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SEISMIC RESPONSE OF REINFORCED CONCRETE BEARING WALLS, 2D AND 3D F.E. SIMPLIFIED ANALYSIS

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ABSTRACT

This paper deals with the behavior of reinforced concrete bearing walls subjected to seismic loading. The presentation focuses on the numerical tools dedicated to nonlinear transient simplified analysis allowing parametrical studies. In a first step, the multifibers beam approach is presented as well as the local nonlinear constitutive equations. Comparisons between experimental results and numerical computation for 2-D and 3-D case-study are presented.

Keywords: seismic engineering, constitutive relations, transient analysis, simplified analysis

INTRODUCTION

Concerning the study of load bearing walls commonly used in France. Research programs (experiments and modeling) have been carried out on the topic focusing around the realization of experiments on mock-ups (scale 1/3rd) performed on a seismic shaking table. The main purpose of this experimental program consists in demonstrating the ability of reinforced concrete bearing walls to bear seismic loading. The specific design concept is based on the multifuse principle favoring rupture occurrence at several storeys for a slightly reinforced concrete wall. This kind of design leads to lower percentages of reinforcements with their optimized distribution which may generate a wider crack pattern allowing the dissipation of great amounts of energy, and as a consequence, a vertical rising of the masses resulting in energy transformation (from kinematic to potential). Thus ductility is obtained thanks to this particular means to dissipate the earthquake input energy.

The studied structure is a mock-up of a building composed of two parallel reinforced concrete load-bearing walls. The behavior of those under the effect of seismic loadings remains a delicate topic with many regards. Indeed, the three principal elements of a calculation must be taken into

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account with attention because of their strong interactions, namely:

- *Discretization of the structure and the choice on kinematics of the elements selected.*
- *The behavior of materials integrating the cracking of the concrete, makes it possible to represent the decreases of stiffness of the structure as well as plasticity of the reinforcements bringing to failure.*
- *Boundary conditions which governs the behavior as well as the mode of rupture.*

Numerical tools have been developed in a 2D framework allowing to deal with in plane seismic behavior of a wall (CAMUS project) considering a simplified analysis concept. This approach of transient nonlinear analysis is based on a simplified description of the structure at a global level coupled to a refine and physical description of the material response at a local level (damage and plasticity coupling, crack opening and closure for cyclic loading).

The 3D response of the mock up has been investigated within the CAMUS 2000 experiments. New loading paths in dynamics including bi-axial flexion and torsion must be now taken into account. The related improvements concerning the 3D modeling of such structures will be pointed out (3D multifibers beam elements and corresponding constitutive relationships for concrete). The efficiency of such numerical tools for nonlinear dynamics is exemplified through experiment-computation comparisons.

SIMPLIFIED ANALYSIS APPROACH

Nonlinear dynamic analysis of civil engineering structures requires large scale calculations, implying delicate solving techniques. The necessity to perform parametrical studies led us to a choice in terms of numerical modeling in order to reduce the computational cost. The response of a structure submitted to severe loadings, depends on a strong interaction between "material" (local non-linearities), "structural" (geometry, mass distribution, joints) and "environment" (interaction of the structure with its support) effects. For concrete structures, the local material behaviors are the major sources of non-linearities in a structure. The wish to keep a good prediction ability for the model guided us to use constitutive equations for materials as refine as possible, taking into account the main physical phenomena (damage, inelasticity, crack-reclosure, ...). At a structural level, the choice of a "simplified approach" has been made by applying simplifying assumptions compromising as little as possible the wealth and quality of results.

Finite Element Code

The choice of using a multilayered F.E. configuration combines the advantage of using beam type finite elements with the simplicity of uniaxial behavior (or uniaxial behavior enhanced to include shear as one can see below). Each finite element is a beam which is discretized into several layers. As previously exposed, this F.E. code is based on a beam formulation. The basic assumption is that plane sections remain plane (Bernoulli’s kinematic) allowing to consider a uniaxial behavior of each layer. This is no longer satisfactory when shear strains take a major role (Dubé 1994). In that particular case the shear strains have to be introduced in the model and the layer behaves now bi-axially. Cross sectional distortion is introduced through a Timoshenko’s kinematic assuming a parabolic distribution of the shear strains over a rectangular cross section.

The local constitutive equations are integrated for each layer of a cross section.

Reinforcement bars are introduced with special layers, the behavior of which is a combination of those of concrete and steel. A mixing homogenized law is considered :

$$\sigma_{layer} = (1-C)\sigma_{concrete} + C\sigma_{steel} \tag{1}$$

C is the relative area of the reinforcement in the layer.

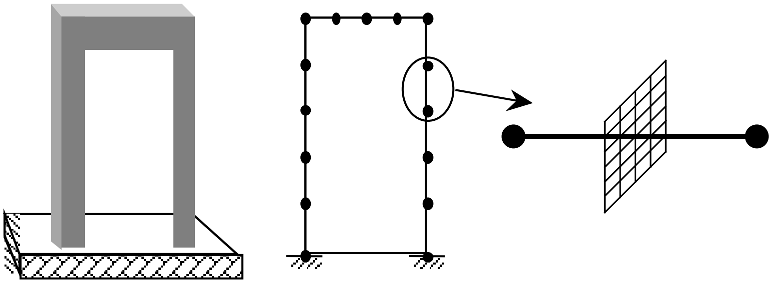


FIG. 1. Multifibers discretization principle

Local Constitutive Relations

In describing the non-linear behavior of reinforcement rebars, we have implemented a classical plasticity model taking into account a non-linear kinematic hardening (Armstrong et al., 1966). Response under uniaxial cyclic loading is presented in figure 2.

Seismic loading, which includes cyclic aspects, produce microcracking in concrete. Some major phenomena have to be taken into account:

- *decrease in material stiffness as the microcracks open,*
- *stiffness recovery as crack closure occurs,*
- *inelastic strains concomitant to damage.*

To account for such a behavior we adopt a continuum damage model (La Borderie 1991), which incorporates two scalar damage variables, one for damage due to tension D_1, the other for damage due to compression D_2 and which includes a recovery stiffness procedure and the description of isotropic inelastic strain. The Gibbs free energy is expressed as follows :

$$\chi = \frac{\langle\sigma\rangle_+ : \langle\sigma\rangle_+}{2E(1-D_1)} + \frac{\langle\sigma\rangle_- : \langle\sigma\rangle_-}{2E(1-D_2)} + \frac{\upsilon}{E}\left(\sigma:\sigma - Tr(\sigma^2)\right) + \frac{\beta_1 D_1}{E(1-D_1)} f(\sigma) + \frac{\beta_2 D_2}{E(1-D_2)} Tr(\sigma)$$

The total strain is : $\varepsilon = \varepsilon^e + \varepsilon^{in}$

$$\varepsilon^{e} = \frac{\langle\sigma\rangle_{+}}{E(1-D_1)} + \frac{\langle\sigma\rangle_{-}}{E(1-D_1)} + \frac{\upsilon}{E}(\sigma - Tr(\sigma)\mathbf{1}) \tag{2}$$

$$\varepsilon^{in} = \frac{\beta_1 D_1}{E(1-D_1)}\frac{\partial f(\sigma)}{\partial\sigma} + \frac{\beta_2 D_2}{E(1-D_2)}\mathbf{1} \tag{3}$$

with ε^{e} elastic strains and ε^{in} inelastic strains. ***1*** denotes the unit tensor and $Tr(\sigma) = \sigma_{ij}$.

Damage criteria are expressed as : $f_i = Y_i - Z_i$ With Y_i, associates forces to damage and Z_i the hardening variable. The evolution laws for damage take the following form :

$$D_i = 1 - \frac{1}{1 + \left[A_i(Y_i - Y_{0i})\right]^{B_i}} \tag{4}$$

$f(\sigma)$ and σ_f are the crack closure function and the crack closure stress respectively. <.>+ denotes the positive part of a tensor. E is the initial Young's modulus and ν the Poisson ratio. D1 and D2 are respectively the damage variables for traction and compression. β1 and β2 are material constants. Figure 2 gives the stress-strain response of that model for a uniaxial traction-compression-traction loading.

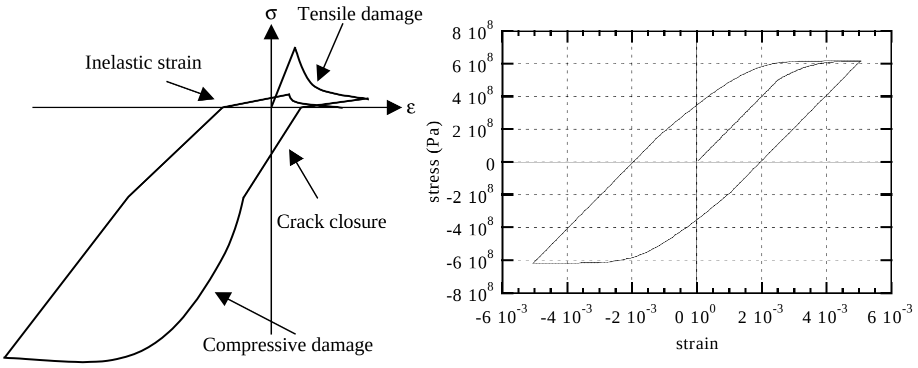


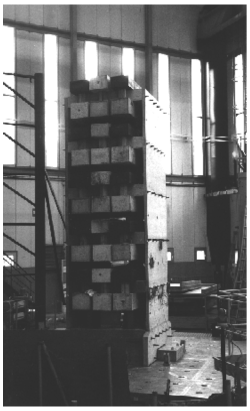
FIG. 2. Uniaxial stress-strain relations for concrete and steel

2-D LOADED R/C BEARING WALL: MODEL CALIBRATION

Experimental Program

The main purpose of the CAMUS experimental program consists in demonstrating the ability of reinforced concrete bearing walls to bear seismic loading. The specific design concept is based on the multifuse principle favoring rupture occurrence at several storeys for a slightly reinforced concrete wall. This kind of design leads to lower percentages of reinforcements with their optimized distribution which may generate a wider crack pattern allowing the dissipation of great amounts of energy, and as a consequence, a vertical rising of the masses resulting in energy transformation (from kinematic to potential). Thus ductility is obtained thanks to this particular means to dissipate the earthquake input energy. To reach this goal, a 1/3rd scaled model has been tested on the shaking table of C.E.A. This mock-up is composed of two parallel braced walls linked by 6 square slabs. A highly reinforced footing allows the anchorage to the shaking table.

The mock-up plans follows in the figure 3. Due to similarity laws between the reality and the mock-up, additional masses of 6.55 t. are positioned at each storey. The mock-up is loaded through horizontal accelerations parallel to the walls. The presence of steel bracing systems at each level disposed perpendicularly to the loading direction prevents any torsion modes occurrence. The accelerograms are modified in time with a ratio of $1/\sqrt{3}$ to take into account the similarity rules. Two types of accelerogram are imposed : Nice S1 for the far field type earthquake and San-Francisco for the near field one.



CAMUS mockup – Description of the test

Boundary conditions	Fixed base	
Scale	1/3	
Height/Length	≈ 3	
Walls	(l/h/d) m	
Floors	(l/l/d) m	1.7x5.1x0.06
Base slab	(l/h/d) m	1.7x1.7x0.21
Normal stress at the base	MPa	1.7x0.6x0.06
Masse	Kg	1.6

FIG. 3. CAMUS mock-up

Numerical Analysis

Calibration

A measure on the original structure of the eigenfrequencies before testing helped us to adjust and calibrate the model in terms of boundary conditions stiffness. Despite the lack of physical meaning, damping is generally introduced in the analysis through viscous forces generated by the means of a damping matrix. This the classical Viscous Rayleigh damping matrix, derived from the general expression proposed by Caughey (1960). The two parameters allow to calibrate the matrix by imposing the value of the damping ratio for two eigenmodes of the virgin structure.The Rayleigh damping coefficients have been adjusted to ensure a value of 1 % on the first mode and 2 % on the second mode. Great attention has been focused on the wish to keep these damping values as stable as possible during all the analysis. This remark may become important for concrete structures for which cracking induces loss in stiffness and by that way a shift of the fundamental frequency. Therefore the damping of the first eigen mode has been chosen so as to remain around the minimum constant range of the Rayleigh diagram.

Experiment-Computation Comparisons

The complete experimental sequence of loading (4 earthquakes) has been simulated thanks to this numerical model. the material parameters used for the analysis are : E=30 000 MPa for concrete with a maximum compressive strength of 35 MPa and 3 MPa for tensile. Concerning the steel, E = 200 000 MPa, elastic limit : 414 MPa with a maximum carrying capacity of 480 MPa.

The table 1 summarizes different comparisons allowing to appreciate the good agreement between experiment and modeling at the global level. The load are expressed at the basis of the walls.

TABLE 1. Global response comparisons

	displacement (cm)		Shear load (kN)		Moment (kN.m)		Vertical l. (kN.m)	
	exp.	comp.	exp.	comp.	exp.	comp.	exp.	comp.
Nice 0.24g	0.72	0.61	65.9	65	200	200	202	190
SF 1.1 g	1.2	1.1	106	90	280	240	271	270
Nice 0.4g	1.35	1.1	86.6	75	280	240	217	225
Nice 0.7g	4.4	3.9	111	120	350	380	312	310

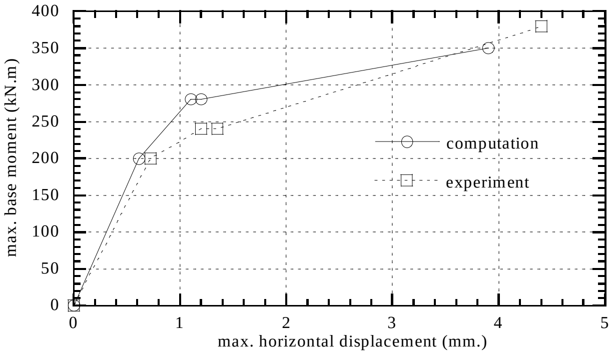


FIG. 4. Load / displacement envelop curve. Structural ductility

The global behavior of the structure is well simulated by the modeling even if during the last level of loading, all the steel bars in the critical sections were broken or buckled. The loss in stiffness and so the decrease of the fundamental frequency is also modeled in a good manner (see Mazars & Ragueneau 2001). A material feature, rarely taken into account is the way the cracks close. In the *CAMUS* program, the major role of the dynamic forces variation allows to quantify this material characteristic. Indeed, by the shock induced as cracks close, the vertical mode is activated and generate important change in the dynamic vertical load (see table1). Modeling such a structural feature become very important for reinforced concrete structures where the design takes into account the interaction between flexural bending and normal loading. The ability of a structure to dissipate energy in the most efficient way is the most important design feature. In figure 4, the maximum bending moment is plotted against the maximum horizontal top displacement for each level of loading. Such a representation allows to keep in mind the great ductility of reinforced concrete bearing walls.

3-D LOADED R/C BEARING WALL

Description of the Specimens and Finite Element Modeling

The main goal of the CAMUS 2000 experiments is to investigate the behavior of reinforced concrete bearing walls subjected to multidirectional seismic loading. The specimen is a 1/3rd scaled mock-up of a 5 storeys building anchored to the shaking table as described in the previous section. The loading is a set of accelerograms applied at increasing level of maximum acceleration in the y and z directions.The mock-up modelling as well as the finite element mesh are presented in the figure 5.

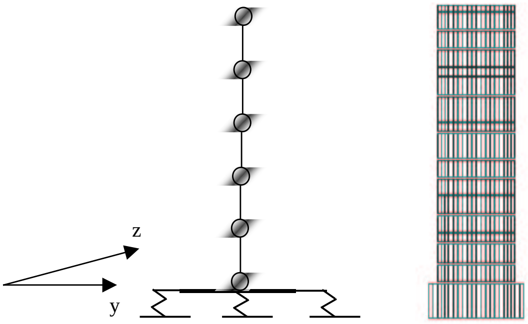


FIG. 5. CAMUS 2000-1 : modeling and FE mesh

The additional masses and the weight load of each floor are concentrated at each storey. The stiffness of the springs below the shaking table is identified so as to feet the first eigenmodes measured on the virgin structure before the seismic loadings. The Rayleigh coefficient used in expressing the viscous damping and calibrated on the previous CAMUS analysis have been kept.

Experiment and Numerical Computation Comparisons

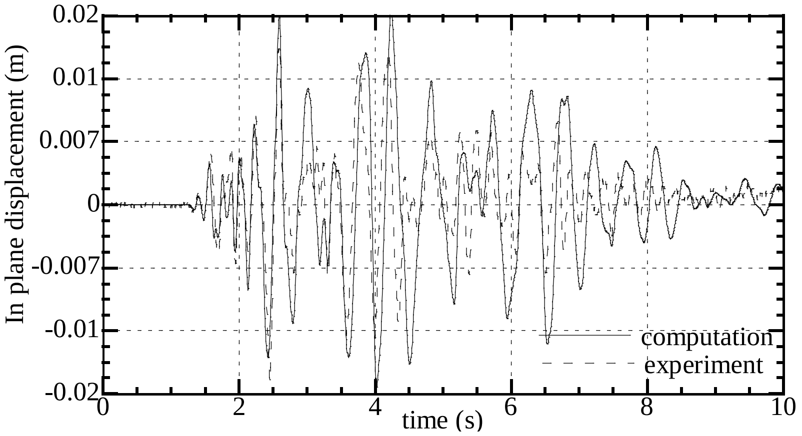


FIG. 6. In plane top horizontal displacement : 0.55 g of maximum acceleration

First results are presented in terms of global flexural moment in the plane (X direction) of the wall and horizontal top displacements in the Y directions for the two levels of loading. These results have been obtained without any calibration according to the experimental results. More investigation for such analysis will be performed on the effects of damping and improvements of the modelling will be carried out to account for torsion and 3 D material behaviors in enhanced beam formulation.

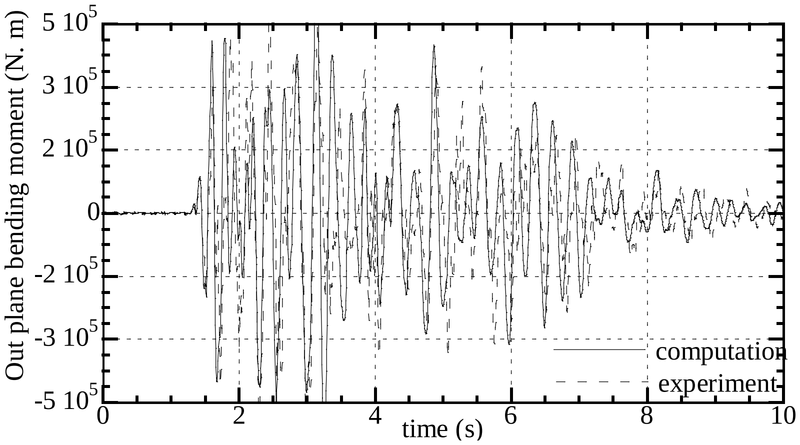


FIG. 7. Out plane bending moment: 0.55 g of maximum acceleration

CONCLUSION

In order to perform nonlinear transient analysis on reinforced concrete structures, it is necessary to pay a great attention to a physical description of materials and to pragmatic solving techniques at the structural level. The simplified analysis, combining an accurate description of material behavior with the mulifibers beams elements, allows to simulate the global responses of large reinforced concrete structure at low computational cost. Two computation examples of bearing walls subjected to 1 or 2 directions of earthquake emphasizes such comments. Improvements of numerical tools are needed for the beam kinematics and material behavior coupling normal and bi-directional shear stress in order to account, in a more physical manner, for the torsion mode, which is automatically activated during 3-D tests.

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