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EXPERIMENTAL AND NUMERICAL STUDY OF RC COLUMNS UNDER BIAXIAL LOADING: AS BUILT

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Abstract. During last decades, have been made many studies about RC columns under uniaxial and biaxial horizontal cyclic loading , however, the knowledge about biaxial behavior is far of uniaxial behavior knowledge. Due to testing difficulties and because there are still open questions regarding the cyclic behavior both in 2D bending with constant axial force, very few experimental studies have, as yet, tackled the more general problem of 2D bending on repaired and retrofitted columns.

In this work is presented the results of an experimental study about behavior under uniaxial and biaxial bending, with constant axial load of as built RC columns. Six columns were tested, three under monotonic loading and three under biaxial cyclic loading with diagonal loading path on as built specimens. After experimental work, was made a numerical nonlinear analysis to evaluate the accuracy of existent models in the representation of the RC columns behavior during a seismic event.

1 INTRODUCTION

Seismic behavior of RC structures is a widely studied theme in the last decades however, the present study had been focused on the behavior of RC columns under biaxial horizontal loading [1,2, 6, 9, 11].

However, many difficulties are still recognized for this analysis approach and, therefore, research must be pursued addressing the biaxial behaviour of RC building columns, bearing in mind that: i) only sophisticated non-linear behaviour models can provide accurate representation of the real structural cyclic response of a given building and, ii), these non-linear hysteretic models have to be calibrated and validated with experimental results obtained from bidirectional tests on RC columns [3]

Experimental research work on the inelastic response of RC members under compression axial force and biaxial lateral cyclic bending loading conditions is currently very limited. Uncertainties concerning the relationship and combination of the two orthogonal horizontal loading paths, associated to the complexity of the experimental set-up, certainly justified this lacuna [4].

From the authors who have studied the biaxial load stand out Bousias et al 1995 [8], with a vast study of biaxial load with constant and variable axial load, other authors began a few years earlier the study of biaxial models as Abrams et al (1987)[13] and Saatcioglou et al (1989)[10]. Tsuno and Park [2004] [7] tested a series of five columns with square section and designed by Japanese rules, from this job resulted two important conclusions, which are the plastic hinge length tends to stabilize by theoretical values, after some cyclic loads and this is indifferent to biaxial load [7] High displacements in the beginning of test cause high degradation and low dissipation of energy, however, if the displacements amplitude begins low and increasing slowly, as standard model of Park, [7,15] the energy capacity of column until ultimate state are the same to uniaxial and biaxial loading.

Low and Moehle [1987] [12] made some tests using rectangular cross section, with different stiffness and strength in each direction. They used three specimens, one tested uniaxially (1) and two biaxially (2 and 3). The specimen 2 was tested with a load 7,5º by diagonal of section and 45º of inclination to lower inertia direction, they got similar results of series D of Saatcioglu (1984)[5]. The third test followed a cloverleaf path, this test allowed conclude that in the major inertia direction, the dissipated energy in the orthogonal direction was the double than with regular square path and in the lower inertia direction happened the same.

Finally Rodrigues et al. [15, 16] tested 17 RC rectangular columns with four types of full-scale quadrangular building columns tested for different loading histories. The horizontal loading patterns considered were Cruciform, diamond, expanding quadrangular and Circular. In this study the comparison of the biaxial results is performed with similar columns under uniaxial load. Based on the obtained results, it was verified that: i) The initial column stiffness in both directions it is not significantly affected by the biaxial load path, ii) when comparing the maximum strength in one specific direction of the columns for each biaxial test against the corresponding uniaxial test, lower values were obtained for all biaxial tests than uniaxial ones. The biaxial loading induces a 20-30% reduction of the maximum strength of the columns in their weak direction, Y, while reductions from 8-15% for the stronger direction, X, iii) the ultimate ductility is significantly reduced in columns subjected to biaxial load paths, iv) The strength degradation is practically zero, in the first loading cycles, increasing after displacement ductility demands of about 3. From the strength degradation analysis, more pronounced strength degradation was observed for biaxial tests when compared with corresponding uniaxial tests, v) the biaxial loading can introduce higher energy dissipation (circular, rhombus and cruciform load paths) than uniaxial loading, as previously recognised by other authors. It was confirmed that the energy dissipation also depends on the column's geometry; vi) The viscous damping highly depends on the biaxial load path. The repetition of cycles, for the same maximum displacement level, has practically no influence on the equivalent damping.

2 EXPERIMENTAL SETUP

2.1 Test Specimens

On this campaign were used cantilever columns, the system were composed by a footing with1.30x1.30x0.50 meters and column with 0.30x0.50x1.70 meters. The reinforcement arrangement is the same at all specimens. At Figure 1 are present a reinforcement arrangement and two of the tested specimens.

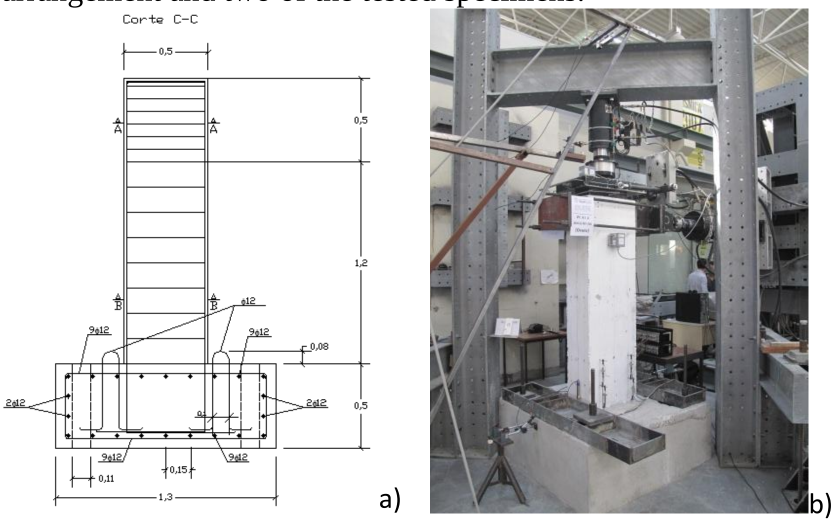

Figure 1 a) Reinforcement detailing; c) Column PC_01_N02

2.2 Testing Setup

The setup shown in Figure 3 was adopted in the experimental campaign. The system includes two, 500 and 200 kN actuator to apply lateral loads with ±100 mm stroke and a 750 kN actuator to impose axial loads, using two reaction frames (lateral and vertical). Both the specimen and the reaction frames are bolted to the strong floor with high strength prestressed rods. In the tests described below, a constant axial load was applied while the lateral loading was cycled under displacement controlled conditions. Since the axial load remains in the same position while the specimen deflects, a special sliding device is used in order to minimize spurious friction effects.

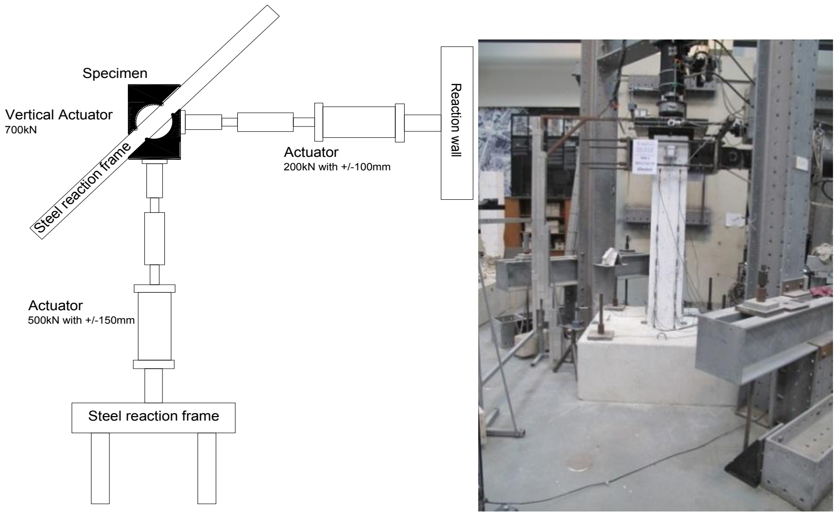

Figure 2 Test setup at LESE laboratory. a) Schematic layout. b) General view

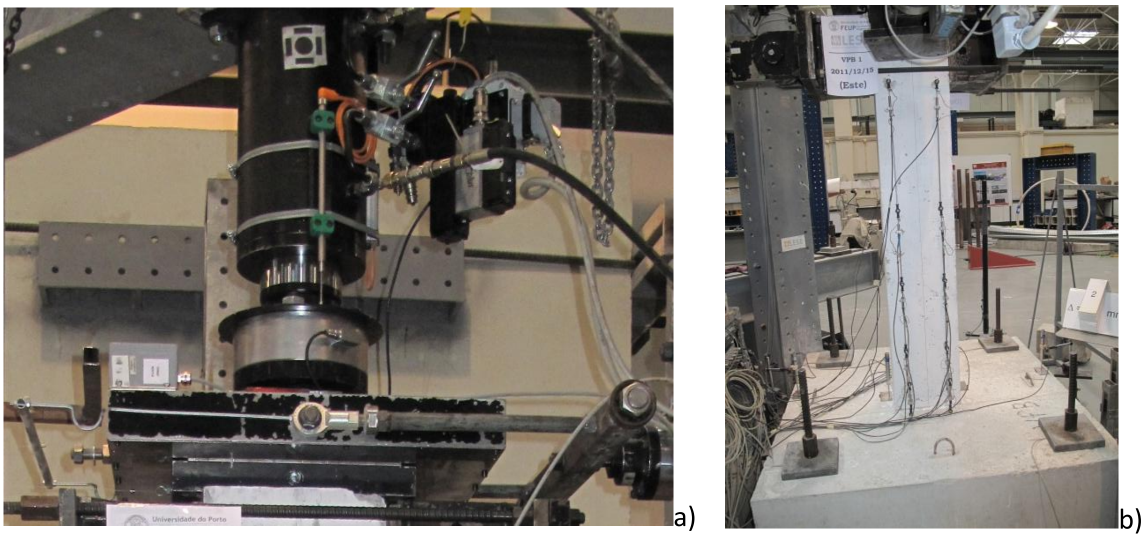

Figure 3 Details of testing setup: a) The axial load sliding device; b) LVDTs

As shown in Fig. 4a, the device consists of two steel plates, the lower one bonded to the specimen top section and the top plate hinged to the vertical actuator, allowing top displacements and rotations on the specimen to occur when lateral loading is imposed. The upper plate is connected to a load cell reacting against the lateral frame in order to measure the residual frictional force between the two plates. This force is then subtracted to the horizontal actuator load, in order to obtain the correct force imposed to the specimen. The hydraulic system of the vertical actuator was designed to keep the oil pressure constant, thus ensuring a constant axial force during the tests. Data acquisition and signal conditioning cards provide direct readings from strain gauges, load cells, LVDTs (Linear Variable Displacement Transformer) and other types of amplified analogical or digital sensors as illustrated in Fig. 4b.

3 NUMERICAL ANALYSIS

Several numerical analyses were performed, using a continuum damage model (Faria and Oliver (1993)) [17] to represent the columns' concrete behavior. That model was initially developed for the characterization of mass concrete structures, such as dams, but has already been used with very good results on the scope of simulating the seismic behavior of reinforced concrete columns (Vila Pouca (2001)[20], Faria *et al.* (2004)[18]). It relates the evolution of the strength degradation and, thus, the damage experienced by the material, with the increase in two internal variables, controlling the performance on tension and compression independently. This model was used in conjunction with a solid element FE mesh (20 node cube elements), refined accordingly to respect the specimen geometry and rebar disposition. As for the rebars, the well-proven Menegotto-Pinto model [19] was adopted as the constitutive behavior controlling the 2 node bar elements responsible for modeling the steel reinforcement. All these models are implemented in the aforementioned Cast3m software.

The numerical load was a simple monotonic biaxial law, calibrated for three different situations, representing different angles between the load axis and the column section's strong direction. The previously mentioned values were 30º, 45º and 60º.

4 RESULTS ANALYSIS

The evaluations of the experimental campaign results were made mostly by comparison with the numerical results. At this stage of the work, it was considered avoid the calibration of parameters needed on cyclic biaxial simulation models and adopt the monotonic model that mostly uses the knowledge of the characteristics of the materials obtained experimentally.

The ultimate displacement allowed by the test setup is 100mm for each side, given by the maximum stroke of hydraulic jack.

Both results, experimental and numerical, are presented at following figures 4 to 10

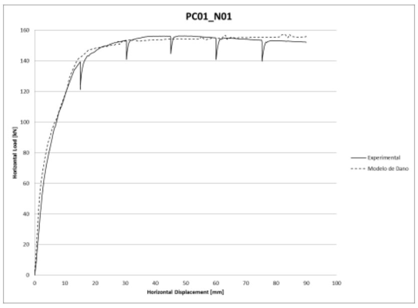

Figure 4 Monotonic Test: Experimental Vs Numerical at strong direction

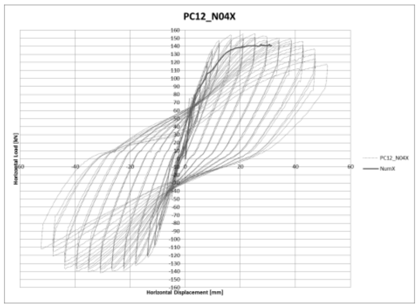

Figure 5 Biaxial Experimental Test Vs Monotonic Numerical Test 30º Test at Strong Direction

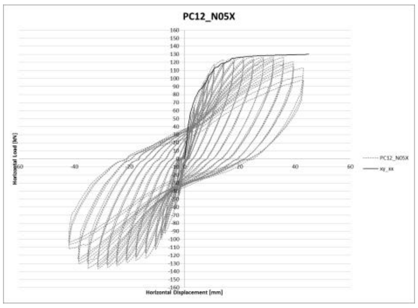

Figure 6 Biaxial Experimental Test Vs Monotonic Numerical Test 45^o Test at Strong Direction

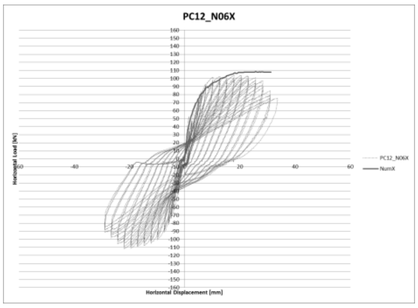

Figure 7 Biaxial Experimental Test Vs Monotonic Numerical Test 60^o Test at Strong Direction

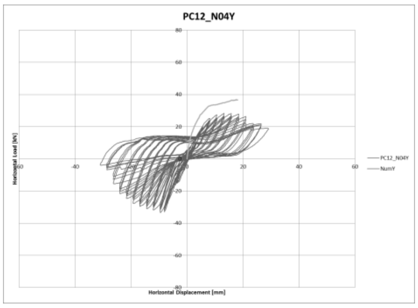

Figure 8 Biaxial Experimental Test Vs Monotonic Numerical Test 30^o Test at Weak Direction

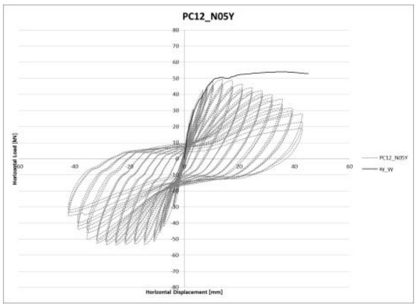

Figure 9 Biaxial Experimental Test Vs Monotonic Numerical Test 45^o Test at Weak Direction

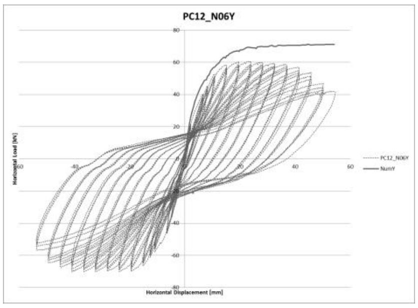

Figure 10 Biaxial Experimental Test Vs Monotonic Numerical Test 60^o Test at Weak Direction

The numerical unidirectional monotonic test on strong direction (Figure 4) has a perfect match with similar behavior comparing with experimental test: same displacement for same maximum horizontal load. The same conclusion is valid for same direction at most of the loading path on bidirectional cases: PC12_N05X and PC12_N06X (Figure 6 and 7). The final part of numerical test didn’t follow the same levels of strength degradation.

Only with PC12_N04X the maximum strength wasn’t achieved, but it has a similar initial stiffness. This experimental test of specimen PC12_N04 did not have an expected behavior, on weak direction. The result is not good, if evaluated the low level of energy dissipation, stiffness and the asymmetric result.

This test was the first of that series and because of that had some problems at the beginning, which had some involuntary and not foreseen movement that cause some stiffness changes. Another consequence is the asymmetric behavior that also couldn't be represented at numerical simulation.

In all cases, on weak direction, the numerical tests have a higher strength capacity and any strength degradation.

4.1 Damage comparison

This analysis pretend to compare the damage and the levels of strain and tensions observed in numerical analysis and compare them with the degradation observed on experimental test. In figures 11 to 14 are present: the observed damage at the tested columns; the concentration of damage at the compression zone; the level of tension at steel rods; and the damage extension in columns height.

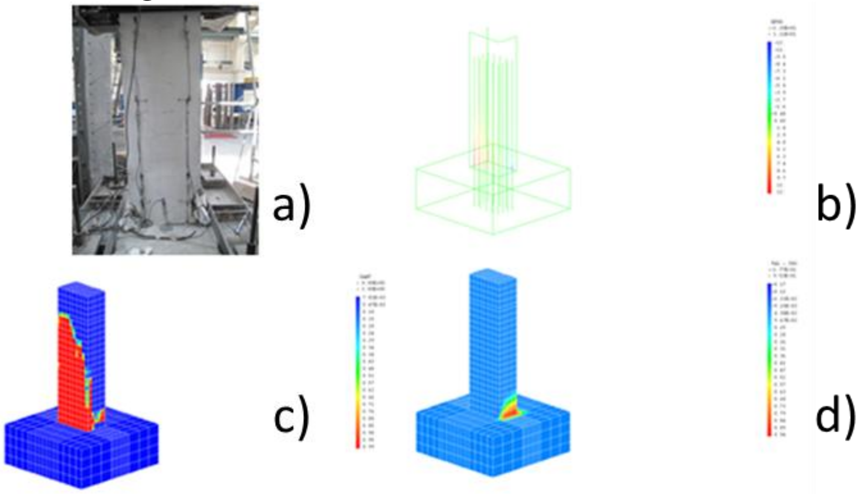

Figure 11: Column PC12_N04 - a) Experimental test; b) Tension at steel bars; c) Damage evolution; d) Compression damage

As shown at figure 11a), the damage caused by concrete compression is concentrated at the base of the column and similar to the damage observed at the experimental test. The figure 11b) shows the tensile deformation that is similar to the experimental test and also the corner bar has a higher tension.

In numerical analysis the damage spread, figure 11c), seems to be exaggerated thought column height.

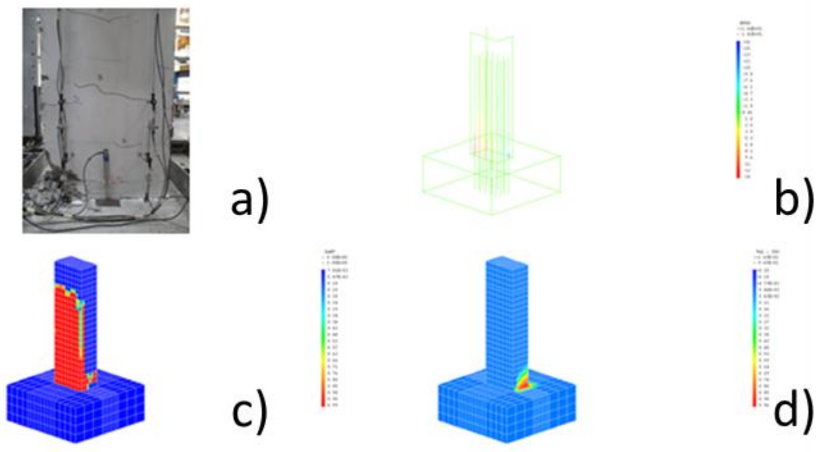

Figure 12: Column PC12_N05 - a) Experimental test; b) Tension at steel bars; c) Damage evolution; d) Compression damage

The PC12_N05 the damage extension is overestimated, figure 12c). As in the previous test the damage is concentrated at plastic hinge region. The figure 12b) has a concentration of traction at longitudinal bars similar to the experimental test, the damage is concentrated at 3 bars of the corner SE, the middle bar of the strong direction does have a soft observed damage as it seen at experimental test. At the compression the damage is highly concentrated at the NW corner, which is shown at figure 12d), the numerical analysis has a similar result of experimental test.

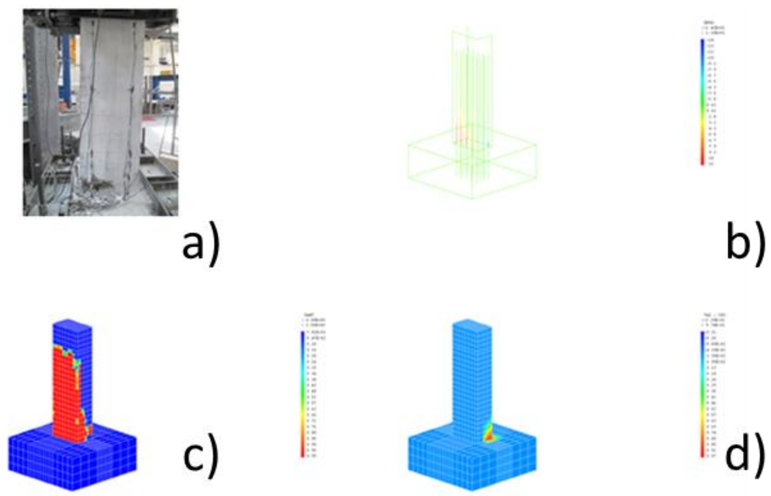

Figure 13: Column PC12_N06 - a) Experimental test; b) Tension at steel bars; c) Damage evolution; d) Compression damage

The test PC12_N06 has a problem with asymmetric cover at all section caused by experimental asymmetric initial damage. Although the numerical analysis cover the principal observed damages, the longitudinal bars with higher tension are the 3 corner bars, figure 13b).

The damage concentration in corner is more visible at this test when compared with previous. Numerical analysis closely approached the damage concentration, figures 13a), 13c) and 13d).

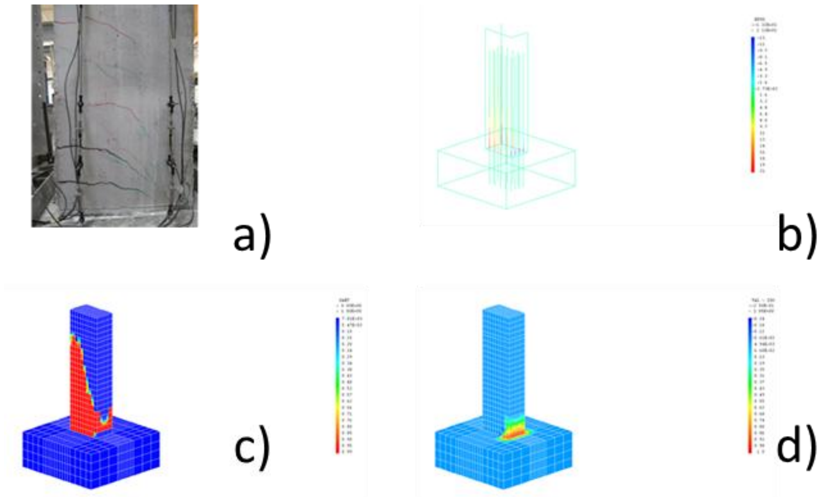

Figure 14: Column PC12_N01 - a) Experimental test; b) Tension at steel bars; c) Damage evolution; d) Compression damage

The uniaxial monotonic test has a wide range of bar deformation at the experimental test. All bars was damaged and, at the end of the test, was visible steel bars buckling.

The numerical analysis, has a good approach of tension at longitudinal bars, the compression is distributed by the total length of weak direction section, at this test wasn't visible a concentrated damage in the corner as happen at biaxial tests. The damage height spread is not realistic.

In all numerical tests the major tensions and strains was observed at steel rods, Figure 11b), 12b), 13b) and 14b), like happened with experimental tests. Due to the observation of steel rods under higher tension, some has buckling phenomena and some broke during the experimental test.

5 CONCLUSIONS

The experimental work allowed to conclude that uniaxial load tests have an higher level of strength capacity and didn't present any strength degradation. This behavior is consistent with the characteristics of biaxial cyclic degradation compared with the monotonic uniaxial degradation. The capacity required for biaxial load tests is higher, due to have strength degradation in both direction, and require a higher deformation capacity.

The numerical model is not sensitive to the experimental conditions, because it couldn't predict a faster strength properties degradation to one side when the opposite side still with full strength capacity. For example, if appear spalling in one direction and do not appear in the opposite direction, the model can't compensate that difference and that create difficulties to validate numerical proposal.

The numerical model can predict effectively the strength capacity with a small margin of error, which can ensure a good capacity prediction to real structures.

The numerical model produced acceptable results to damage analysis however it is overestimate the damage extension at column height.

The model can achieve the concentrated damage at the section corner to used biaxial load patterns.

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