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FROM THIN TO LARGE REINFORCED CONCRETE PIERS, COLUMNS AND WALLS. MODELLING CONCEPT ADAPTED TO THEIR NON-LINEAR RESPONSE UNDER SEISMIC LOADING

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ABSTRACT

The non-linear behaviour of reinforced concrete structures is an important factor which has to be well understood. Specially when these are subject to severe seismic actions. In this work we were brought to study these aspects in some different type of reinforced concrete piers and shear walls (squat walls). The constitutive law used for modelling the concrete takes into account most major characteristics of the material behaviour. In the particular case of a slender pier the geometrical non-linearity is also taken into account. While for squat elements shear strain is also integrated, through a damage model, in the numerical tool.

KEYWORDS

seismic analysis - reinforced concrete structures - material non-linearity - bridge piers - squat elements - shear walls - shear effect - multilayered finite element -

INTRODUCTION

Among different structural elements, reinforced concrete bridge piers, columns or walls, are strategic elements for security aspects of constructions to which they belong. Their failure might sometimes cause great amount of damage. Their functioning is directly linked to their geometrical aspect (slenderness). For which three major categories of structural element may be as follow :
- slender elements, for which geometrical-non-linearity demonstrate their sensibility,
- squat elements, for which shear effects increase their brittle behaviour.
- intermediate elements, for which shear effects as well as geometrical non-linearities can be neglected.

In that framework the present paper constitute an overview of concepts developed at L.M.T. Cachan around damage models conceived for the prediction of the behaviour of concrete structures under seismic loading. Other utilisation of these numerical tools within different national and international research programs (Carvalho 1993, Bisch & Coin 1994) have treated other seismic behaviour aspects of structures, or their constitutive elements.

MECHANICAL DESCRIPTION

Geometrical differences between squat and a slender structural elements, such as piers, may considerably modify the importance of different mechanisms activated during cyclic loading. Simplifying assumptions made in the elaboration of analytical formulae may become more or less acceptable when treating these structures. Using beam elements to treat both structures might suffer the lack of particular features for each type of structures. Concerning squat ones, shear strain may become non negligible, while for slender elements second order non-linearities induced by the geometrical variations also have to be considered.

When treating squat R.C. elements it may be important to take into account shear deformations which are no longer negligible compared to flexure strains. Figure 1 is an illustration of the tip displacements estimated error when shear strain is not considered. The structure is a cantilever beam with different slenderness ratio (Dubé, 1994).

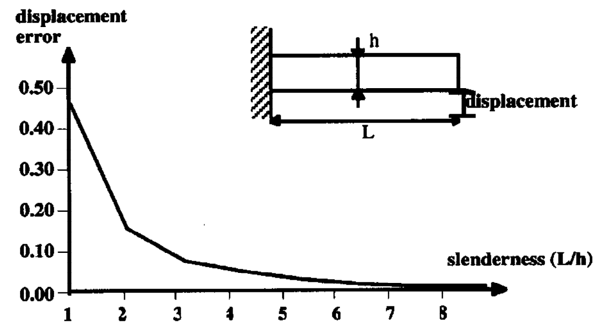

Fig. 1, Relative error on the tip displacement when shear strain is not taken into account for different slenderness ratio (L/h) for an elastic linear analysis

Slender elements for which stability aspects may need special precautions, shear effect can be neglected.

Slender and squat structural elements may also behave in total different manners at their failure. While a slender element can undergo high ductility because of its progressive damage advance, squat ones may not since their failure is highly brittle. So different treatment may be expected for their modelling.

NUMERICAL TOOLS

To simulate concrete behaviour under cyclic loading (loss and regain of stiffness as microcracks open and close) we use a damage model (La Borderie 1991), which incorporates two scalar damage variables acting on the stiffness of the material, one for damage due to tension, the other for damage due to compression, also including recovery stiffness procedure and the description of anelastic strain.

In order to limit the size of the problem an optimum discretisation is sought. This consists of establishing a compromise between a very fine modelling of the structure which is costly and a cheaper coarse modelling which may not provide sufficient local information. We have decided to use a multilayered f.e. configuration. This approach combines the advantage of using beam type finite elements, with the simplicity of uniaxial behaviour enhanced to include shear while at the same time providing sufficient local information (Crisfield 1984, Dubé 1994, Mazars *et al.* 1994, Timoshenko *et al.* 1970).

APPLICATIONS

Application n° 1 : Seismic Analysis of a Bridge Pier

Multi-span motor way bridges of moderated span are commonly employed in France for over-crossing highways (Fig. 2). These structures are entirely made of reinforced concrete.

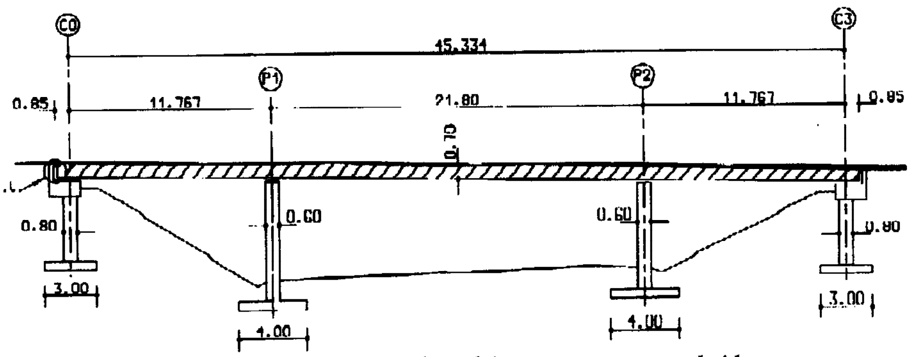

Fig. 2 Plan of a typical multi-span motor way bridge

In this work we have studied the non-linear seismic behaviour of a single pier. Regarding the direction for which this structure has to be studied, it may be considered slender (L/H= 10.2) when ground motions are parallel to the bridge axis, and squat (L/H=1.2) in the perpendicular direction. Figure 3 illustrates all dimensions of the structure, the mechanical modelling adopted, and the mesh of the model. In each direction, segments of the pier are modelled by multilayered beam elements. A concentrated additional mass is placed at the top of the structure representing the portion of the deck mass supported. The model is anchored at its base in both directions.

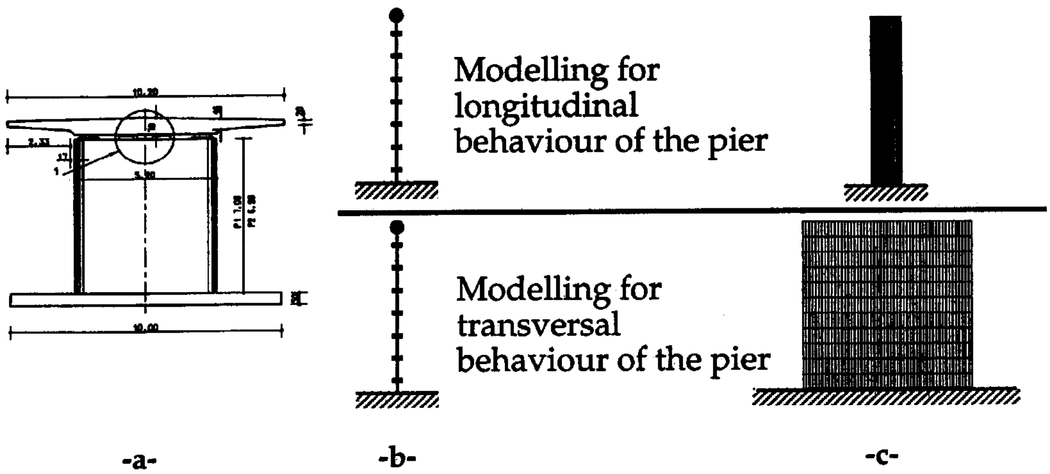

Fig. 3 (a) geometry of the pier, (b) adopted mechanical modelling (c) finite element multilayered mesh

Mechanical characteristics of materials are as follow :
Concrete : E_c= 34 GPa, tensile limit ft= 2.4 MPa, compressive limit fc= 30 MPa
Reinforcement steel : Es= 215 GPa, fe= 400 MPa

To avoid any complexity in understanding the analytical results only one ground accelerogram was used. Different levels of intensity were then obtained by amplifying the magnitude (amplitude) of that signal. The signal used is a synthetic accelerogram generated by a computer program CASTEM 2000 using a normalised spectrum corresponding to the site of the structure.

Comments on analytical results for transversal behaviour

Analysis were made taking 6 different levels of ground acceleration. The maximum values of accelerograms were 0.31g to 1.86g. Global results (top displacements, base shear and moment) obtained are summarised in different diagrams. Within each, comparisons are made between elastic and non-linear behaviour, considering for each the influence of shear strains.

* Figure 4 is a representation of maximum top displacement values obtained for each analysis (elastic, non-linear, with and without shear effect). These values correspond to peak displacements observed on time history results.

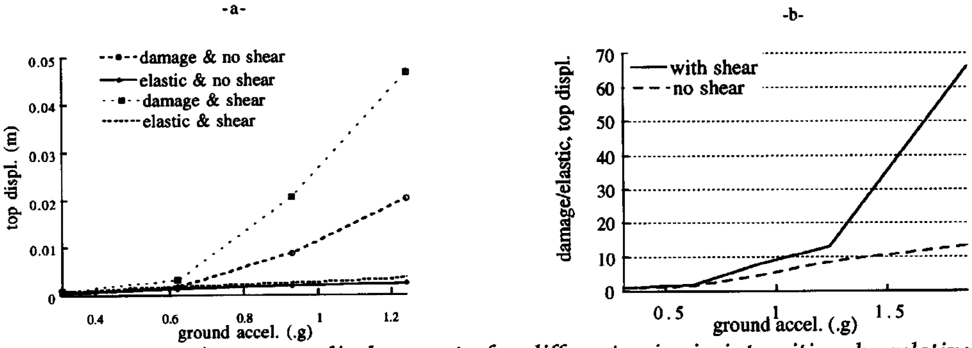

Fig. 4 a- Maximum top displacements for different seismic intensities, b- relative variation of top displacement (damage/elastic analysis) with and without shear effect

Figure 4.b contains ratios of damage to elastic top displacement for both with and without shear consideration. It appears that within damage analysis great relative differences may be obtained when seismic intensity rises. One can see that even for low differences with elastic analysis, the influence of damage is significant. For shear this influence is highly raised by amplifying these displacements. So, at least for top displacements, neglecting shear strain is not a conservative measure.

* Linear elastic analytical results corresponding to maximum values are shown on Fig. 5. It can be seen that base shear forces and moments are generally lower when shear strains are taken into account. This can be explained as a result of the additional shear compliance.

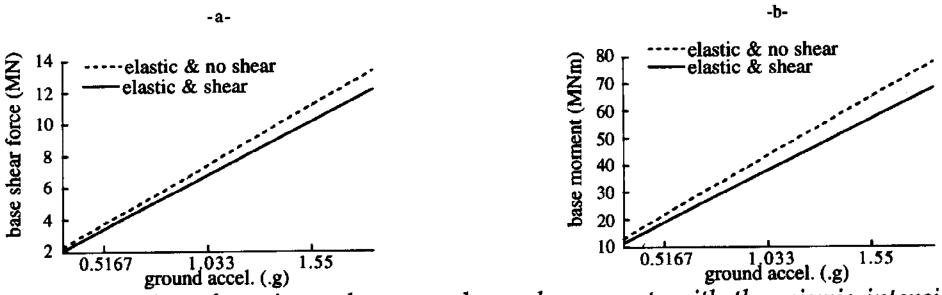

Fig. 5 Variation of maximum base : a- shear , b- moment, with the seismic intensity when the behaviour is elastic. Comparison when shear effects are included or not.

* Figure 6 is the variations of maximum base shear forces and moments for each seismic intensity when damage non-linearity is taken into account.

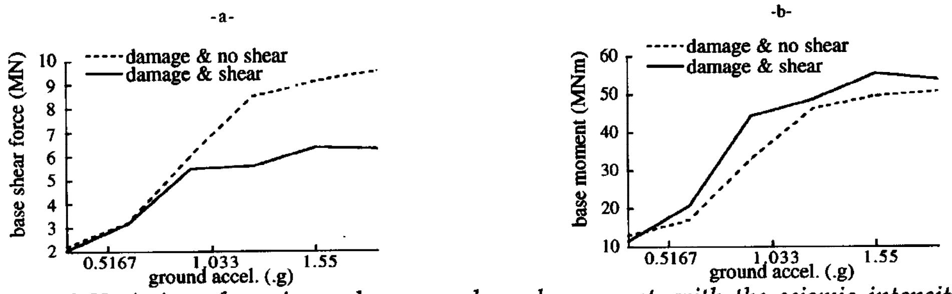

Fig. 6 Variation of maximum base : a- shear, b- moment, with the seismic intensity when the behaviour is damage non-linear. Comparison when shear effects are included or not.

It is not easy to understand the differences and to explain their individual behaviour. For that Fig. 7 is given below in which elastic and damage results are compared, in the case where shear effects are included.

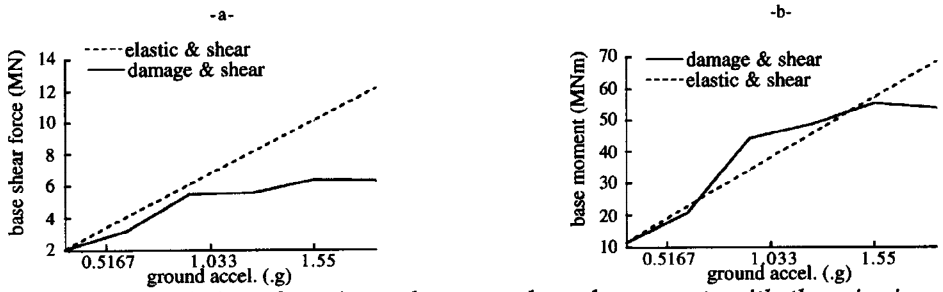

Fig. 7, Variation of maximum base : a- shear, b- moment, with the seismic intensity when shear is included. Comparison between elastic and damage behaviour

It is interesting to note that for some excitation levels, non-linear damage base moments are greater than elastic ones. Considering the fact that damage concept results in lowering the stiffness of the model, all non-linear shear forces had to be lower than the elastic ones. To explain this phenomena we have plotted on Fig. 8 variation of the eigen frequency of the model at each level of seismic action, at the end of the analyses. This was obtained using time history signals. A sharp decrease can be observed for the second and third analysis. When observing the spectrum of the used accelerogram, Fig. 9 it can be seen that for different values of the eigen frequency, the level of excitation is not the same. Thus we can deduce that the loading is not linear for these analyses.

This demonstration is very important since using a reduction factor to reduce elastic forces necessary to design the structure would be totally wrong. This is why no advantage must be taken in using the left branch of the period spectrum, since any degradation in the structural material (concrete cracking or reinforcement yielding) would shift its eigen period to the right hand side.

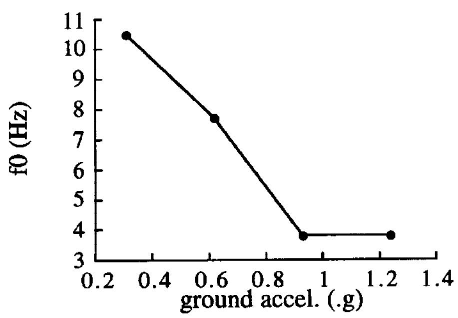

Fig. 8 Eigen frequency variation as a result of progressive damage of the structure

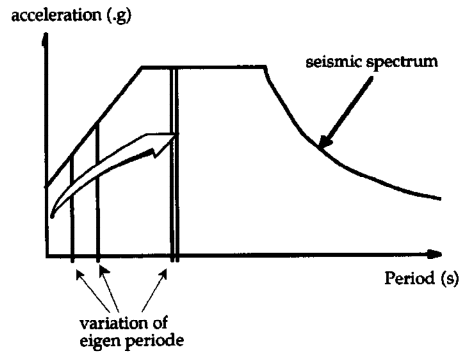

Fig. 9 Spectrum of the utilised artificial accelerogram and the evolution of the eigen period of the model

Because of their high eigen frequencies, such structures are very sensitive to these aspects. The progression of damage in the structure is also an interesting information (Fig. 10). At the end of each analysis a damage map is given. The damage zones correspond to the presence of macrocracks in that part of the structure.

It is clear that the progression is rapid between the third and the forth analysis. While for slender elements this is generally much slower.

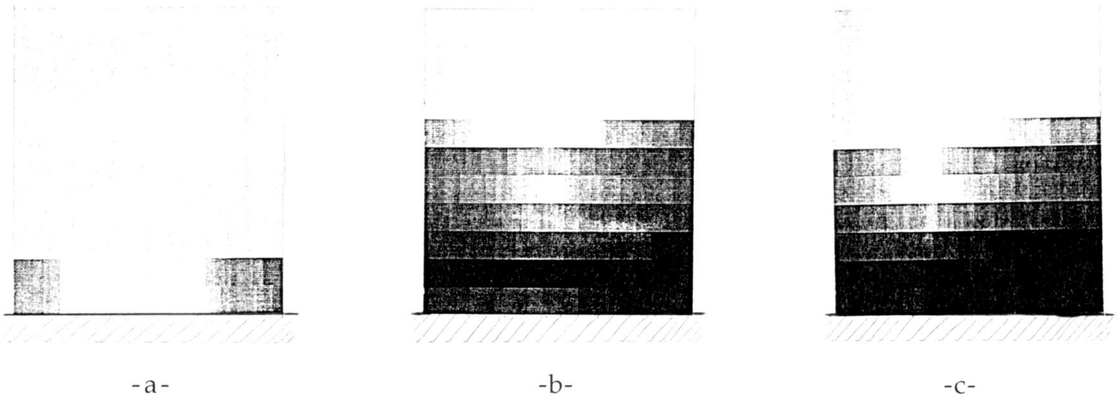

Fig. 10 Damage map. gray areas correspond to microcracked concrete and the darker ones to macrocracked a- after 2nd level analysis amax=0.62g, b- after 3rd level analysis amax=0.93g, c- after 4th level analysis amax=1.24g

Comments on analytical results for longitudinal behaviour

The behaviour of the same structure but in the other direction was also studied (fig. 3). Since the height-width ratio in this case is about 0.1, there was no surprise to obtain negligible influence of shear strains on the results. Severe structural damages caused significant frequency shift, but in this case the initial eigen frequency was approximately on the plateau of the spectrum. So after damage the seismic action had diminished, inversely to the other direction analyses. More yielding of reinforcements was also observed for this structure. For the design seismic intensity, the ratio between elastic and non-linear base moment was found to be about 2.6. This value of *force reduction coefficient* is acceptable for this type of structure.. Concluding that here no particular precautions have to be made, regarding shear effects and/or geometrical non-linearities.

Application n° 2 : Industrial Type Shear Wall

For this application we have studied the seismic behaviour of a shear wall typically employed for nuclear industries. This work has taken place in the framework of an International Standard Problem proposed by the Nuclear Power Engineering Corporation (Japan) and the French laboratory network G.E.O. Experiments taken place at Japan on Tadotsu shaking table for this structure, our aim was to simulated numerically its behaviour. The testing program of 6 different seismic intensities was applied to this structure. The structure is composed of a web wall limited by two flange walls, a base slab and a top slab (Fig. 11). In order to reproduce the vertical stress present in a real structure, additional masses were also attached to the top slab. The mechanical scheme adopted (fig. 11.c) respect faithfully the geometrical and mass positioning features of the real structure in plane. However base slab connection with the shaking table and the stiffness of the table were assumed to function not as a fixed anchor, but allowing some base rotations. The finite element multilayered modelling containing 15 elements with a mean number of 29 layers per element, is also shown on figure 11.c.

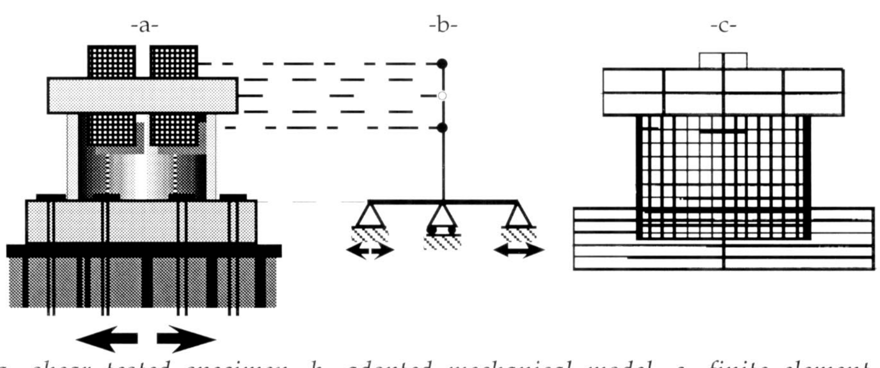

Fig. 11, a- shear tested specimen, b- adopted mechanical model, c- finite element modelling

Concerning the consistency of the specimen; vertical 1.2% reinforcements of 391 MPa yield strength and 188,000 MPa Young's modulus, concrete tensile and compressive limits ft= 2.3 MPa and fc= 29.2 MPa respectively, with an elastic modulus of 23,000 MPa.

With a height/width ratio of 0.7 it is obvious that shear effects should be significant. So for this reason both analyses were made in order to quantify its importance. After all analyses time history data were treated for extracting maximum values for the total base shear force and the relative (base to top) displacement. These results are summarised in fig. 12 and compared with those obtained during the shaking table test. The comparison is confident for nearly all experiments except the last one where the structure had reached its ruin on the table.

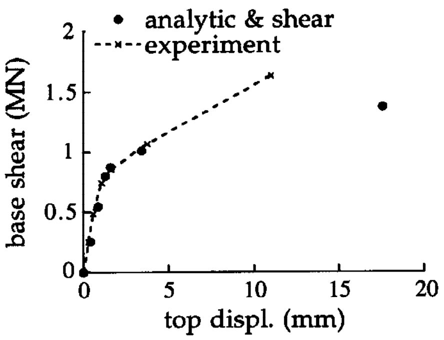

Fig. 12, Maximum responses of base shear force and top displacement. Comparison between experimental and analytical results

Concerning the influence of shear effect, when this was not considered, completely different results were obtained. Figure 13 is a comparison of maximum values between these two analyses (with and without shear strains). It is obvious that not only top displacements and base forces are very different, but also damage is nearly absent.

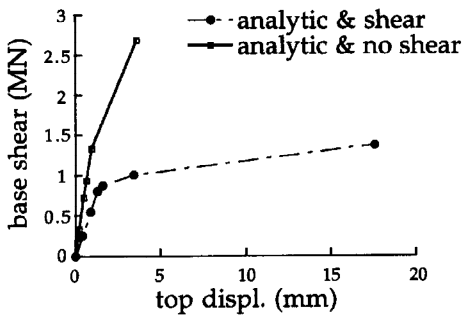

Fig. 13, Maximum values of base shear. With and without shear effect, analytical results

Time history comparisons for low intensities (not damaged) and height intensities (highly damaged) are also promising (figure 14). In the first case it can be seen that the aspect of responses are much the same even if the amplitude is very sensitive to the chosen damping ratio values. Experimental and analytical responses of the highest and the lowest load level show a significant reduction of frequency value.

Frequency representation of time history results for each load intensity (fig. 15) indicates that the eigen frequency vary significantly as a result of concrete damage and steel yielding.

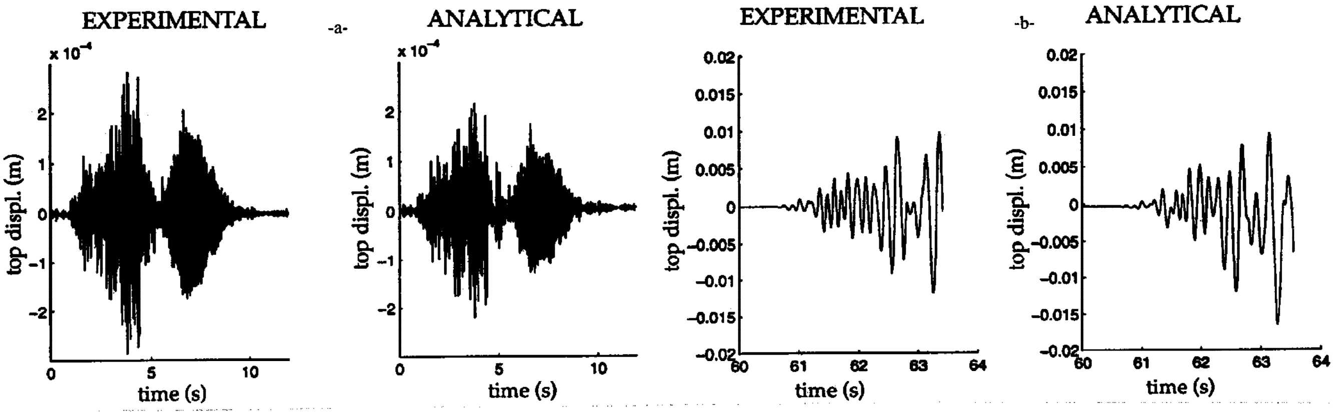

Fig. 14, Time history comparisons. a- low intensity, so no damage, b- high intensity with considerable damages

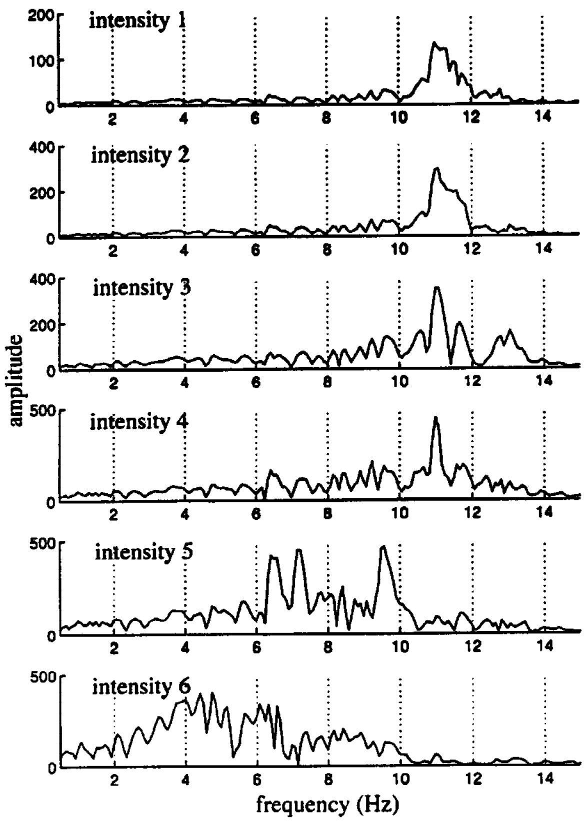

Fig. 15, Spectra obtained from time-history results for each load level

CONCLUSION

The seismic behaviour of an element of a concrete structure is assigned by different phenomenon (damage of concrete and its functioning, yielding of reinforcements, boundary conditions, second order geometrical effects, ...). To apprehend finely, by simulations, their response to an earthquake, it is necessary that these different phenomena should be taken into account. However, to remain in an domain where the size of problems reside reasonable, the use of analysis based on simplified methods is necessary. It is in this context that we propose, through various examples, the influence of such or such phenomenon. And the pertinence of the simplified representation regarding other aspects. The realised tool includes all these aspects, and simplifications respect compromises and its utilisation can be adapted to problems on occulting secondary phenomena. Examples presented in this paper show, specifically through the slenderness of elements considered, the interest of the tool developed at LMT Cachan. The applications aimed constitute a help in setting up rules introduced in earthquake engineering codes.

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