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SMART 2008: SEISMIC DESIGN AND BEST-ESTIMATE METHODS ASSESMENT FOR RC BUILDINGS SUBJECTED TO TORSION

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ABSTRACT :

Reinforced concrete buildings exhibiting 3D (i.e. torsion) and non-linear effects are a main concern in the field of earthquake research and regulation. In the last decade, several reinforced concrete specimens have been tested under seismic excitations in order to study the seismic behaviour of shear walls, but without significant 3D effects.

In order to assess the capability of structures exhibiting 3D effects to withstand earthquake loads as well as seismic loads induced to their equipments, a reduced scaled (1/4th) model of a 3 stories reinforced concrete structure with 3D effects was tested between June and September 2008 as part of the SMART project on AZALEE shaking table (EMSI Laboratory – CEA Saclay – France).

The aim of this project is (1) to compare and validate approaches used for the dynamic responses evaluation of RC structures subjected to earthquakes and exhibiting both 3D (torsion) and non-linear behaviours, (2) to evaluate loads induced to internal equipments, (3) to quantify margins in design methodologies and (4) to carry out realistic methods to quantify variability in order to produce fragility curves.

This paper presents the first part of the 'SMART' project, which consists in a blind predictive benchmark, with more than 40 registered teams worldwide.

The modelling of the structure has been conducted based on conventional data. The seismic input motions selected consist in design spectra and a set of bi-axial (real and synthetic) horizontal accelerograms (corresponding to the same sequence to be tested during the experimental phase). The objectives are (1) to evaluate conventional design methods for structural dynamic response and floor response spectra calculations and (2) to compare best-estimate methods for structural dynamic response and floor response spectra evaluation including various practices, depending on participant's own experiences.

This phase was followed, since June 2008, by a test campaign at low seismic level (3 real bi-axial accelerograms sets – pga = 0.05g) and 10 identical synthetic accelerograms sets with increasing pga (ranging from 0.1 to 1g).

KEYWORDS: Blind predictive benchmark, Reinforced concrete structure, Torsion, experimental test, Numerical analyses

1. GENERAL PRESENTATION

In order to assess the seismic tri-dimensional effects, such as torsion and non-linear response of reinforced concrete structures, a reduced scaled model (scale of 1/4th) of a typical electrical nuclear reinforced concrete building is tested, since June 2008 on AZALEE shaking table at Commissariat à l'Energie Atomique (CEA Saclay, France). This test, supported by CEA and Electricité de France (EDF), is part of the "SMART-2008" project (Seismic design and best-estimate Methods Assessment for Reinforced concrete buildings subjected to Torsion and non-linear effects).

The first part of the project is a blind prediction of the structure behaviour under different seismic loadings. It is presented as a contest, opened to teams from the practicing structural engineering as well as the academic and research community, worldwide. This blind predictive benchmark should allow us to compare and validate approaches used for the dynamic responses evaluation of reinforced concrete structures subjected to earthquake and exhibiting both 3-D and non-linear behaviours. The main objectives of the blind predictive benchmark are to:

- Assess different conventional design methods of structural dynamic analyses, including floor response spectra evaluation,
- Compare best-estimate methods for structural dynamic response and floor response spectra evaluation.

Each participant has completed a predefined Excel file available on the CEA-SMART website. This article presents the main results based on the study of the participants' outputs, especially the ones from the conventional analyses.

1.1. Participants' presentation

43 international teams registered to participate to the SMART 2008 benchmark and 33 sent their results in due time to be taken into account in this paper. The participants came from 20 different countries worldwide and were equally representatives of the three main types of the civil engineering professional activities (Figure 1).

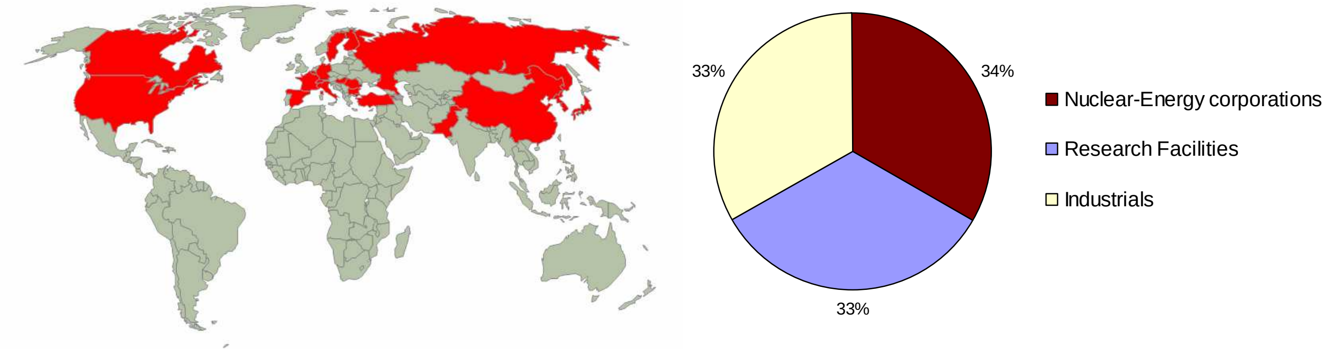


Figure 1: Participants nationality and field of activities

2. SMART PROJECT PRESENTATION

The 1/4th scaled model to be studied is a trapezoidal, three-story reinforced concrete structure (Figure 2). It is representative of a typical, simplified half part of an electrical nuclear building. It is composed of three walls forming a U shape. Two of those walls have openings. The walls and slab are 10 cm thick.

The wall's foundations are made of a continuous reinforced concrete footing, lying on a 2 cm high steel plate. The reinforcement steel bars are welded to this steel plate. The reinforced concrete column is directly anchored on a steel plate. The steel plates are bolted on AZALEE shaking table.

The bare structure weight about 11T. Additional loading are placed on each slab in order to represent the real loading of the referential structure. The total weight of the SMART specimen is therefore of about 46 T.

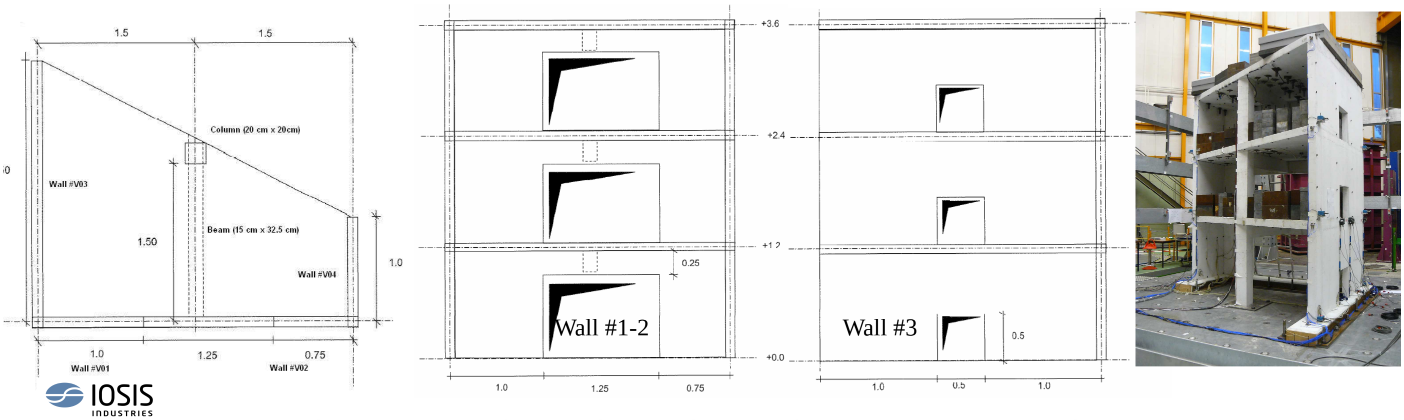


Figure 2: Plan view and elevations of the SMART2008 specimen

The specimen has been designed according to the French nuclear methods, with a peak ground acceleration for the response spectrum anchored at 0.2 g. This seismic loading corresponds to a Safe Shutdown Earthquake (SSE) in a low to medium seismic area (equivalent to a magnitude of 5.5 with a distance of ~10km).

The specimen will be tested for 13 sets of bi-axial horizontal accelerograms on AZALEE shaking table at CEA (a 6 degrees of freedom shaking table, plate : 6m x 6m, payload : 100 Tons).

2.1. Analyses to be performed by the participants

Four types of analyses were required at this stage of the blind predictive benchmark:

- A static analysis to verify the static behaviour of the structure under self weight and horizontal forces,
- A modal analysis to check the Eigen values,
- A conventional analysis in order to assess design seismic methods. Each participant had to conduct this analysis according to his/her own standard procedure. A response spectra, corresponding to the SSE, for different damping values as well as a set of two synthetics horizontal accelerograms (derived from the design spectrum SSE at 5% damping) were provided to the participants,
- A best-estimate analysis, in order to compare those results to the experimental ones. For this analysis, the 13 sets of accelerograms, which were going to be inputted successively to the shaking table during the experimental phase were provided to the participants.

2.2. Input data available

In order to perform the different analyses required, each participant had access to the following input data:

- The geometrical description of the structure: (formwork, reinforcement drawings, anchorage description),
- The expected material properties (mechanical characteristics according to Eurocode 2),
- The additional loadings description, applied on each slab,
- The scaling factors applied to the specimen (length, dimension, time, mass …),
- The seismic inputs (response spectra for different damping values and 13 sets of bi-axial horizontal accelerograms).

The input data mentioned above is the one generally assumed and available at the preliminary design stage of the construction.

No experimental test was performed during the blind predictive benchmark as the specimen was being built and finished by January 17, 2008. The tests on concrete cylinders were available end of July 2008.

3. PARTICIPANTS' HYPOTHESES

This section will present the main hypotheses used by the participants. This section is extremely important to better understand the differences in the participants' outputs.

3.1. Softwares and computational models

A variety of numerical software (16) has been used to perform the different analyses required (Figure 3). The two main computational codes used are SAP2000 and ABAQUS for both the conventional and the best-estimate analyses.

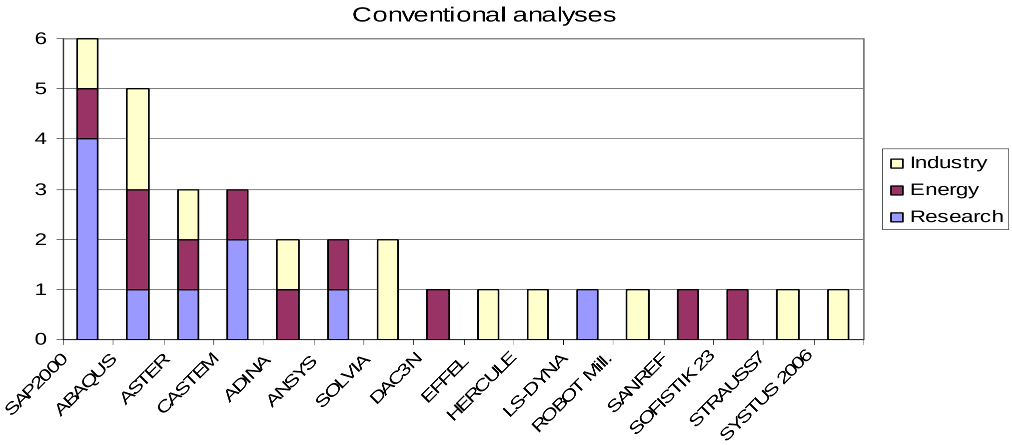


Figure 3: Softwares used by the participants

Even if different codes have been used to perform the different analyses, more than 93% of the participants used the same model for the conventional and the best-estimate analyses. In fact, five main types of models have been identified:

- Type 1: Shell/beam/solid: the walls are generally modelled using shell elements, whereas the beams and the columns are modelled using shell, fibre or beam elements and the foundations are defined by solid elements,
- Type 2: Shell/fibre: the walls and the foundations are modelled using shell elements, whereas the beam and the columns are modelled using shell, fibre or beam elements,
- Type 3: Solid: only solid elements are used,
- Type 4: Shell: only shell elements are used,
- Type 5: Lumped mass: the specimen is modelled using a combination of sticks and punctual masses,
- Type 6: Shell/frame + springs: the model is defined using shell elements and beam elements. In order to account for the nonlinearity of the model, the walls (and foundations) are modelled using springs in critical areas in the height of the 1st floor.

More than 75% of the participants modelled their walls with shell elements, whereas more than 62% used solid elements for modelling the foundations. Only one team used a simplified model for the conventional model specifically. There was no surprise at this stage.

3.2. Young modulus

A value of concrete Young Modulus, according to the Eurocode 2, was prescribed in the benchmark specifications (Reinforced concrete C30/37 – E = 32,000 MPa). 62% of the participants used directly this value. Generally, the participants used the same value for the conventional and best-estimate analyses (Figure 4). No explanation could be given for the choice of some of the participants to use higher value than 32000 MPa. However, it is common practice in some engineering companies to use reduced (up to one half) the values of Young modulus to take into account the concrete degradation (cf. ASCE 43-05 recommendation).

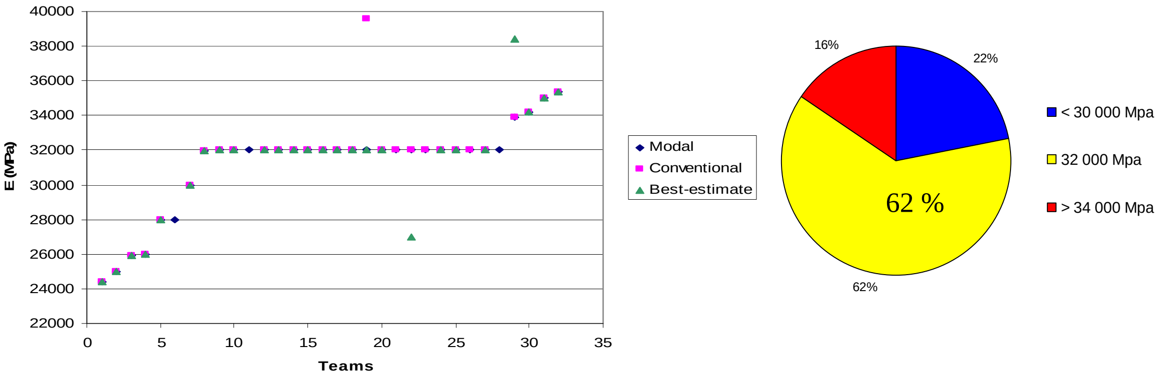


Figure 4: Young modulus used by the participants

3.3. Damping ratio

The damping value to be used in a structural analysis is always a difficult parameter to evaluate, and depends on the type of analysis performed. In general, each country's building code specifies a set of values for conventional analyses, depending on the field of activities (i.e. civil, nuclear …). For example, in France, it is a conventional practice to use for reinforced concrete structures 7% in the nuclear conventional design and 4 to 5% in the civil engineering one. In order to better understand each participant's own conventional method, it was decided not to impose a value for this benchmark's phase. Figure 5 presents the damping values used in this blind predictive benchmark, for both the conventional and the best-estimate analyses. It can be observed that the 5% damping value is chosen the most. Moreover, lower damping values are generally chosen when performing non-linear time-history analyses.

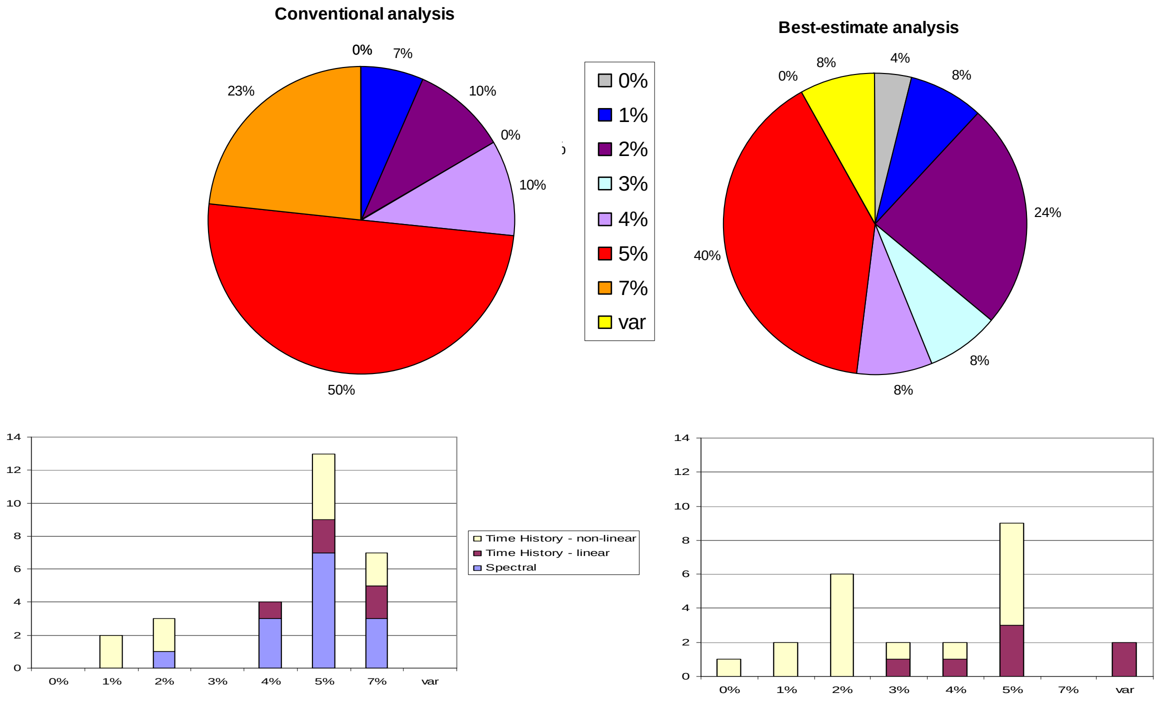


Figure 5: Damping ratio depending on the type of analyses

3.4. Conclusion

Just based on the analysis of the main hypotheses made by all the participants, it is obvious that there should be a huge variability in the results of the conventional and best-estimate analyses. The outputs investigation is presented in the following paragraphs, for the conventional analyses. However, it appears clear at this stage that some guidance is missing in our actual building codes regarding, in particular the damping values, the concrete Young modulus and the definition of simple models (to avoid, for conventional analyses, to develop too complex ones), specially when most of the national codes already take into account many different structure behaviours in the prescribed values.

4. BLIND PREDICTIVE BENCHMARK'S OUTPUTS

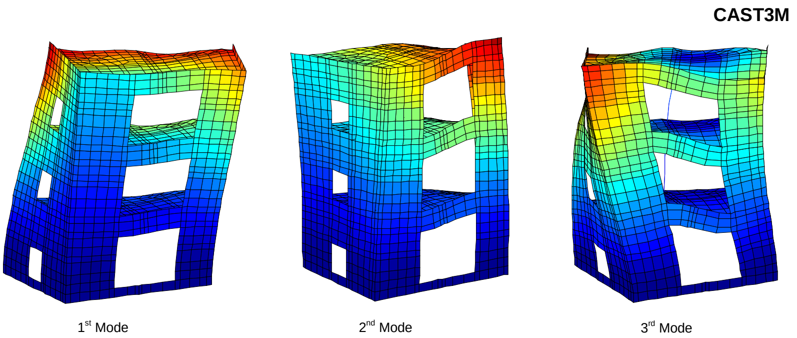
In this section, the main outputs of the blind predictive benchmark are going to be presented.

4.1.Modal analyses

The 5 first Eigen-frequencies have been computed by each participant, considering the specimen fixed at base. Due to some hypotheses' discrepancy, outputs' variability was expected. This variability is higher for the highest mode (cf. Table1). However the mode shapes are generally the same for all participants: [mode 1 – flexural mode mainly along x-x, mode 2 - flexural mode mainly along y-y and mode 3 – torsional mode. Figure 6 presents the 3 first modal shapes of the structure computed with CAST3M.

Table 1 : 5 first frequencies

Mode number	Mean Value	Minimal Value	Maximal Value	Standard Deviation
1	9.11	7.24	14.72	1.17
2	16.36	12.31	28.57	2.72
3	31.45	25.39	39.69	2.69
4	33.60	26.85	47.72	3.57
5	36.36	27.44	62.25	7.43



1st Mode 2nd Mode 3rd Mode

Figure 6: 3 first Eigen modes

4.2.Conventional analyses

Three main types of conventional analyses were performed by the participants: the spectral analyses (48%), the linear time-history analyses (17%) and the non-linear time history analyses (35%) (cf. Figure 7). When performing spectral analyses, the SRSS combination was generally preferred in order to combine the horizontal seismic directions. For the time-history analyses, the 2 accelerograms were applied in each horizontal direction simultaneously.

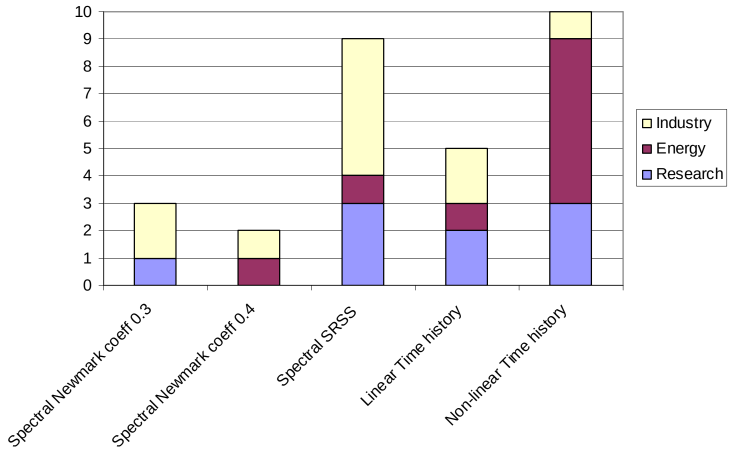


Figure 7: Type of analyses and direction's combinations

The resultant forces and moments were computed at the centre of mass of the specimen at the top of the foundation's level. Figure 8 presents the outputs for the two horizontal resultant forces. The discrepancy observed can be explained by the different types of analyses, seismic combinations as well as material properties and damping values used. All those parameters results in a high variability in the participants' outputs. [Note that the most extreme results can generally be explained due to some unit errors and misunderstanding between internal forces and resultant forces.]

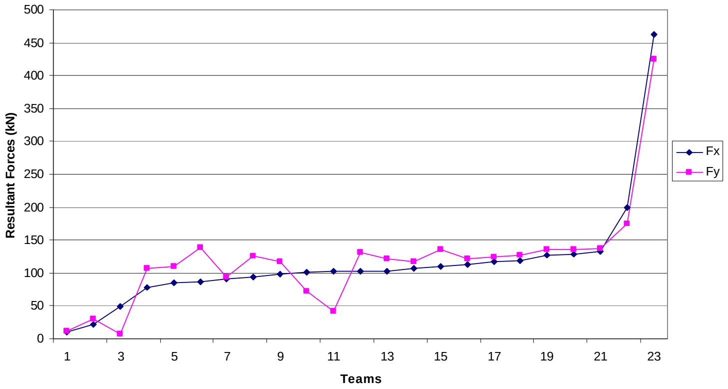


Figure 8: Horizontal resultant forces

The relative displacement and absolute acceleration were required at 7 specified locations on each slab. Figure 9 presents those outputs at roof level in the X-X direction.

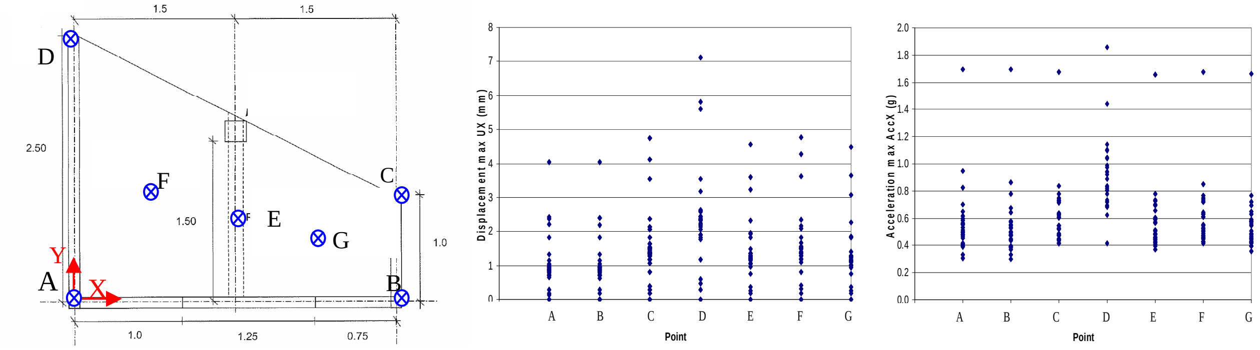


Figure 9: Maximum relative displacements and absolute acceleration at roof level along x-x

One more time, the high variability of the results was surprising but expected due to the disparity in the participants' hypotheses. It is however important to note that the specimen is quite rigid and the maximum displacements are quite small (in the millimetre range). As for the acceleration, a simple analogy with a regular structure will lead to a maximum acceleration at roof level of 4 times the nominal acceleration, which is equivalent to about 1g. All the results presented above are in the right range. Moreover, it is important to notice that conventional methods are generally associated with national codes with specific induced margins.

The last investigation presented in this article will concern the floor response spectra. Figure 10 presents the envelop of the floor response spectra at roof level for the X-X and Y-Y directions. It can be observed that many participants used a enlarged band to derive their conventional floor response spectra. This seems to be a common practice, especially in the energy/ nuclear field. However, no trend could be defined based on those outputs.

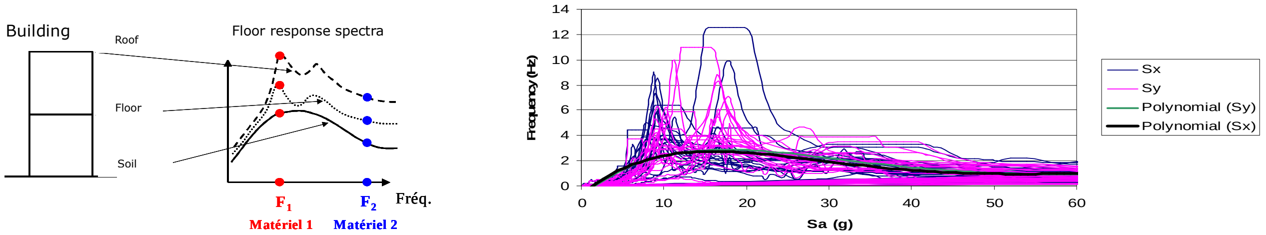


Figure 10: Floor response spectra at roof level

5. CONCLUSIONS

Due to the diversity of the participants and of their practice, it appears there is a huge variability in the participants' hypotheses (types of model, material properties, damping values, concrete density and mass modelling, types of analyses performed, seismic combinations …). Even if all the participants anticipated the same global behaviour of the structure, this did not allow us to define real trends in the participants' outputs. The variability and specially the fact that all the results are so scattered should lead us to investigate deeper the subject, without forgetting that each national code has a global approach not presented in this benchmark and of course implicit calculations' design rules.

Today, the computational tools are more and more powerful, which allow us to model more complex behaviour. There is a need, therefore, to better understand and quantify the uncertainties in the input parameters, in order to better apprehend the structure's capacity under seismic loadings. This should lead us to provide some guidelines for all field of activities related to civil engineering, regarding:

- Guidelines to develop simplified models for conventional analyses,
- Guidelines for the damping values to use according to the type of analyses ,
- Some guidelines or recommendations, such as ASCE 43-05, in order to better understand the value of concrete Young modulus to use and for which purpose. Some work could be done in order to identify how to degrade this value based on the structural damage's evolution.

Our future work is to launch the next two phases of our SMART project:
Phase 1b: Blind predictive benchmark: The modelling of the structure will be based on real in situ material data and known seismic inputs. Those results will be finally compared to test results at various levels of seismic excitation (including "under-design" and high "over-design" levels). This phase will end in December 2008.
Phase 2: Variability quantification and fragility assessment: Due to high cost and large amount of time needed to assess variability based on experimental approaches, this phase will essentially be numerical. Tests results from phase 1 may be used for post-adjustments of models. The objectives are the following :

- Quantify variability in the seismic response of the structure and identify contribution coming from uncertainties in input parameters and random variables,
- Investigate and compare different methods for fragility curves elaboration.