

Effects of cyclic biaxial shear loading on the seismic response of RC columns

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SUMMARY:

In past earthquakes the effects of bidirectional cyclic loading have shown to produce larger damage and lower ductility than similar uniaxial excitations in concrete columns. In this paper an experimental and numerical study is carried out on two identical columns subjected to uniaxial and biaxial loading with constant axial load. The specimens were designed to fail in combined shear-flexure; therefore, exhibit fragile behaviour. Numerical simulation is performed by means of a full 3D sectional formulation which considers the interaction of tangential forces (shear and torsion) and confinement. After describing the test setup and model calibration, the experimental and simulation results are presented and discussed. They show that biaxial shear loading affects the shear mechanisms, producing larger transversal strains for the same load intensity and lower crack angles. These larger strains reduce concrete ultimate axial strains which may produce premature failure.

Keywords: biaxial loads, biaxial test, shear, non-linear, reinforced concrete

1. INTRODUCTION

In reinforced concrete (RC) structures under earthquake, the columns can be exposed to simultaneous forces and moments. Corner columns in buildings and piers in curved or skewed bridges can be subjected to cyclic combined flexure and axial loads, shear loads and torsion moments. Furthermore, shear forces and concomitant moments can take place in more than one direction reaching similar magnitudes for reasons such as: the dynamic response of the structure, orientation of the structure with respect to seismic excitation, aftershocks, among other causes.

Effects of bidirectional lateral loads were showed in the columns of Imperial County Services building, where they had excessive damage under the Imperial Valley earthquake, 1979 (Shepherd and Plunkett, 1983). A decrease in ductility and resistance has been experimentally evidenced in columns under bi-directional, as well as more damages and residual deformations with respect to the unidirectional loading (CEB, 1996, Kawasuchima et al., 2003, Tsuno and Park, 2004, Rodrigues et al., 2010). However, the number of experimental results is limited. Experimental studies have been performed to evaluate energy dissipation and performance of columns designed with current code requirements and under different load paths and type loading (Bousias et al., 1995, Mosalam et al., 2002, Qiu et al., 2002, Hachem et al., 2003, Dhakal et al., 2007, Chang, 2010, Khaled et al., 2011, Rodrigues et al., 2012). In spite of this, provisions of seismic design have not been traduced into specific recommendations, except for the reduction of shear strength contribution of concrete under biaxial loading recommended by (Wong et al., 1993, Kowalsky and Priestley, 2000). One possible explanation for this is the not completely understood mechanics of this problem, together with the additional complexity introduced by the randomness of the loading path.

On the other hand, numerical simulations of buildings and bridges under seismic loads are performed with one-dimensional elements (frame elements) because they are computationally very efficient with respect to three-dimensional elements. In one-dimensional elements, the strategy of the formulation is

to reduce the three-dimensional strain field to one-dimensional strain field on a cross section, i.e. a sectional analysis (Marí, 1984). Traditionally, sectional analyses have been performed considering only the axial-bending deformations to simplify the problem (moment curvature analyses). Then, the cross-section is divided into small elements (fibre elements) whose response is characterized by a uniaxial constitutive equation according to corresponding material and the state stress assumption. Therefore, the effects of tangential forces (shear and torsion) are not considered. Currently, some sectional formulations have been derived to account for tangential forces. To account for 3D loading of cross section total interaction sectional analyses (TINSA) can be used (Bairan and Mari, 2006a, Bairan and Mari, 2006b). This formulation resolves the coupled problem and three-dimensional strain field in cross section.

The aim of this research is to contribute to the understanding of the behaviour of columns under bidirectional cyclic loading which are vulnerable to shear failure and to provide recommendations for seismic evaluation and design. This paper presents an advance of the experimental campaign conducted including the results of the simulations with sectional model TINSA. Two columns with light transversal reinforcement under unidirectional and bidirectional loading are studied; additionally, possible strategies to consider three-dimensional effects for code provisions are exposed.

2. EXPERIMENTAL PROGRAM

2.1. Specimens and test setup

The two circular cantilever columns were tested under quasistatic cyclic loading. The specimen dimensions corresponded to one-half column height of a typical five-story-building in scale 1:1 or an overpass bridge with integral deck in scale 1:2. Both specimens had identically dimensions and reinforcement. The specimens consisted on the column, a footing and a cap beam used to introduce the horizontal and vertical forces, see Fig. 1. The cross section of the column had 350mm of diameter. The columns were design so flexural-shear failure. Accordingly, light transverse reinforcement were provided and consisted of closed circular hoop, 6mm of diameter, with 90-degree hooks and spaced at 200mm; the first hoop, nearest to base, was set at 100mm; the volumetric transverse steel ratio for 200mm spacing corresponded to 0.5% (volume of hoop to volume of core, out to out of hoop). Longitudinal reinforcement consisted of 12 deformed bars, 16mm of diameter, without lap splices and distributed uniformly around the hoop; the longitudinal reinforcement ratio correspond to 2.5% (steel area divided by gross section area).

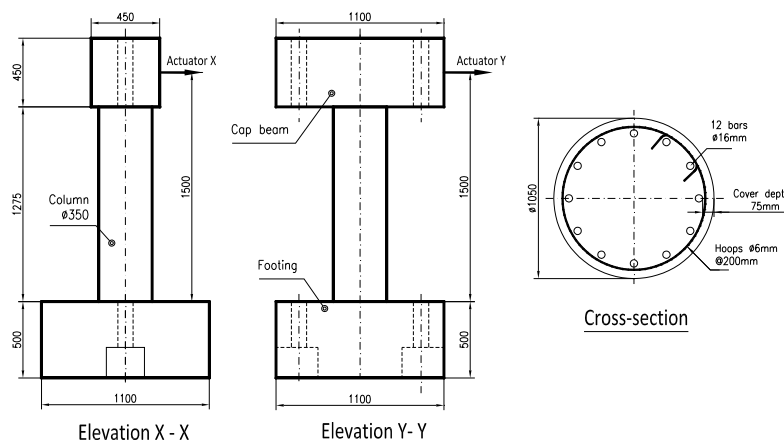


Figure 1. Specimen dimensions and reinforcement

The footing was post-tensioned to strong floor with four high steel bars. The column was loaded axially using two high steel bars; the bearings of the bars were placed in the footing and cap beam, spherical plain bearing and a fixed bearing were used, respectively. The specimen was loading laterally with actuators located at 1.5m from base of the column; two actuators were coupled

orthogonally (directions X and Y) at cap beam for bidirectional loading and only one actuator (direction X) for unidirectional loading. The test setup for bidirectional loading is showed in the Fig. 2.

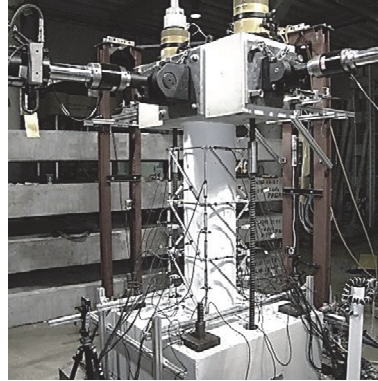


Figure 2. Test setup for bidirectional loading

2.2. Materials

The specified concrete class was C40/50, consistency was fluid concrete, aggregate weight was normal and maximum size was 20mm. The specimens were fabricated in precast concrete plant. All components of specimen were cast monolithically with a single concrete batch, self-compacting concrete was required. The mechanical properties were obtained from standard test on cylindrical specimen (150x300) at testing day (180 days approx.). The compressive strength and Young modulus were 57.5 MPa and 37 GPa, respectively. Both longitudinal and transverse reinforcement were specified as steel grade B500-SD ($f_{yk}=500$ MPa, special ductility class) supplied in coils. Tensile yield strength was obtained from standard test, resulting 546 MPa for longitudinal reinforcement and 506 MPa for transverse reinforcement.

2.3. Test program and instrumentation

The lateral load was applied as displacement imposed in the top column by mean of one or two orthogonal actuator(s). The recommendations by ACI (2005) and Shen et al.(2006) were adopted for the lateral loading history; thus increasing amplitude lateral displacement are defined as ratio of reference deformation, see Fig. 3a. The corresponding displacement to yielding of first longitudinal bar was adopted as reference displacement (Δ_y) estimated after a simplified plastic hinge analyses as described in (Priestley and Park (1987) and CALTRANS (1999). In the bidirectional test, load path followed the quatrefoil pattern show in the Fig. 3b. Each amplitude displacement was repeated, three and two cycles for unidirectional and bidirectional loading, respectively. The axial load was constant during the test; both specimens were subject to axial compression of 1100 kN ($\approx 0.2f_cA_g$).

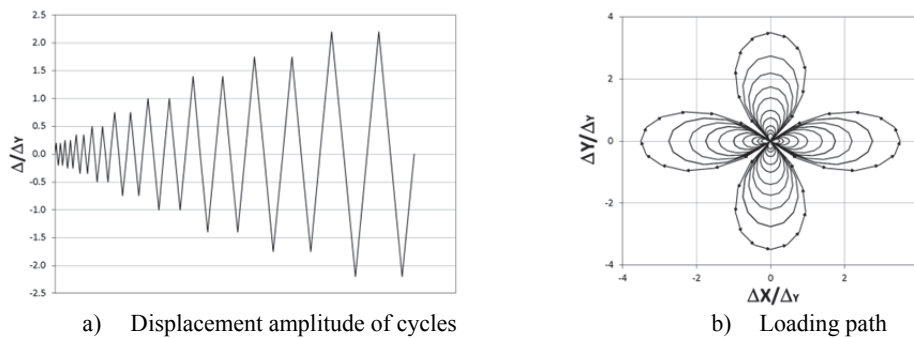


Figure 3. Loading history and loading path

The specimens were instrumented externally and internally. In both directions, X and Y, the deformations of specimens were measured by mean of displacement transducer fixed on independent

frame structure. Yield penetration, flexure and shear deformations were monitored by an arrangement of 52 displacement transducer attached to column and distributed on four sides, see Fig. 4. In plastic hinge region, strain gage were installed on longitudinal bar and hoops in each quadrant and three heights, see Fig. 4.

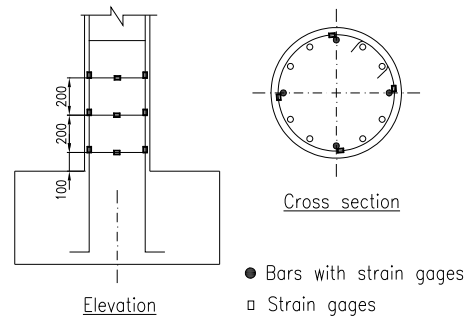


Figure 4. Strain gages on reinforcement steel bar and hoops

2.4. Experimental observations

2.1.1. Unidirectional loading test

Flexure cracking was observed at $0.75\Delta_y$ which progressed diagonally in subsequent cycles. Cover spalling close to base of column was observed at $1.4\Delta_y$ together with vertical cracking which propagated in subsequent cycles. During the cycles corresponding to $1.75\Delta_y$, diagonal cracks progressed to tension side. The test was finished when the loading completed the cycles for $2.2\Delta_y$ when a reduction of the lateral resisting load larger than 20% was observed followed by concrete spalling between 200-500mm from the base and buckling of longitudinal reinforcement, see Fig. 5a.

2.1.1. Bidirectional loading test

Horizontal flexure cracking was observed at $0.75\Delta_y$. During cycles of $1.0\Delta_y$ amplitude, both vertical and diagonal cracking took place followed by a quicker connection between them than in the unidirectional case. Diagonal cracks took place with lower angle, with respect to the element's axis, than in the unidirectional test. The test was stopped at the start of first cycle with amplitude of $1.75\Delta_y$ because of a sudden drop of lateral column strength caused by spalling of concrete between 100-400mm from the base, followed by longitudinal reinforcement buckling, see Fig. 5b.

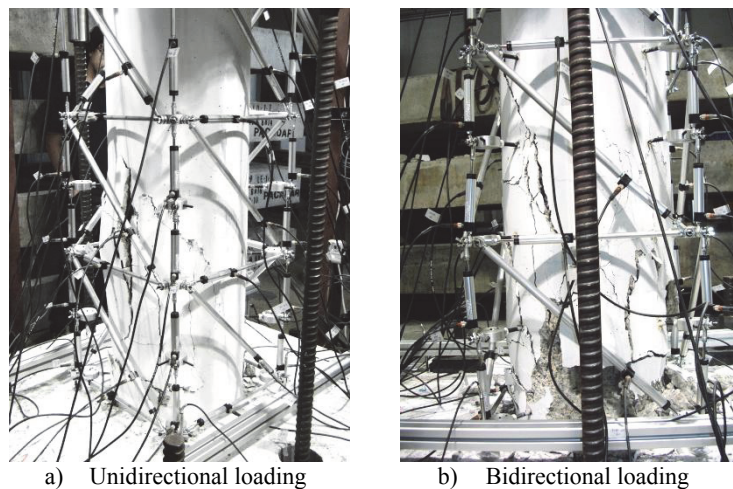


Figure 5. Final state of columns

2.4. Test results

Figures 6 and 7 show shear force-displacement histories for the unidirectional and bidirectional tests respectively. The shear forces were obtained from equilibrium equations in order to reflect P- Δ effects produced by the axial load and lateral displacements at 1500mm from the base. The envelopes curves are compared in Fig. 8 where the lower ductility of the bidirectional specimen is evidenced.

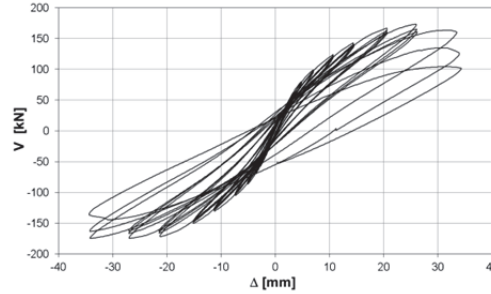


Figure 6. Shear force-displacement histories of unidirectional test

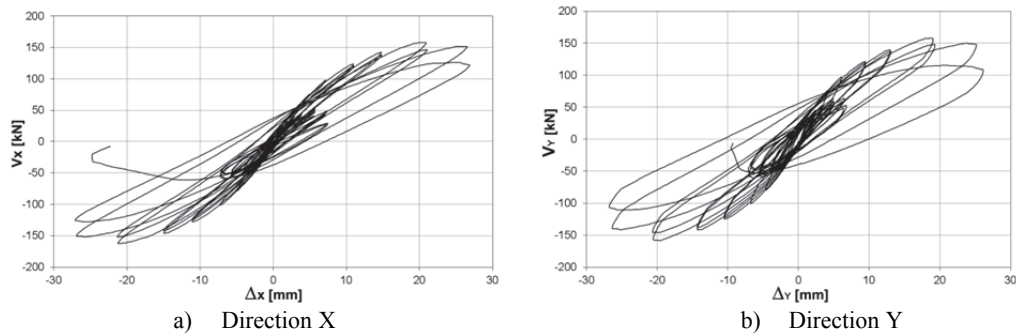


Figure 7. Shear force-displacement histories of bidirectional test

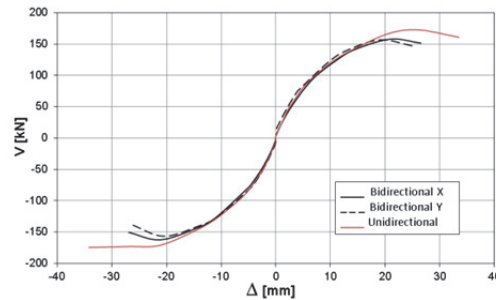


Figure 8. Unidirectional and bidirectional envelopes

3. NUMERICAL ANALYSIS

Nonlinear sectional analyses were performed with TINSA model (Total interaction nonlinear analysis). The cross section of the columns, with nominal dimensions, was discretized in areas, lines and point elements which corresponded to concrete, hoop and longitudinal bars, respectively. The mechanical properties of concrete and steel were considered after the material characterization conducted during the experimental program.

3.1. Materials modelling

Concrete was modelled with 3D constitutive equation based on the rotating-smeared crack approach and uniaxial-equivalent model on in each principal direction (Bairan and Mari, 2007). In compression state, backbone curve proposed by (Collins and Porasz, 1989) was used with linear behaviour for unloading reloading. In tension state, linearity is assumed before and after cracking. After cracking, a softening branch is considered according the model proposed of (Okamura et al., 1985). Different paths were used for unloading and reloading in tension according to partial damage model and total damage model, respectively (Chen and Han, 2007). The effects of compressive stiffness recovery due to cracks opening/closing were also included (Maekawa et al., 2003). Three-dimensional strength were quantified by mean of the 5 parameter failure surface of (Willam and Warnke, 1975) and strain at peak load by model of (Mander et al., 1988). Lateral strains evolution have been considered according to a new formulation proposed by the authors which adequately reproduces the expansion of concrete considering the type of concrete, confinement stresses, as well as the type of confinement, i.e., active or passive. Details of the formulation are not the scope of this paper; however, Fig. 9 shows examples of the model performance at different situations.

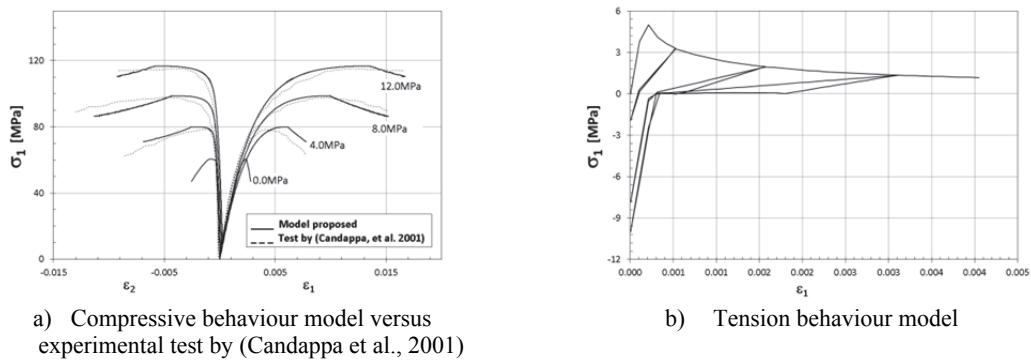


Figure 9. Concrete constitutive model

Both longitudinal and transverse reinforcements were modelled by a uniaxial constitutive law for steel considering a multi-spring model (Chen and Han, 2007, Maekawa et al., 2003). Material behaviour was considered as elastoplastic with kinematic hardening in each spring in order to reproduce Bauschinger effect through a redistribution of yield limit, Fig.10. Bar buckling, bond splitting and expansion concrete by bond splitting were not included in the model.

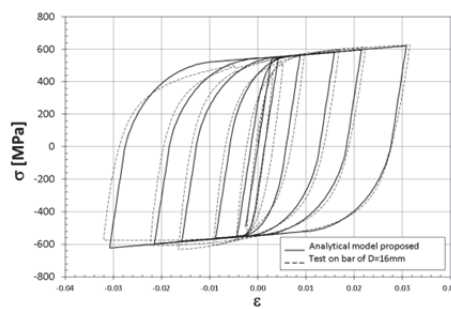


Figure 10. Steel constitutive model and comparison against experimental test

3.2. Loads and analysis results

The analyses were performed for the cross-section at 0.8D (D=depth of circular column) from the base, shear span (M/V) of 1150 mm. Axial load was constant with the same value applied in the experimental test. Both unidirectional and bidirectional incremental cycles of curvature deformations were imposed equivalent to the displacements imposed in the tests.

Figures 11 and 12 show the moment-curvature and shear-strains for both uniaxial and bi-axial loading. The two conditions types of behaviour are compared in Fig. 13, where the lower ductility and residual curvature of biaxial loading are noticed. The shear load-strain curves show a reduction of the resisting shear force and similar maximum shear deformation. However, the bidirectional specimen shows premature failure while the uniaxial one is capable of resisting additional cycles.

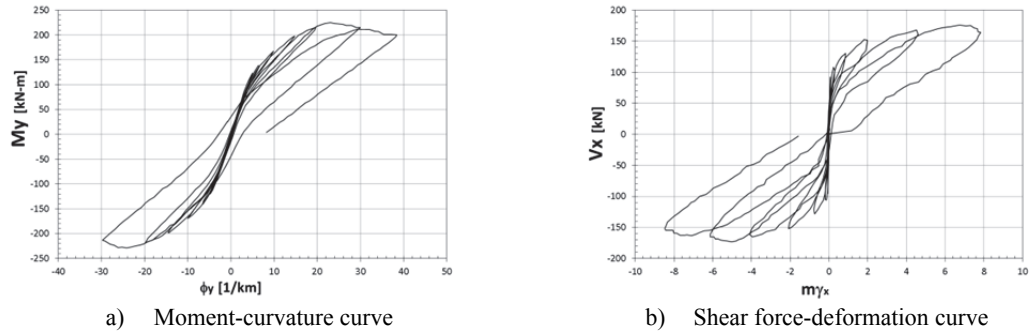


Figure 11. Results of unidirectional analysis

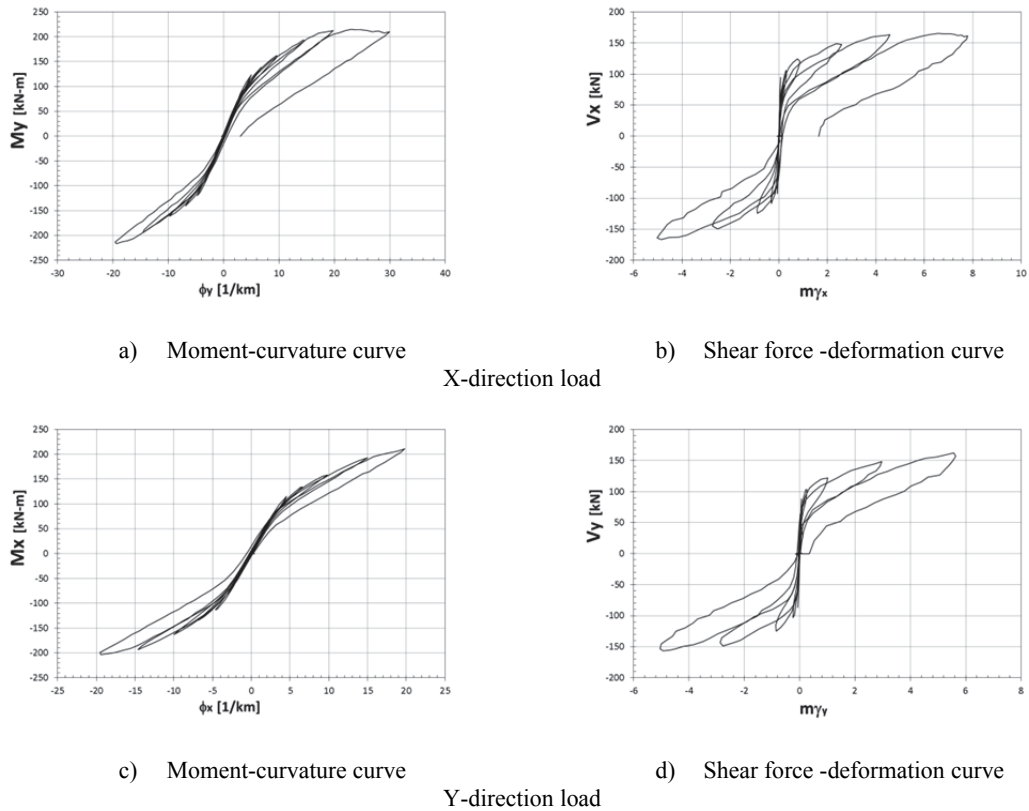
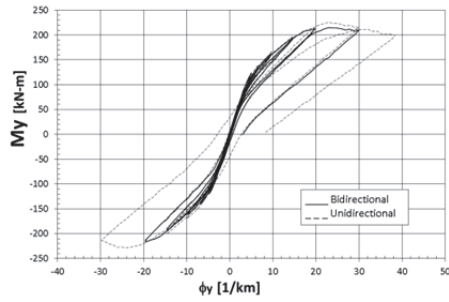
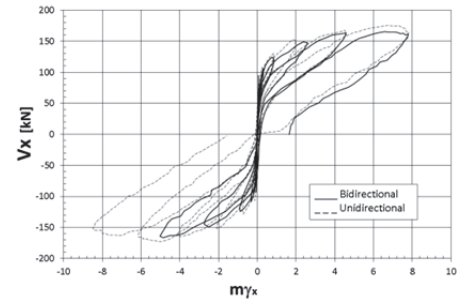


Figure 12. Results of bidirectional analysis



a) Moment-curvature curve

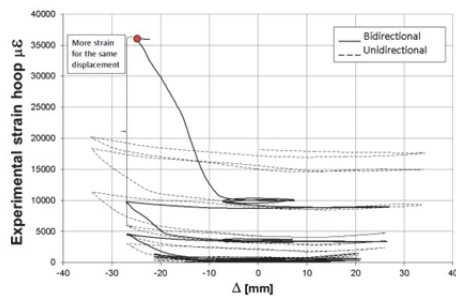


b) Shear force -deformation curve

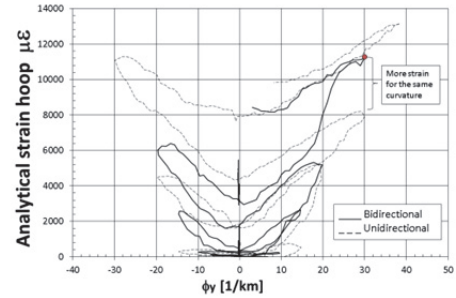
Figure 13. Results of bidirectional analysis

4. DISSCUSION

In Figure 14a the evolution of the strains in the hoop are presented for two specimens. Figure 14b show a numerical simulation of the results using the cross-section model. It should be noticed that for a given deformation demand (displacement or curvature) the hoop strain follow similar paths both for biaxial and uniaxial loading. However, in the biaxial specimen there is a sudden increase of the strain on the hoops' strains prior to failure that is not observed in the unidirectional specimen, this effect results after tangential stresses and the transversal strains of concrete in compression (Poisson effect). The phenomenon is also observed in the numerical simulation. This large magnitude in the transversal strains produces failure of concrete at lower deformation demand than in the 1D case.



a) Experimental observation against lateral deformation



b) Sectional simulation against curvature

Figure 14. Evolution of hoop strains

Currently, it is commonly accepted in most design provisions that the ultimate strain of confined concrete occurs when the transversal reinforcement reaches its ultimate strain. This concept is deduced after observations in regions where concrete is mainly loaded in compression, therefore lateral strains are mainly driven by Poisson effects. However, the interaction of other forces, e.g. skew shear forces, torsion, etc., produces additional stresses and strains. In this test, these additional strains are evidenced in the lower crack angle observed in the bidirectional demanding larger strains in the transversal reinforcement for the same load level. These strains should be considered together with those directly related to Poisson effect and might reduce the effective confinement pressure, thus reducing the ultimate strain of concrete.

5. CONCLUSIONS

The cyclic response of two concrete columns has been experimentally and numerically studied both in uniaxial and biaxial loading including axial load, bending and shear. The elements were designed in order to fail in combined shear-flexure. Concrete spalling took place prior to failure, followed by buckling of longitudinal bars. Diagonal cracks were significant in both the cases; however the effect of bidirectional loading resulted in lower crack inclination, with respect to the element's axis.

Experimental observations highlighted differences in cyclic behaviour and ductility, introduced by the bidirectional loading and the evolution of transversal reinforcement. These results are also observed in the numerical simulation conducted with the cross-section model accounting for 3D loading and tangential forces.

The analysis of the results suggests that the additional lateral strains produced by the interaction of bidirectional loads and shear reduces the effectiveness of confinement pressure of the hoops producing concrete failure at lower ultimate strain than the predicted by current provisions.

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