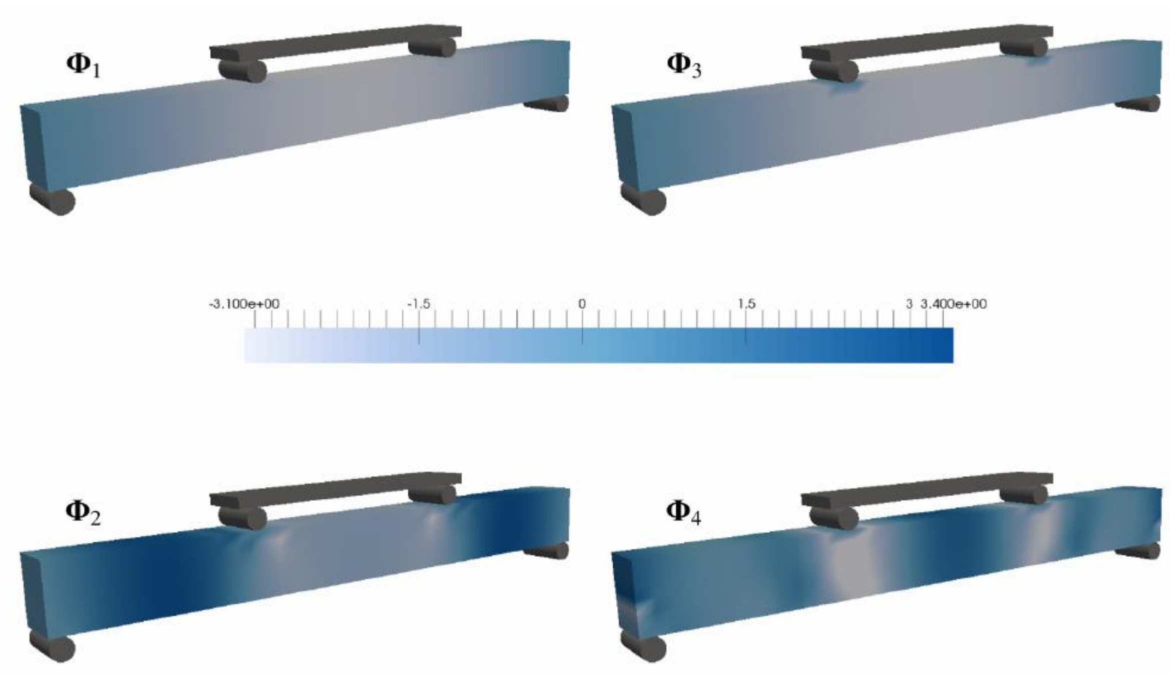
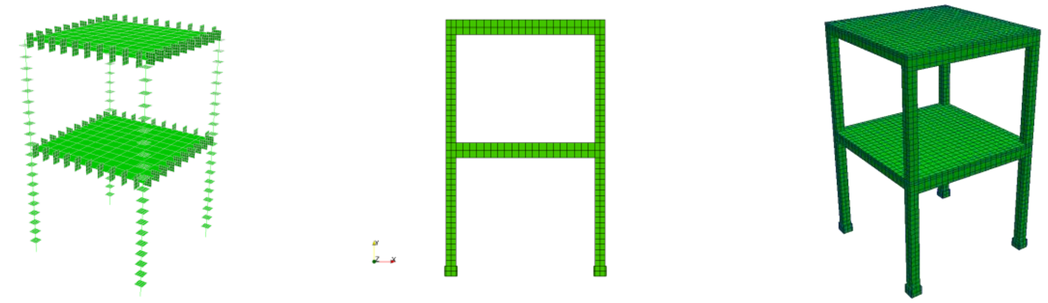


Figure 5: Cyclic 4 point bend test of a reinforced concrete beam. Spatial modes decomposition: prediction of damage.

This method was implemented into the LATIN algorithm, which uses an iterative approach to solve the nonlinear aspect of the equations of the mechanical problem. This work presents the extension of the classical time-space LATIN—PGD algorithm to parametric problems for which the parameters are considered as additional variables in the definition of the quantities of interest, as well as the application of such method to a damage model with unilateral effect, highlighting variability on both material parameters and the amplitude of the loading. The feasibility of such coupling is illustrated on numerical examples for reinforced concrete 3D structures subjected to different types of cyclic loading conditions (tension—compression, bending). Its implementation in a framework of uncertain loads and signals will be the subject of a later thesis (CEA-IRSN-ENS).

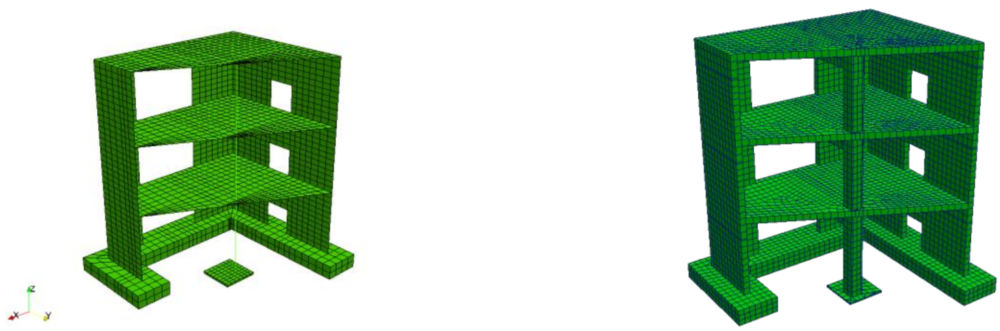
3. Structural applications: simplified models and uncertainties propagation

It is fundamental to provide engineers with quantitative pieces of information to assess the influence of material parameters uncertainty on a given index characterizing the structural response, for multiple modelling strategies and for different structural typologies. The undertaken work provide also a critical review of the development studies carried out within the framework of the Work-package #3 by analyzing the ability of a modelling strategy to propagate more or less the material uncertainties. More specifically, two reinforced structures have been considered: SMART 2013 (walls and slabs) (Richard et al, 2016) and BANDIT (beams and columns frame) (Garcia et al., 2012). Such structures were modelled by different strategies (1D, 2D and 3D). To illustrate the modeling strategies used, the finite element meshes of the both structures considered are presented in figures 6 and 7.



(a) 1D approach (b) 2D approach (c) 3D approach

Figure 6. Modeling strategies used for the beam-column structure (BANDIT).



(a) 2D approach (b) 3D approach

Figure 7. Modeling strategies used for the wall-slab structure (SMART 2013).

For each model, a certain number of material parameters were considered as random variables (concrete tensile strength, fracture energy, steel yielding stress, damping ratio, concrete Young modulus). A probabilistic study has been carried out in order to assess the variability of some output quantities (ZPA, maximum spectral acceleration, dissipated energy, etc.). The obtained results allow for classifying the uncertainties based upon their effect on quantities usually used by civil engineers. Such categorization is fundamental for engineers who have to make choices in terms of modelling techniques in their daily practice, whether it is a design or assessment activity. Making such a choice is often conditioned by the sensitivity of the results with respect to the initial uncertainties of the data. The present work provides engineers with trends which should help them in their decision-making process. The final output of the present work is shown in figure 8. We can notice that estimations of coefficients of variation related to selected structural responses are provided, for different modeling strategies and structural typologies.

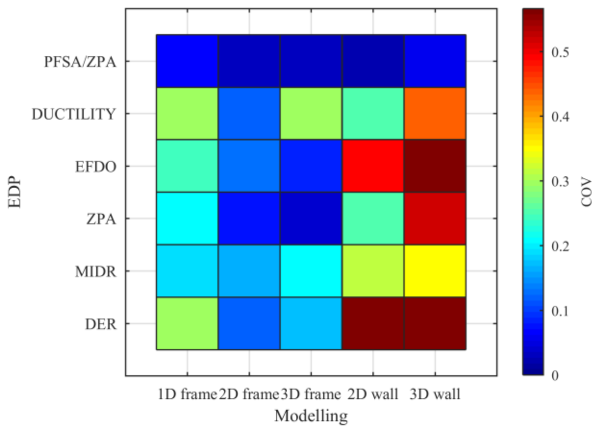


Figure 8. Variability of selected structural responses as a function of the modeling strategy and structural typology.

4. Conclusions

Several types of modeling of reinforced concrete structures, accounting for the nonlinear behaviour of materials, under seismic loading, have been studied. They are adapted to the various kinds of structural elements present in RC buildings of nuclear power plant. Their objectives cover both robustness analysis under earthquake loading and the evaluation of dynamic loadings transmitted to safety-related equipment housed in buildings.

Several proposals have been made to enrich the nonlinear phenomenological description of reinforced concrete beams and columns; the work has to be continued in order to evaluate them in industrial situations. Several nonlinear models of reinforced concrete plates have benefited from improvements and their use in representative situations has shown their efficiency for application in seismic engineering and safety margin reassessment. Finally, three-dimensional models have been improved in order to make more accessible a refined analysis of the behaviour of critical RC structural elements.

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