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Division V

COMPARATIVE ANALYSIS OF NONLINEAR PUSHOVER AND TRANSIENT SIMULATIONS OF REINFORCED CONCRETE BUILDINGS

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ABSTRACT

Non-linear calculations are increasingly made in seismic analysis: they allow for taking into account the damage of materials, global and local stiffness losses, forces redistribution and energy dissipation mechanisms developed in the structure. This type of calculation leads to a more realistic evaluation (compared to linear elastic analyses) of the ultimate seismic capacity of structures. There are two types of approaches: quasi-static pushover and transient dynamic calculations.

One pushover analysis gives results in terms of displacements, forces and strains for several different levels of earthquake and damping ratios. However, the choice of the input loading profile can be problematic (torsion, secondary earthquake direction). Pushover calculations are performed over the theoretical limits of their range of validity.

Nonlinear transient calculations can be performed thanks to the current computing resources. The concomitance of the directional effects of the earthquake and the influence of secondary modes are then correctly modelled. However, one must perform several simulations (usually 5) for each earthquake level: this approach is much more computation means demanding. The modelling of the dissipation due to the structural damping and nonlinearities can remain an open question.

This paper is part of a process of comparison of the two approaches. The retained case study is a regular low rise building. Structural elements are modelled by multi-layer shell and multi-fibre beam elements. The nonlinear constitutive law of concrete models the cyclic behaviour in tension and compression, with damage and irreversible strains in compression and rotating crack tensile damage. The constitutive law for rebar steel is elastoplastic with linear kinematic hardening. We observe the displacement per floor (global criterion) and strains in materials (local criterion). All calculations are carried out with Code_Aster software.

INTRODUCTION

Nonlinear calculations are more and more carried out concerning seismic analysis: they allow to take into account damaging of materials, associated losses of rigidity and repartition of stresses, cf. for examples regulations (ATC 40, 1996 ; FEMA 356, 2000 ; FEMA 440, 2005 ; EC8, 2005). This kind of calculation enables to justify margins with respect to classical linear elastic calculations and modal-spectral analysis. We distinguish two kinds of approach: quasi-static push-over and transient dynamics calculation.

A simple push-over calculation enables to calculate the displacements, stresses and deformations for several earthquake levels and several damping ratio. However, the choice of the input loading profile can be problematic (torsion, secondary directions of earthquake). Push-over calculations are more and more realized at the theoretical limits of their validity domain (Krawinkler, 1996).

The current calculation means allow to realize nonlinear transient calculations. The simultaneity of the directional effects of the earthquake is then correctly modelled, as well as the influence of secondary modes. Nevertheless, we must realize several simulations (5 in general) per earthquake level: this approach is way more expensive in terms of calculation means. The model dissipation, due to the structural damping and non linearities, can remain an open issue.

This article is part of an approach of comparison of the two models. The kept scenario is a regular and small-height building. We are studying the influence of the loading profile on the results of push-over calculations. Finally, we compare the results of the two approaches by observing the envelope displacement per levels, global criteria, and the deformations in the materials, local criteria. All the calculations are made with Code_Aster software.

DESCRIPTION OF THE FINITE ELEMENTS (FE) MODEL

Description of the retained structure

The structure is a simple building in reinforced concrete with three levels of 4 meters height each. It is composed of beams and posts for the bracing in the X (longitudinal) direction, two concrete walls for the bracing in the Y (transversal) direction, three floors and a raft. The slabs of each floor are supported by the beams. The concrete walls have a 25 cm thickness, the slabs have a 30 cm thickness and the raft has a 50 cm thickness. The beams have a rectangular 40 cm x 80 cm section and the posts have a rectangular 50 cm x 70 cm section.

All the elements of the structure are made of reinforced concrete. The concrete walls and slabs are composed of two perpendicular reinforcement rows on each face. Each reinforcement element is made of 1HA12@250 for the walls, 1HA14@150 for the slabs and 1HA25@250 for the raft.

The beams are made with 16 horizontal HA20 reinforcement bars equally distributed between the top and the bottom. The posts are made with 12 vertical HA25 reinforcement bars.

Common values are used for the mechanical characteristics of construction materials.

Structure's model

The model is realized with Code_Aster software. The reinforced concrete slabs and walls are modelled with shell DKT multi-layers elements for concrete; combined with offset uniaxial elements for the reinforcements. The posts and beams are modelled by multi-fibbers beams elements representing the section of concrete with its reinforcement bars. The size of each mesh element is around 0.6m. The model of the soil-structure interaction is simply based on springs distributed under the raft. Considering these hypothesis, the main eigenmodes are as presented in table 1.

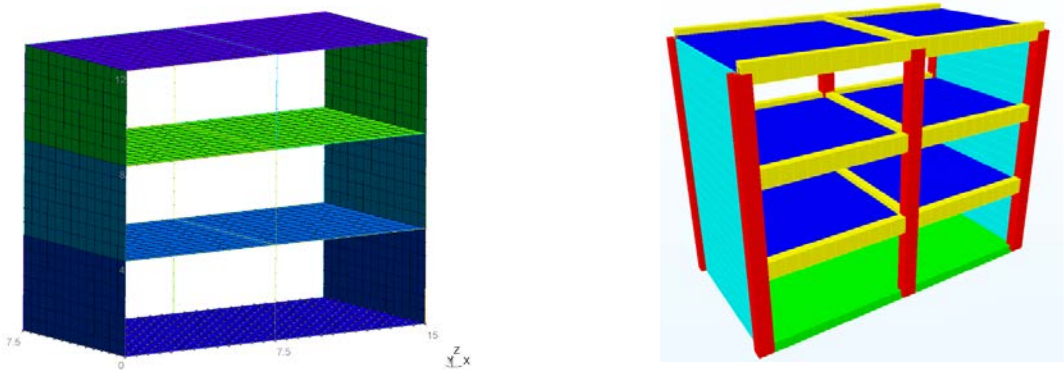

Figure 1. View of the mesh and voluminous representation of the model

Table 1. Main eigenmodes of the structure

n	f [Hz]	a [m/s^2]	ζ [%]	Masse modale effective [%]		
				Direction X	Direction Y	Direction Z
1	2.08	5.04	7	65.8	0.0	0.0
2	3	6.64	7	0.0	59.6	0.0
4	7.41	8.62	7	6.2	0.0	0.0
5	8.44	8.35	7	0.0	0.0	67.7
16	21.57	5.07	7	0.0	26.2	0.0
29	33.33	4.15	7	21.2	0.0	0.0

Materials' constitutive laws

The model includes a model of the nonlinear behaviour of the reinforced concrete. An elastic linear behaviour is adopted for the raft.

The nonlinear concrete constitutive law is based on a damaging model in traction rotating-crack type with a negative linear strain hardening and a damaging model in compression modelled by irreversible deformations which law of evolution is ruled by a Drucker-Prager criteria on stress and a strain hardening which is first positive and then null (parabola – rectangle strain hardening).

The reinforcement constitutive law is elastoplastic with a linear strain hardening.

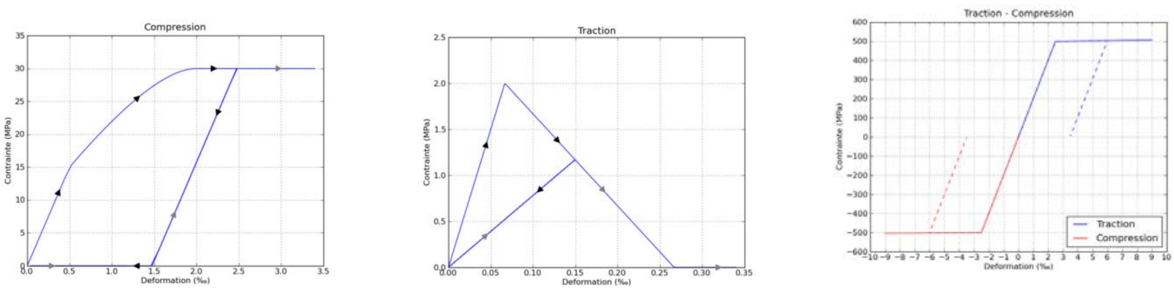

Figure 2. Concrete's behaviour in simple compression (a) and in simple traction (b) and steel's behaviour (c)

NONLINEAR QUASI-STATIC PUSHOVER CALCULATIONS

Method

The name of the pushover method reflects its major principle which is the acquisition of a Stress – Displacement curve by pushing the structure in a progressive way. More precisely, it is a static calculation based on a nonlinear model where the applied stresses are horizontal and distributed over the height based on a relevant acceleration profile (Chopra et al., 1999). The intensity of this loading profile is then increased in order to reach a target displacement.

The aim is to solve the equation of static for each stress increment η:

$$\underline{\underline{K}}(\underline{X})\underline{X} = -\eta \underline{\underline{M}}\underline{\mathbf{\Gamma}}$$

where $\underline{\underline{K}}$ and $\underline{\underline{M}}$ are the rigidity and mass matrices, $\underline{X}$ the displacement vector and $\underline{\mathbf{\Gamma}}$ an acceleration profile.

The displacement of a point of the structure and the resultant of the shear stress at the base are then measured for each loading increments. These two quantities are then transformed into Acceleration - Displacement graphic of an equivalent 1-DOF system, cf. (Vezin, 2015) for the details of this transformation, depending on the shape of the loading profile.

In this part, the operating points, intersection of the capacity curve and the demand curve, are calculated with the average spectrum of the 5 accelerograms for a 7 % damping ratio.

Influence of the loading profile on the pushover response

For each loading directions, three unidirectional acceleration profiles are considered:

- modal, according to the major eigenmode in the direction considered;
- based on the acceleration obtained with a modal-spectral analysis (Quadratic Complete Combination);
- uniform.

One also consider a fourth loading profile, multi-directional, as a combination of the modal loading in the direction considered and 0.4 times the modal loading profile in the perpendicular direction, in the spirit of the Newmark combination. This additional analysis aims to measure the influence of the multi-directional effects of an earthquake.

Results in X direction

The accelerations applied to the nodes of the FE model are presented on Figure 3.

For each loading profile, we use the displacements of the centre of the roof to compute the capacity curve. The capacity curves are superimposed on the spectrum of earthquake demand, for three levels of earthquake (reference R, 2 × R, 3 × R). We can observe that for this building, the loading profile doesn’t influence the pushover curve, even if we consider a multi-directional loading

(Figure 4), as long as conversion multiplying factors (effective mass and participation factor) are adapted to the shape of the loading profile (Vezin, 2015).

The lateral displacement of the structure for each level is presented on Figure 5. Its evolution doesn't show a significant influence of the loading profile (the maximal difference of 2 mm for the earthquake's level 3 × R is to be compared with the 44 mm of displacement reach at the +12 m level).

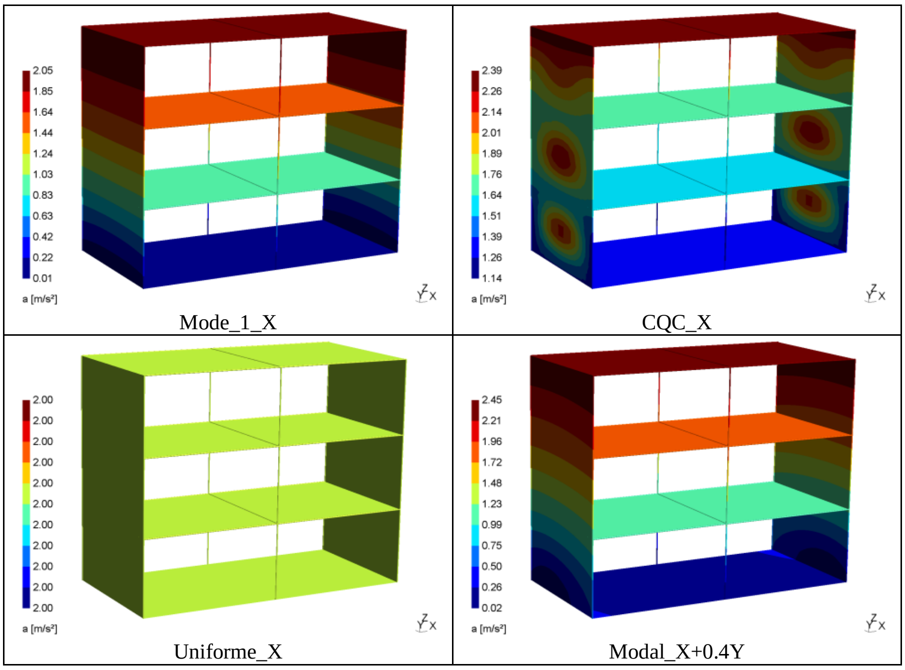

Figure 3. Loading profiles – X direction

A comparison between the deformations into the materials (compression in concrete and traction in the reinforcements) has been carried out; several results are presented on Figure 10 and Figure 11 for the identified operating points. The differences between the deformations are negligible.

For this small regular building, the loading profile has no influence on the behaviour in the direction of bracing.

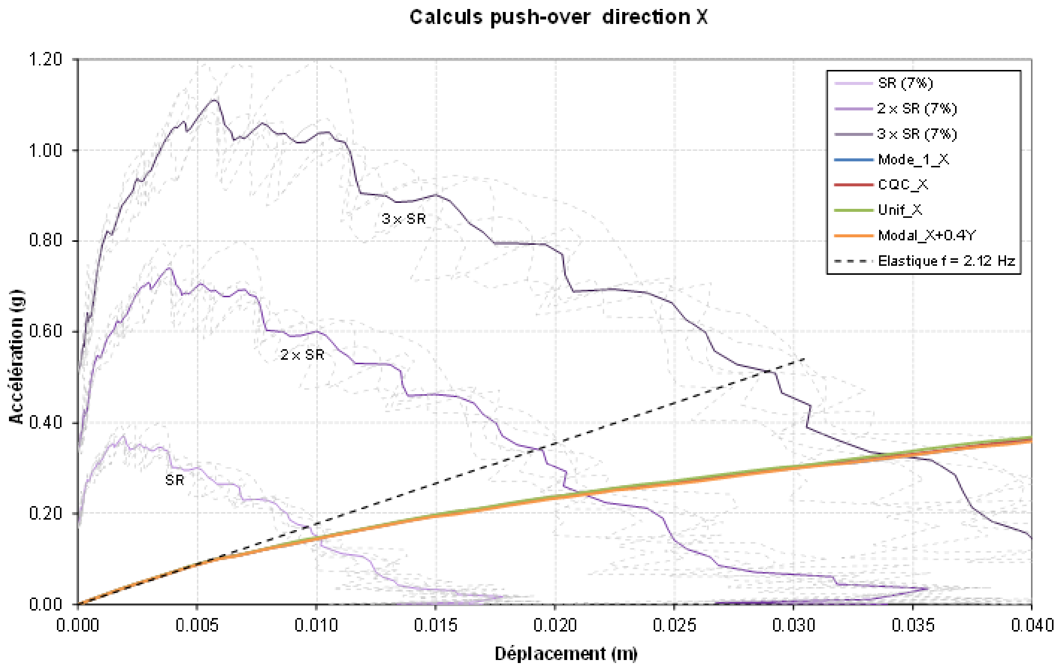

Figure 4. Capacity curves and earthquake demand – X direction

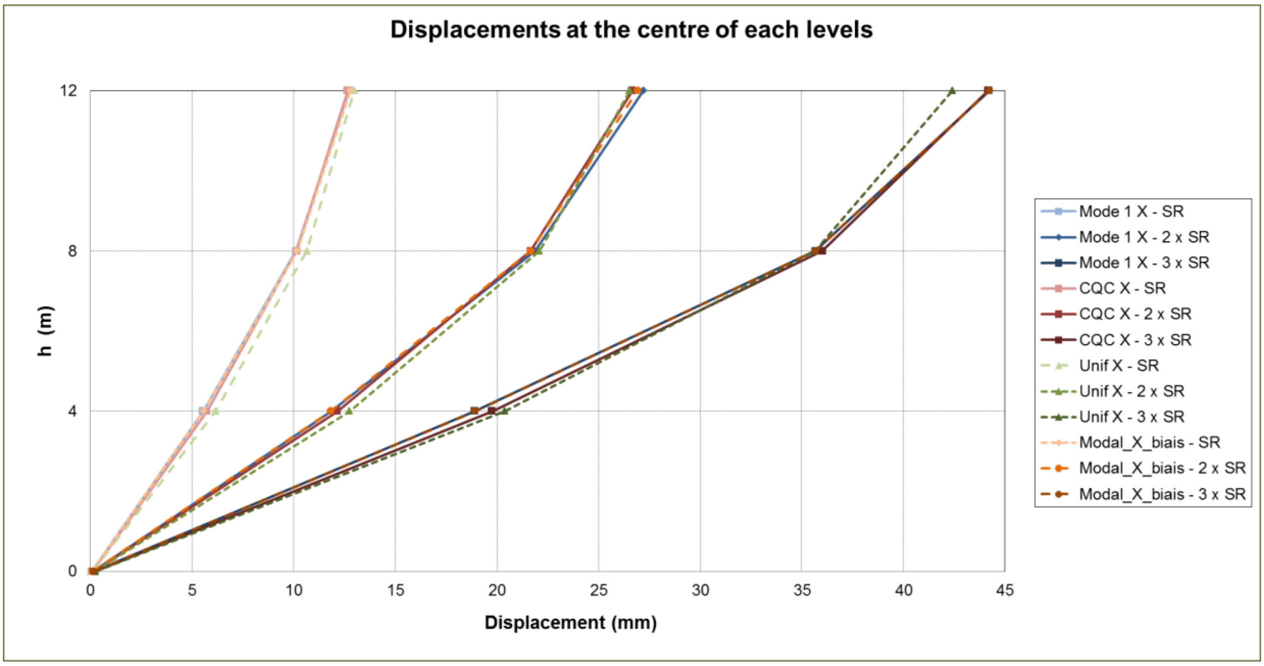

Figure 5. Lateral displacement per levels from the pushover analysis for the three levels of earthquake considered

Results in Y direction

The accelerations applied on each node are presented on the next figure.

The capacity curves are superimposed on the spectrum of earthquake demand, for three levels of earthquake (reference R, 2 × R, 3 × R). One can observe that for this building, the loading profile doesn't influence the pushover curve as long as the loading is omnidirectional (Figure 7). The presence of an additional loading in the orthogonal direction implies a nonlinear behaviour for a weaker loading. Nevertheless, the difference on the identified operating points or on the displacement per level (Figure 8) is lower than 10%.

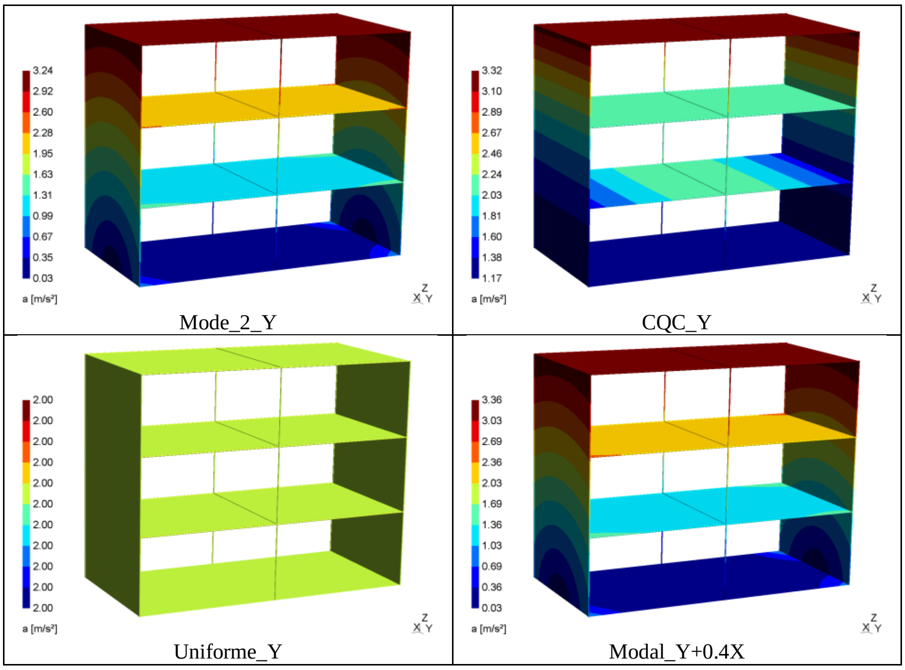

Figure 6. Loading profiles – Y direction

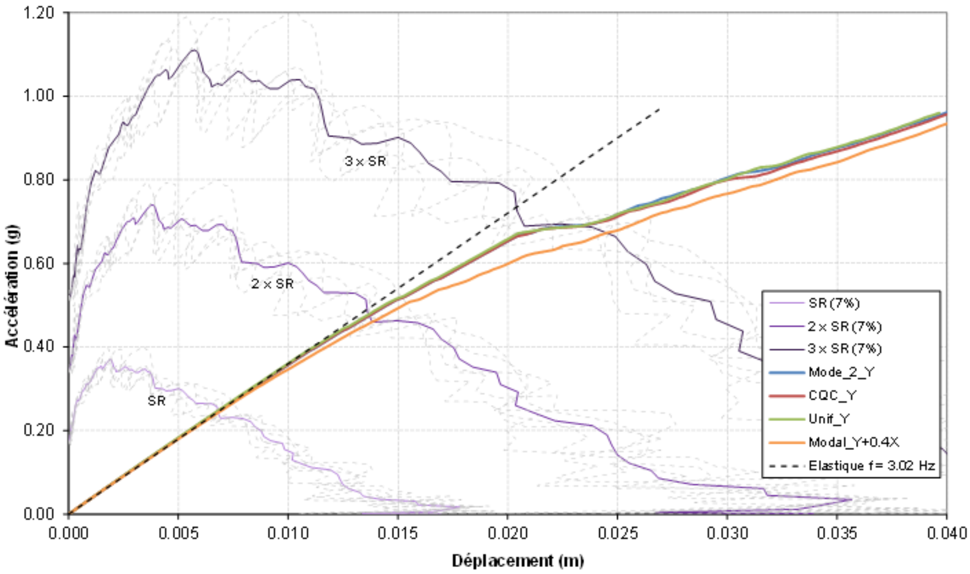

Figure 7. Capacity curves and earthquake demand – Y direction

The differences between the deformations profiles are weak for the three omnidirectional loading profiles. The measured deformations are clearly higher for the multidirectional calculation. Generally speaking, the highest deformations are more local for the 3 × R earthquake's level.

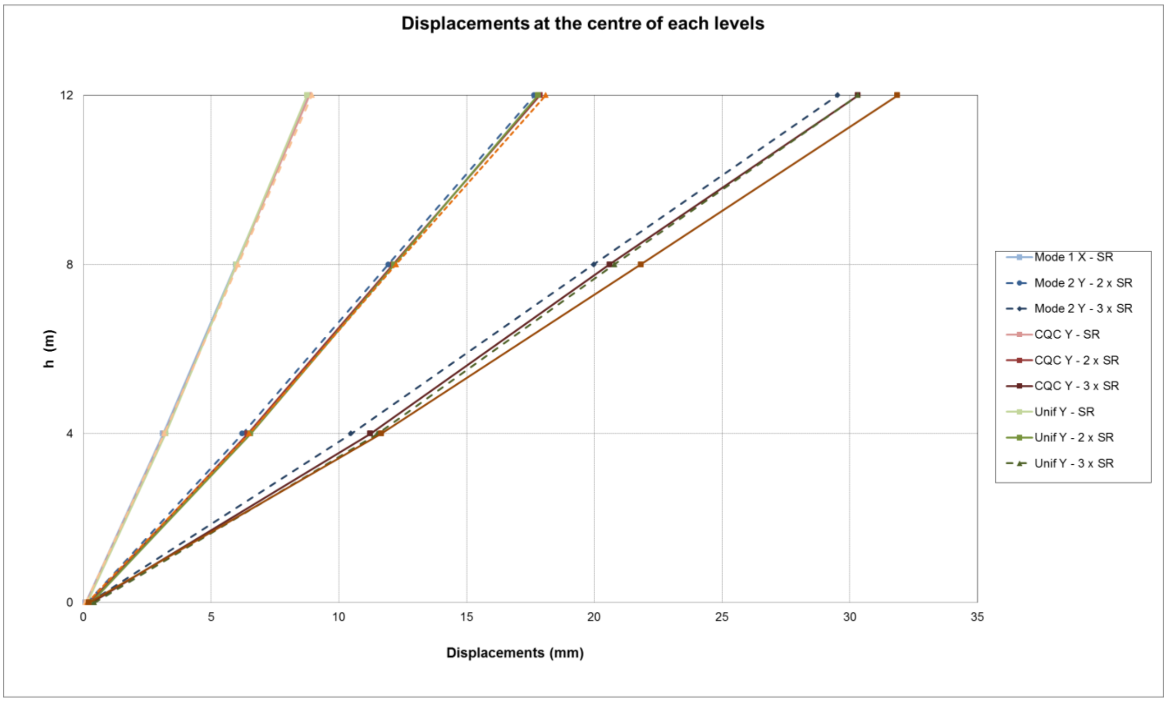

Figure 8. Lateral displacement per levels from the pushover analysis for the three levels of earthquake considered

NONLINEAR TRANSIENT CALCULATIONS

Method

The transient calculation (Gérardin and al., 1996) allows, if constitutive laws and damping are well chosen, to well describe the structure's behaviour during the entire duration of the earthquake. The aim is to solve the equation of dynamic for each time step:

$$\underline{\underline{M}}\,\underline{\ddot{X}_r} + \underline{\underline{C}}\,\underline{\dot{X}_r} + \underline{\underline{K}}(\underline{X_r})\underline{X_r} = \underline{F_{stat}} - \underline{\underline{M}}\,\underline{\Delta}\ddot{X}_s(t)$$

With $\underline{\underline{K}}$, $\underline{\underline{C}}$ and $\underline{\underline{M}}$ the rigidity, damping and mass matrices, $\underline{X_r}$ the relative displacement vector, $\underline{F_{stat}}$ the external static loading and $-\underline{\underline{M}}\,\underline{\Delta}\ddot{X}_s(t)$ the inertia loading.

In order to solve this equation we use a Hilbert-Hughes-Taylors (HHT) integration scheme which adds a small numerical damping on the highest frequencies and then diminishes the risk of numerical instability. One makes sure that the dissipation of energy caused by this scheme remains negligible in the global energy equilibrium.

Model of the dissipation in transient calculations

One of the major transient calculation problematics is the model used for dissipation. Here, we use a damping matrix $\underline{\underline{C}}$ because the constitutive laws don't allow to take into account the whole dissipation phenomenon: here, this matrix depicts the share of the viscous damping associated with the elastic linear behaviour.

The main methods of modeling are the Rayleigh damping, with an elastic or tangent stiffness matrix, and the modal damping. Following primary calculations, the modal damping has been retained because it leads to the most satisfying results. On each interesting mode, a 2% damping ratio is affected.

A global energy balance is built for each time increment, taking into account the repartition of the dissipation during the earthquake:

$$\Delta W_{ext} = \Delta E_{tot} + \Delta E_{cin} + \Delta W_{amor} + \Delta D_{num}$$

W_{ext} is the external force work, E_{tot} the total energy (associated to the constitutive law), E_{cin} the kinetic energy, W_{amor} the damping forces work and D_{num} the energy dissipated by the HHT scheme.

One determines the share of the dissipation attributable to the constitutive law (e_{tot}) and the one attributable to the damping matrix (w_{amor}), on the whole earthquake history We also make sure that $d_{num} \sim 0\%$. One can note, in Table 2, that the share of dissipation due to the damping matrix diminish as well as the share due to the dissipation law increases when the earthquake level, and so the nonlinearity level, increases. However, the biggest share of the dissipation remains realized by the damping viscous strains. In this table, we give the average value on the 5 accelerograms and a characteristic value (average+ 0.95 standard deviation) which integrates the dispersion of the input signals.

Table 2. Share of dissipation of de constitutive law and of the damping matrix

	Average value			Characteristic value		
	1 x SR	2 x SR	3 x SR	1 x SR	2 x SR	3 x SR
e_{tot} [%]	5.2	5.5	6.1	6.5	7.0	7.3
w_{amor} [%]	94.0	93.1	92.0	95.7	95.0	93.4

COMPARISON OF THE TWO APPROACHES

In order to compare both methods, we compare the extremal displacements per level, which allow us to reach information on the structure global behaviour (Figure 9).

For the transient calculations, we display the average value on the 5 combinations of accelerograms and also the characteristic values (average ± 0.95 standard deviation), which gives an indication of the uncertainty scale due to the variability of the signals used. For the pushover calculations, we measure the displacements corresponding to the earthquake's level and the considered damping. We first note that the displacement profiles have a very similar shape when we compare to pushover and transient methods, for both directions. We also note that, despite the fact that we have a 2% modal damping, the results of transient calculations are, at best, close to the results of a 5% pushover for a 1 × R earthquake's level: the dissipations due to the constitutive law leads to a diminution of the displacements, that we can reproduce by adjusting the damping targeted for the pushover calculation. Finally, when the earthquake's level increases, and so the structure nonlinearity's level, the dissipation increases and we get closer to the 7% pushover calculations for the 3 × R earthquake's level.

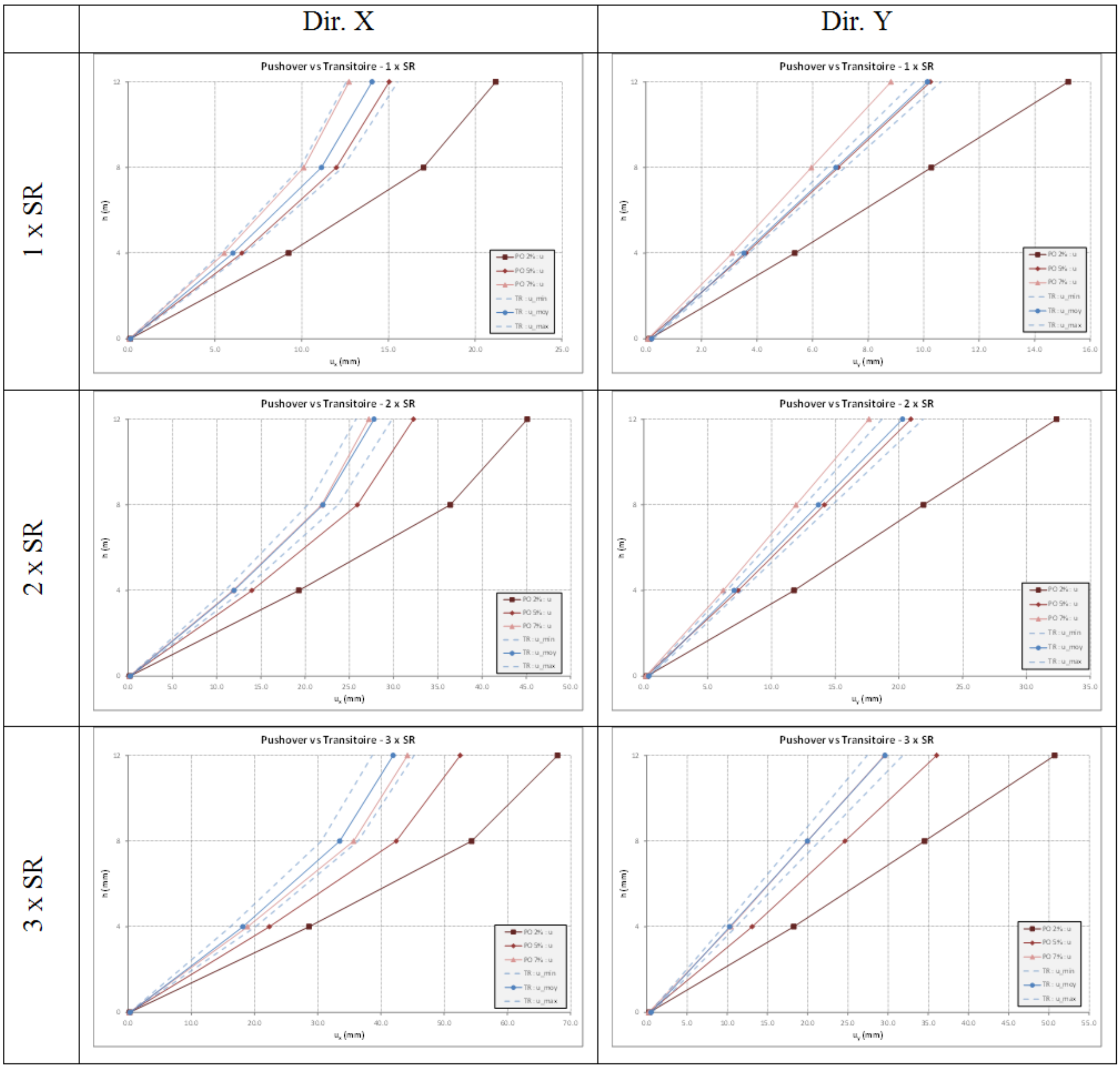

Figure 9. Comparison of the displacements per level between the static pushover calculations and the transient nonlinear calculations

We compare the deformations in materials in the following figures. The deformations from the transient calculations are the average values from the 5 sets of accelerograms; the deformations from the pushover calculations match with a 7% damping hypothesis. The deformations from the transient calculations are of the same order of magnitude as those from the pushover calculations, with similar profiles: we find again in the transient calculations, multi-directional, the identified profiles on omnidirectional pushover calculations.

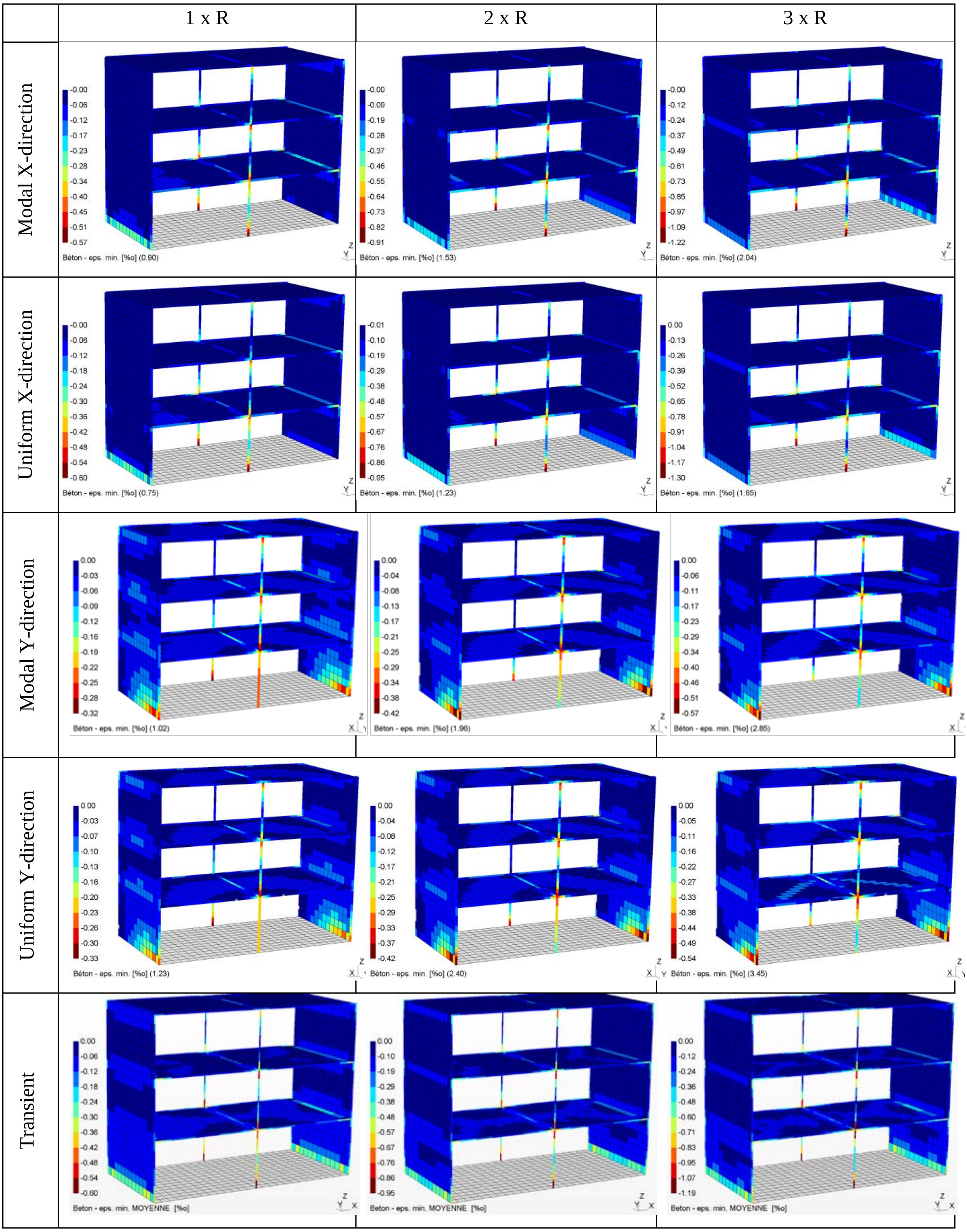

Figure 10. Comparison of the minimal strain (compression) in concrete for different push-over loading profile and for transient computations

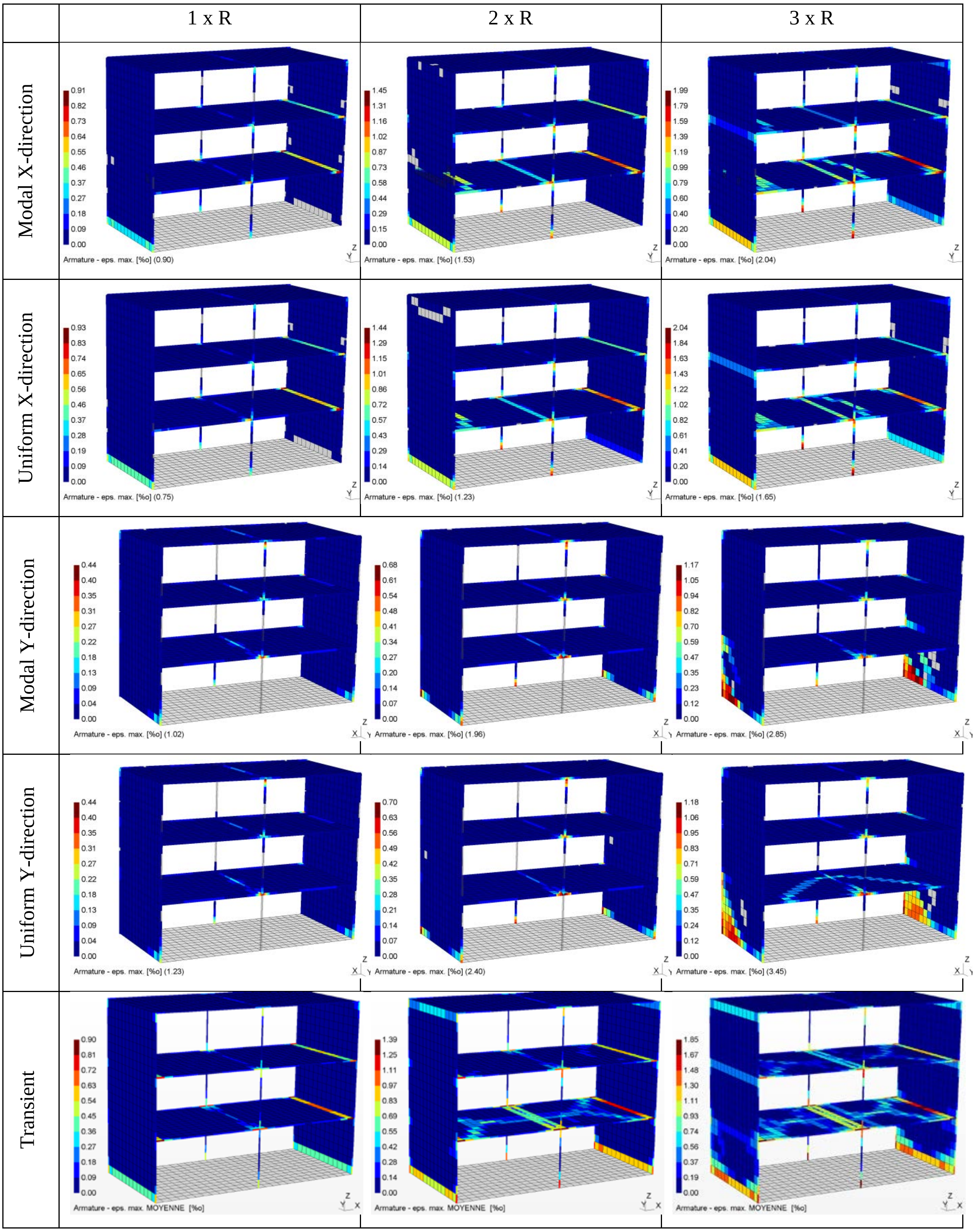

Figure 11. Comparison of the maximal strain (traction) in reinforcement for different push-over loading profile and for transient computations

CONCLUSION

This paper compared the pushover and nonlinear transient methods on a regular three levels building.

On this building, four loading profiles have been retained for two directions X and Y (modal, QCC, uniform, multi-directional). Per directions, the results (displacements, strains and deformations) are similar. We note an influence of the secondary direction only for the (Y + 0.4X) case: the additional load in the wall direction leads to a 10% difference of the operating point.

Transient calculations have been realized for three earthquake's levels. These calculations take into account the simultaneity of the solicitations, the earthquake's multidirectional aspects and allow modelling the structural damping in a proper way. The share of dissipation due to nonlinearities of the constitutive law (balanced with the total dissipation) increases with the earthquake's level; the one due to viscous damping diminishes.

On this regular building, the response (displacements and deformations) are very comparable between the quasi-static pushover and transient approach: the lateral displacement curves per level have similar magnitudes and profiles. We also note that with increasing earthquake level, the transient results identifies with push-over results with an increasing damping ratio.

For this regular building, a pushover calculation in each direction allows to correctly approach the dynamic behaviour of the building. Moreover, with the retained hypothesis for the study, the seismic spectrum must be used with a damping ration between 5 and 7% on the pushover calculations and allows transposing the dissipation due to the nonlinearity of the constitutive law. This dissipation level might seem weak but, even for a 3 × R calculation, the reinforcements haven't plasticized yet.

The works started here is continuing in two directions. First, pursue this exercise with higher earthquake levels, until the reinforcements plasticize significantly. The numerical computations are in progress but are made significantly harder to converge, due to the higher level of nonlinearity. Second, introduce an irregularity in the structure, for example by drilling a concrete wall, which will imply dissymmetry and global torsion effects.

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