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CRACKING STUDY OF A REINFORCED CONCRETE BEAM

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ABSTRACT

Reinforced concrete beam behaviour is studied during cracking by means of a finite element model. Dynamic and static experimental test results made in E.T.S. Ingenieros Industriales of Madrid have been used to develop this work. A detailed description of the model has been done as well as a sensibility analysis in order to define cracking parameters. Model and experimental test results have been compared. Finally, the evolution of a crack in concrete beam has been simulated using VCCT (*Virtual Crack Closure Technique*).

Keywords: reinforced concrete, cracking, finite elements, VCCT

INTRODUCTION

The main objective of this project is to simulate the global behaviour (statics and dynamics) of a reinforced concrete beam under different cracking levels, using only one finite element model.

Previously, some finite element models of the same concrete beam were done in the Structures Department of the E.T.S.I.I.M, in order to reproduce both static and dynamic behaviour. However, these models only succeeded in the simulation either static or dynamic behaviour separately.

So, the objectives of this project are the following ones:

- Predict the global behavior of a reinforced concrete beam under different degradation levels by means of a finite element model. Thus, it will not be needed to resort to experimental tests continuously.
- Make the finite element model validation through a comparison between simulation and test results.
- Perform a sensibility analysis to determine the correct value of cracking parameters.
- Analyze a single crack evolution, once concrete beam is degraded, by means of VCCT (*Virtual Crack Closure Technique*).

Because of the complexity of this problem, an implicit non-linear calculation will be implemented using MSC.Marc, which is a software based on implicit non-linear analysis developed by MSC.Software.

MODELING THEORY

Two aspects are very important to take into account when a reinforced concrete beam is being modelled: reinforcements model and concrete behaviour law. Marc options used in the model are described below:

- REBAR elements: this option defines material, relative position, number, orientation and section area of the reinforcements.
- ISOTROPIC, PLASTICITY and CRACK DATA define the concrete behaviour law in tension and compression.

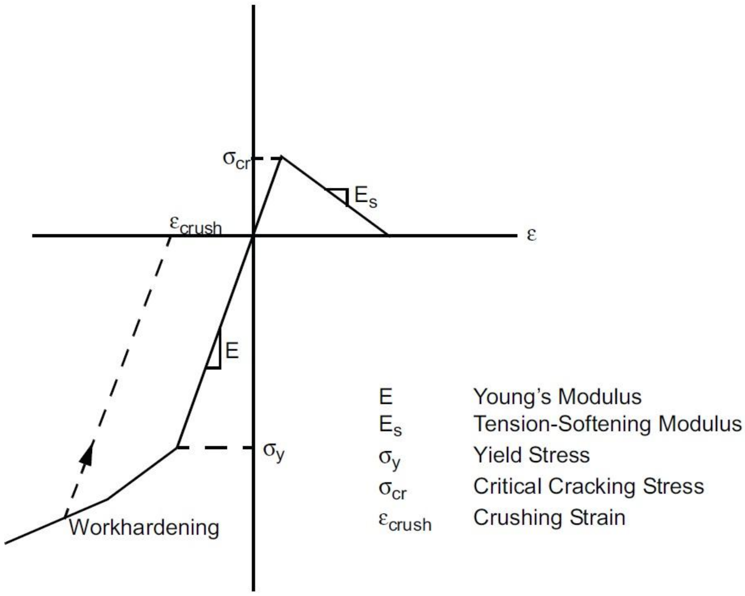

Fig.1 Concrete behavior law

ISOTROPIC option defines elastic zone by means of Young Modulus (E) and Poisson Coefficient (ν).

PLASTICITY option controls concrete plasticity when it works in compression through Yield Stress (σ_y) value.

CRACK DATA option allows simulating cracking in the concrete when it is working under tension. Two parameters are defined: Critical Cracking Stress (σ_{cr}) and Tension Softening Modulus (E_s). For higher stress values than Critical Stress, cracking conditions are reached. Then, tension softening shows how concrete elements are not able to carry load once they have been degraded.

- INSERT option defines displacements compatibility between concrete and reinforcement elements. REBAR elements are embedded and tied into concrete ones.

EXPERIMENTAL TEST CAMPAIGN

The tested concrete beam is 4.54 m length and rectangular cross sectioned (0.22 m x 0.32 m). Reinforcements are placed as it is shown in the picture below.

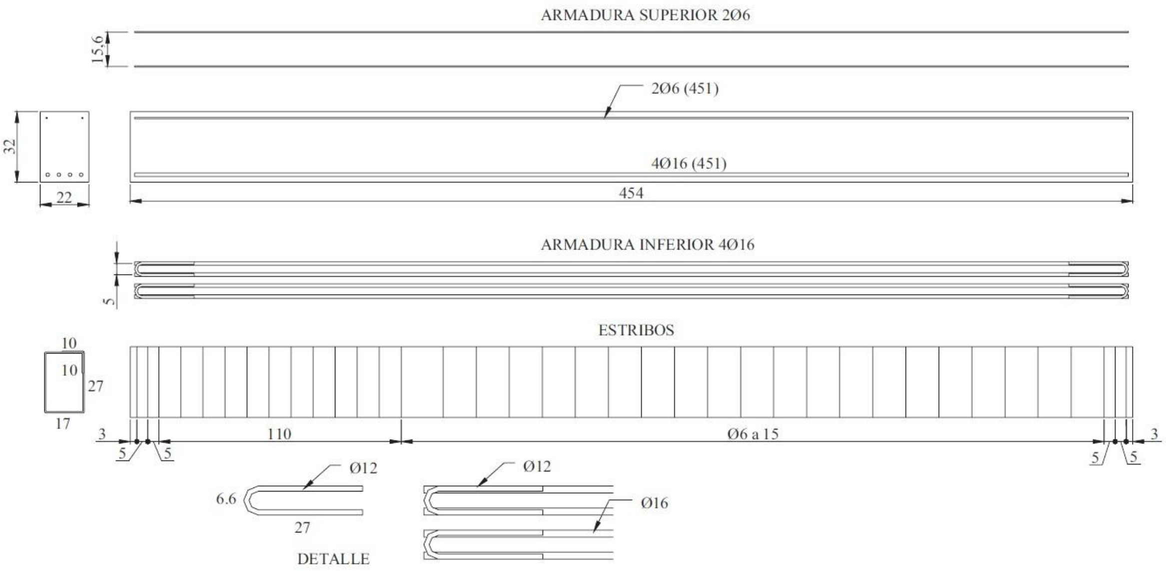

Fig.2 Reinforced concrete beam draft

Experimental tests are divided in static and dynamic tests. Static ones are divided in two different types as well:

- Primary test: a new maximum load level is reached for the first time.
- Secondary test: maximum load level is not exceeded.

As it can be seen in the picture below static tests are four points bending tests:

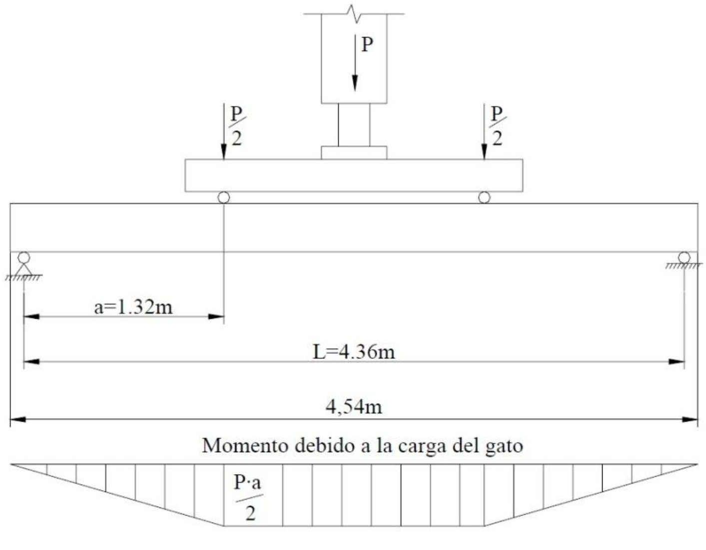

Fig.3 Concrete beam diagram

On the other hand, dynamic modal tests have been done under different boundary conditions, with masses placed over the beam and with the beam hanging.

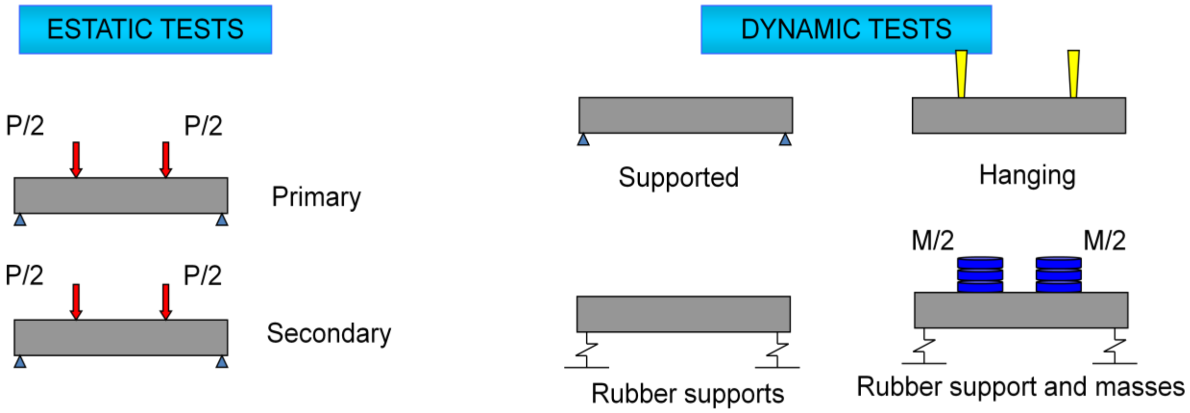

Fig.4 Boundary conditions for dynamic modal tests

Several tests have been done loading concrete beam under different cracking levels. Depending on the load level, three main states can be observed: “noval” (10.4 kN), “elastic” (48.9 kN) and “service” (77.6 kN). Tests were made until the next load levels: 8 kN, 20 kN, 40 kN, 60 kN, 80 kN and120 kN.

Fig.5 Tested concrete beam in structures laboratory of E.T.S. Ingenieros Industriales of Madrid

At the end of each test some variables are measured by means of sensors like gauges and LVDTs:

- Applied load.
- Mid-section beam deflection.
- Concrete deformations.
- Steel reinforcements deformations.
- Crack separation

FINITE ELEMENT MODEL

Reinforced concrete beam has been modelled as a plane stress finite element model.

Concrete elements are simulated with QUAD4 elements whose thickness corresponds to beam width.

Reinforced steel elements are two nodes beam elements, whose area corresponds to reinforcements section.

The global mesh size is 3 cm which covers correctly the concrete coating. The model is made up of 1926 nodes and 1802 elements.

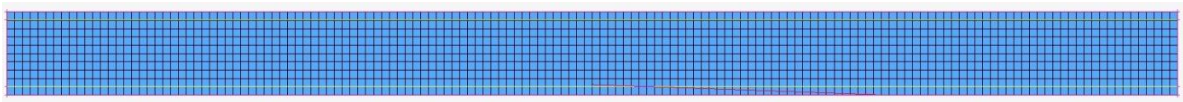

Fig.6 Finite Element model of the reinforced concrete beam

Regarding materials behaviour law, concrete will be defined by:

- Linear elastic parameters: Young Modulus ($E = 2.9309 \cdot 10^{10}$ Pa) and Poisson Modulus ($\nu = 0{,}25$).
- Plasticity behaviour in compression: Yield Stress ($\sigma_y = 13.2$ MPa).
- Cracking behaviour under traction: Critical Cracking Stress ($\sigma_{cr} = 1.8$ MPa) and Tension-Softening Modulus ($E_s = 8 \cdot 10^7$ Pa).

Due to the non-evidence of cracking parameters values, some tests were made before performing the final model. These tests consisted of checking how, both Critical Cracking Stress and Tension-Softening Modulus, affect three aspects: modal frequencies after concrete degradation, cracking load and numerical convergence.

It was concluded that Critical Cracking Stress has a great influence in modal frequencies after the beam is degraded and, also, in cracking load. On the other hand, Tension-Softening Modulus affects numerical convergence so much because as the slope increases, there is an abrupt stress decreasing for little variations in deformation, which results in difficult convergence. This phenomenon could be observed for E_s values greater than 10^9 Pa.

In order to make correct simulations of the experimental tests, boundary conditions must be as similar as possible to real structure ones. Beam supports are not totally stiff but flexible. They have been simulated using spring elements whose vertical stiffness is $k_y = 5.8 \cdot 10^7$ N/m

Regarding applied loads, two point loads have been defined (P/2) in order to simulate the total applied over the beam (P) through a hydraulic jack.

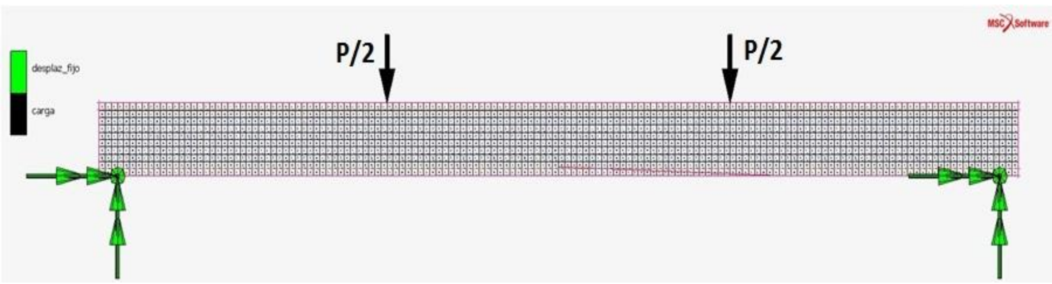

Fig.7 Loads and boundary conditions applied in FE model

SIMULATIONS AND CALCULATION PROCEDURE

Experimental tests which have been simulated are: 8 kN (“noval” phase), 20 kN (elastic phase) and 40 kN (elastic phase). For each one, three different load cases have been defined:

- Dynamic modal analysis previous to static load.
- Nonlinear static analysis
- Dynamic modal analysis posterior to beam degradation.

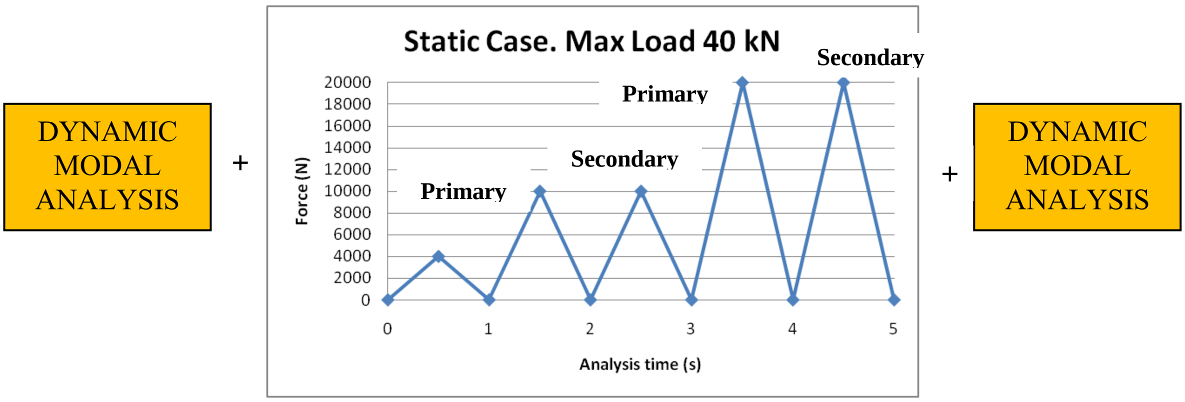

Fig.8 Diagram of the calculation procedure

As it can be seen in the picture above, an incremental loading process is performed with a fixed number of increments (250 increments for each loading-unloading cycle). The same procedure is used for the other two static cases (Max load: 8 kN and Max load: 20 kN).

This way of simulate loading-unloading process is very similar to experimental test procedure, so it will allow to observe the differences in results between primary and secondary analysis. Another phenomenon which will be observed perfectly, following this way of simulation, is the stiffness decrease in the concrete beam after its degradation. It will be checked in the diminution in normal modes frequencies obtained in dynamic modal analysis performed after the static case. If this last modal analysis is done under “large strain” conditions, the stiffness matrix used by this analysis will be modified (differential stiffness) because it will take into account the remaining strain (cracking strain) which will appear after concrete degradation. This is one of the most powerful features of this calculation procedure.

RESULTS

Regarding static tests, the following results were obtained: micro-strains in tension and compression reinforcements and, additionally, in concrete; deflection in the mid-section of the beam; curvature and cracks separation.

One of the most important aspects, which must be validated in the model, is the difference between primary and secondary tests. Pictures below show micro-strain in compression reinforcement in a load-unload cycle until 20 kN.

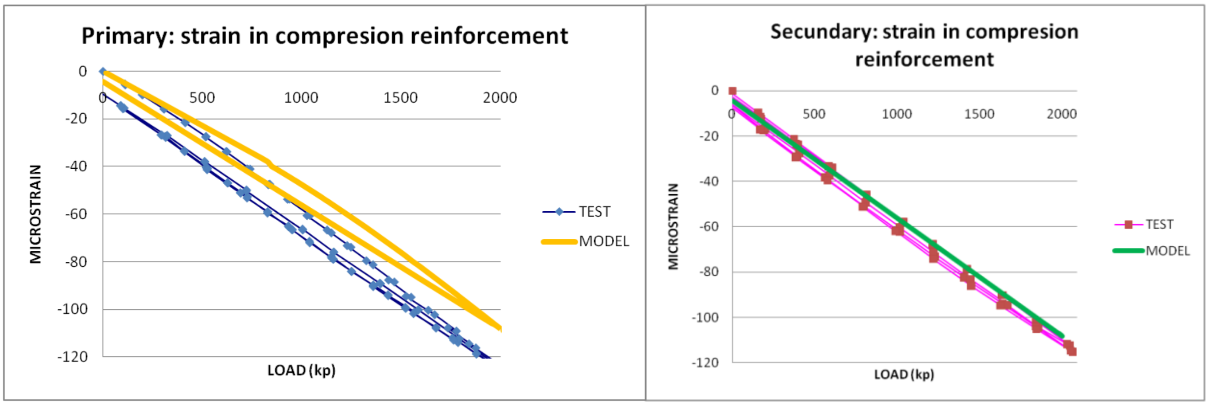

Fig.9 Load-unload cycles until 20 kN for strains in compression reinforcement. Test-model comparison

Primary analysis corresponds to the first time a maximum load level is reached, so nonlinear behavior is expected in the load cycle because of concrete is beginning to crack. However, when it is loaded again until the same load level (secondary), concrete does not suffer more degradation, so a linear behavior is expected. Both phenomena can be observed in experimental tests and simulations.

Another result that was observed in experimental tests is that crack separation was uniform, so they appeared each 16 cm approximately. This fact could be reproduced in the FEM model, as you can see in the picture below, maximum values of Cracking Strain (cracking zones) appear each 15-18 cm.

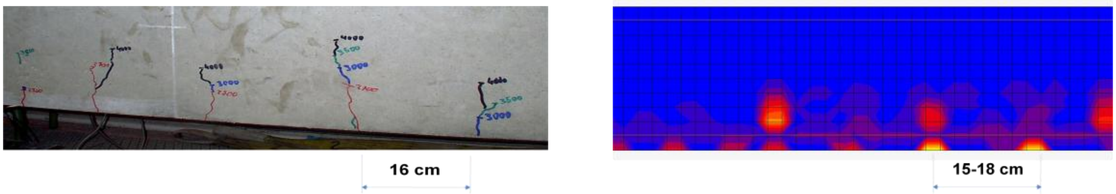

Fig.10 Crack separation. Test-model comparison

Regarding dynamics, dynamic modal tests were done under different boundary conditions. In this project, dynamic modal analyses have been done with the beam under three conditions:

- Free-free without load
- Supported without load
- Supported under three load levels (8 kN, 20 kN and 40 kN)

Tables below compare dynamic modal test results with simulation ones. As it can be observed for "free-free" and "supported without load" conditions the differences are less than 1 %. Therefore, global stiffness beam is correctly fitted in the FEM model.

Table 1 Dynamic modal analysis/test under free-free conditions

Mode	Model Frequency (Hz)	Test Frequency (Hz)	Error (%)
1	57.82	57.26	- 0.98
2	154.47	154.12	- 0.23

Table 2 Dynamic modal analysis/test for supported without load beam

Mode	Model Frequency (Hz)	Test Frequency (Hz)	Error (%)
1	25.80	25.86	0.23
2	79.60	79.74	0.18

Tables below show frequencies obtained in dynamic modal tests and FEM model after degradation. They are decreasing with respect to frequencies obtained in supported beam without load. Therefore, as concrete is cracking beam is losing stiffness.

Table 3 Dynamic modal analysis/test for supported and loaded beam (20 kN)

Supported beam P=20 kN			
Mode	Model Frequency (Hz)	Test Frequency (Hz)	Difference (%)
1	23.30	24.59	5.25
2	72.44	77.03	5.96

Table 4 Dynamic modal analysis/test for supported and loaded beam (40 kN)

Supported beam P=40 kN			
Mode	Model Frequency (Hz)	Test Frequency (Hz)	Difference (%)
1	19.95	23.56	15.32
2	63.37	72.99	13.18

As load level increases, difference between test and model frequencies increases as well. This is due to a recovery crack phenomenon which was observed in experimental tests that consists of cracks closure when beam was unloaded. So, concrete beam stiffness was a bit recovered. However, this phenomenon could not be seen in simulations to the same extent than in experimental tests.

CRACK SIMULATION: VCCT

As the way in which cracks in concrete are growing affects a lot in static and dynamic results after beam degradation, the aim is to study the growth of an isolated crack in detail. For the time being, this is only a preliminary analysis.

VCCT (*Virtual Crack Closure Technique*), available in MSC.Marc, is used for this study. Moreover, an alternative model of the concrete beam is defined. Next changes have been made:

- Finer mesh model, composed of 15927 nodes and 15438 elements.
- Only one point load applied in the mid-section of the beam, to ensure that this section is the most susceptible to crack.

The main conclusion of this preliminary VCCT analysis is that crack stops growing in the point where stresses change from tension to compression (neutral axis).

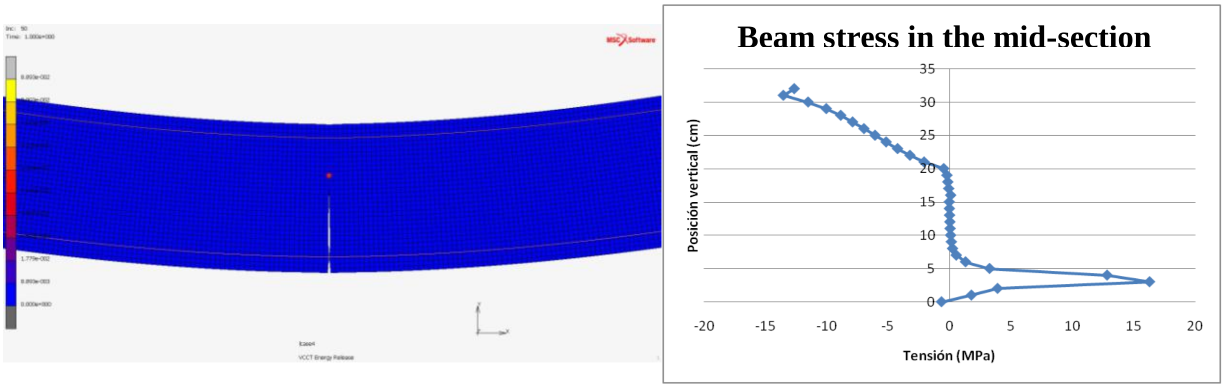

Fig.11 VCCT analysis results

CONCLUSIONS

The principal conclusion of this project is that a FEM model has been developed and validated to simulate the overall static and dynamic behavior of a reinforced concrete beam under different cracking conditions. To achieve this:

- Model static results have been fitted with experimental test results: overall behavior of load-unload cycles, differences between primary and secondary tests and crack separation.
- Dynamic stiffness of the beam before degradation is fitted.
- Stiffness decreasing after concrete cracking has been checked.
- A calculation procedure has been developed not only to analyze this beam but also other reinforced concrete structures.
- A preliminary analysis of the evolution of a crack has been performed with VCCT technique. First results are physically logical.

REFERENCES

BUYUKOZTURK, Oral. *Nonlinear Analysis of Reinforced Concrete Structures*, Computers & Structures, Vol. 7, pp. 149-156. (1977)

DE LA RICA LLAMAS, Adriano. *Estudios dinámicos y estáticos de una viga de hormigón armado. Influencia de la fisuración*, Proyecto Fin de Carrera, Dpto. Estructuras y Construcciones Industriales, ETSII, Madrid (2003)

LU Xiao; LU XinZheng; ZHANG WanKai; YE LiePing. *Collapse simulation of a super high-rise building subjected to extremely strong earthquakes*, Science China Technological Sciences. (2010)