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STATE-OF-THE-ART REVIEW Open Access

Behaviour of reinforced concrete column under biaxial cyclic loading—state of the art

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Abstract

The cyclic behaviour of reinforced concrete columns has been object of many experimental studies in the last years, mostly focused on the unidirectional loading of columns under constant axial load conditions. In this research work, the existing test on reinforced concrete (RC) columns under biaxial load has been reviewed, underlying their main findings. In general, the experimental results show that the RC columns' response is highly dependent on the loading pattern, and the biaxial loading induces a decrease in the maximum strength and anticipates each damage state. Thus, in columns where demands are expected with large moments in both directions, specific detailing should be provided in their critical regions in order to improve the columns' performance and avoid premature failure.

Keywords: RC column, Seismic behaviour, Cyclic behaviour, Biaxial testing

Review

Introduction

Columns are key structural elements for the seismic performance of buildings. Therefore, special attention should be given to their structural response under load reversals. Moreover, earthquake effects generally require the inclusion of two horizontal component loads that are recognised to be more damaging than single direction actions. The interest in the inelastic response of axially loaded members under biaxial bending moment histories is relatively recent, and the available experimental results are limited. This is possibly due in part to the uncertainty of combining histories of bending moments in the two orthogonal directions, adding considerable complications to the problem.

The practical result is that our present-day knowledge of the inelastic behaviour of reinforced concrete (RC) columns under biaxial cyclic moments is much behind than our understanding of their behaviour under uniaxial cyclic bending with axial load. In fact, besides the fibre-based models, the existing simplified analytical models are not mature enough to be incorporated into code standards, by contrast with uniaxial simplified global models which are already accepted in international codes Rodrigues et al. (2012b). This paper aims at providing a brief review of past experimental studies in the field of biaxial behaviour of reinforced concrete RC columns and to identify the existing open problems.

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Typical causes and consequences of column failure during earthquakes

The earthquake performance of RC buildings has been well documented from the observation of past seismic events. The collapse of a RC building is caused, in the majority of cases, by the failure of the vertical members. The seismic behaviour deficiencies of RC buildings can be associated with design, detailing and construction deficiencies, as well as deterioration and structural modifications. Varum (2003) points out the ten most common causes of failure or damage in RC buildings: (1) lack of stirrups/hoops, confinement and ductility; (2) bond/anchorage/lap-splices slipping and bond splitting; (3) inadequate shear capacity; (4) inadequate flexural capacity; (5) inadequate shear strength of the joints; (6) influence of the infill masonry on the seismic behaviour of frames; (7) vertical and horizontal irregularities, abrupt change in structural and/or element properties; (8) higher modes' effects; (9) strong-beam weak-column mechanisms; and finally, (10) structural deficiencies due to architectural requirements.

Some of these categories are in fact related to design, detailing and construction deficiencies, for which the extensive damage or collapse of structures can occur through the contribution of many of these causes. Columns properly designed for earthquake loading are able to prevent brittle failure and to have a ductile behaviour. In fact adequate reinforcement and detailing is very important in providing the ductile behaviour of RC elements EASY (1997). Moreover, the flexural behaviour is conditioned by the axial force and by the amount of reinforcement in the plastic hinge region. Figure 1 shows examples of RC columns with failures associated with inadequate flexural capacity after an earthquake event, although in these examples, shear and confinement deficiencies are also evident (transversal reinforcement with large spacing at the columns extremities).

Deficient flexural behaviour can be more evident in exterior corner columns where varying levels of axial force can be expected during earthquakes, leading to high levels of axial force. In some cases, it may be difficult to differentiate flexural compression and shear compression failure, as both take place in or near the column ends and involve crushing Otani (2002).

Inadequate transversal reinforcement in terms of size, spacing and detailing is the principal cause of shear failure of RC columns. This problem can be increased in exterior corner columns in buildings with in-plan irregularities Varum (2003). Columns with shear failure commonly exhibit a diagonal fracture in the column mid-zone, as illustrated in Figure 2a,b. Another typical cause of shear failure is related with insufficient area of transversal reinforcing steel, with wide spacing and deficiently anchored to the concrete core, where ties should have enough length or proper bar bents to promote adequate splice anchorage (see Figure 2c).

Beam-column connections play also an important role in the seismic behaviour of RC buildings; poor behaviour of beam-column joints can lead to the collapse or severe damage of buildings during earthquakes. In some cases, the beam longitudinal reinforcement is not properly anchored in the beam-column joint Otani (2002; see Figure 3a) or there is no adequate transverse reinforcement in the joints (see Figure 3b,c).

The contribution of non-structural elements to the structural response is typically not considered in the design of new buildings and in the assessment of existing ones Rodrigues et al. (2010b). In the case of the infill masonry panels, two principal mechanisms have been often observed. The first is associated with cases where masonry infill walls leave a short portion of clear column, creating the so-called short column; this situation is caused by openings in the infill walls, for doors or windows, or for landing slabs of staircases. If this effect is not considered in the design, a short column is actually developed with increased stiffness which becomes subjected to shear force level that can lead to shear failure of the column, as illustrated Figure 4a. The second is related to the absence of the infill masonry panels in one storey, frequently in the ground floor storey due to its use for car parking or commercial areas, which induces an abrupt change of the storey stiffness, leading to a potential global soft-storey mechanism Vicente et al. (2010, 2012). Moreover, the asymmetric distribution of the infill masonry panels can drive torsion phenomena not predicted in the design, which can induce additional unconsidered forces, especially in the concrete columns of the outer frames Fardis (2006).

Experimental studies on the seismic behaviour of RC columns

Introduction

The experimental study of RC elements under earthquake loads is very important since it permits the observation and measurement of the particular performance of the element. Regarding the behaviour of RC elements under lateral loads, a large number of various types of studies have been carried out in past years which, apart from the specific subject of each study, have generally

Figure 1 Flexural deficient behaviour in RC columns. (**a**) In the San Salvatore Hospital, in the 2009 earthquake in L'Aquila, Italy; (**b**) in a residential building, in the 2011 earthquake in Lorca, Spain.

Figure 2 Shear deficient behaviour in RC columns in residential buildings in the 2009 L'Aquila earthquake. (**a**) Square column (Rodrigues et al. 2010a); (**b**) circular column (Ricci et al. 2011); failure is related to the transversal reinforcing steel; (**c**) deficient flexural/shear behaviour in a corner column in a residential building in the 2011 earthquake in Lorca, Spain.

covered elements with or without axial loads, as well as uniaxial and biaxial bending. In the case of zero axial force, these studies are typically associated with beams; therefore, most of them focus only on the uniaxial behaviour of these elements. Columns are studied with non-zero axial load, constant or variable, under uniaxial or biaxial bending. In the case of slender elements, the behaviour is governed by flexure, but depending on the cross-section geometry and the shear span ratio, the shear force can also represent an important subject for the study. Studies of RC elements can, therefore, also be divided into elements where the global behaviour is governed essentially by flexure or by shear, or by both mechanisms.

In view of the present study, it is important to perform a retrospective review of experimental tests performed on rectangular columns under horizontal loads, especially with biaxial behaviour. The response of RC members subjected to axial loads together with biaxial bending moment reversals is recognised as a very important research topic for building structures in earthquake-prone regions. On one hand, studies of the response of RC building columns to earthquake actions deal in general with its three-dimensional response, due to the random characteristics of the earthquake direction and to the actual building irregularities. On the other hand, the biaxial features of bending moment histories applied to a given RC column section tend to reduce its actual capacity and to accelerate the strength and stiffness deterioration process during successive load reversals. In addition, the 3D response of frame structures to actual earthquake motions generally does not induce the same type of increased deterioration in beams because they behave essentially in only one direction (vertical), i.e., the potential development plastic hinges in beams are not aggravated by that fact. This means that both the biaxial loading effects in columns and the 3D features of the general structure response positively contribute to inelasticity and damage concentration in the columns rather than in the beams, which is essentially the opposite of what present-day design code requirements created to avoid collapse of RC frame structures under lateral load reversals (plastic hinges in the beams rather than in the columns) CEB (1996).

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 justify this gap.

As a consequence, current knowledge concerning the inelastic response of RC columns under biaxial cyclic moments is very much less than that of the uniaxial cyclic bending behaviour with compressive axial load (CEB 1996; Marante and Flórez-López 2002; Paulay and Priestley 1992).

The available test results for biaxial bending under constant axial load (CAL) are not so extensive when compared to those on uniaxial bending, although they have been delivered over a period of almost 30 years. On the basis of an extensive analysis of international experimental databases and from a literature review of studies covering tests on rectangular RC columns subjected to cyclic loading, a statistical analysis was performed based on the data collected for 453 column tests (see Figure 5). From the data analysis, it was verified that (1) only 27 of these columns (6%) were tested with variable axial load (VAL) and (2) only 56 (12%) were tested in biaxial loading conditions. These statistical figures emphasise the insufficient experimental results for the comprehensive characterization of the biaxial cyclic behaviour of RC columns.

Figure 3 Inadequate joint behaviour in residential buildings. (**a**) Inappropriate anchorage of beam longitudinal reinforcement; (**b**) deficient detailing of a beam-column joint in a residential building (2009 earthquake in L'Aquila, Italy); (**c**) RC building collapse in the 2011 earthquake in Lorca, Spain.

Due to testing difficulties and because there are still open questions regarding the cyclic behaviour both in biaxial bending with constant axial force and in uniaxial bending with simultaneously varying axial load, very few experimental studies have, as yet, tackled the more general problem of biaxial bending with varying axial force (CEB 1996; Coelho 1992), as can be seen in Figure 5. From the literature review, only the tests performed by Low and Moehle (1987; two columns) and by Chang (2010a; two columns) refer to rectangular cross-sections with different dimensions and amount of longitudinal reinforcement in the two principal directions, leading to different characteristics in terms of stiffness and strength.

In recent years, a very small number of tests have also been performed in beam-column sub-assemblages where the columns were subjected to biaxial loading (Suzuki et al. 1984; Monti and Nuti 1992; Li et al. 2008; Akguzel and Pampanin 2010).

The next sections present a summary of the previous works involving experimental studies performed with

Figure 4 Column failure due to the presence of non-structural elements. Short column effect caused by window openings in residential building. (**a**) 2009 earthquake in L'Aquila, Italy and (**b**) 2011 earthquake in Lorca, Spain.

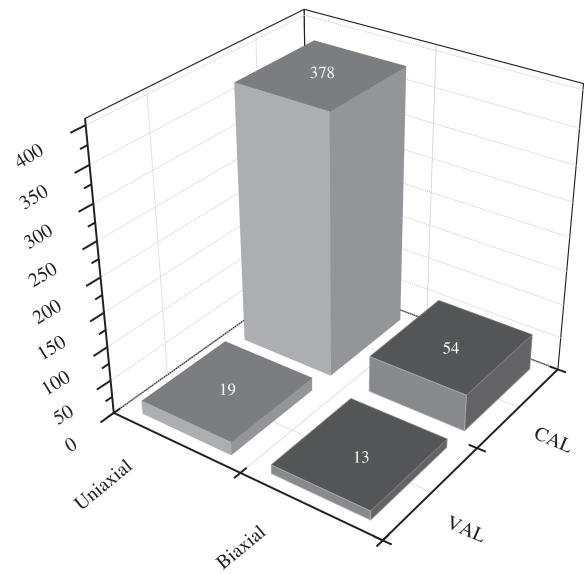

Figure 5 Experimental tests on RC rectangular columns according to function of the loading conditions. Uniaxial or biaxial, and CAL or VAL. Statistics are based on a review of the literature and test databases (Rodrigues et al. 2013).

biaxial bending. The analyses focus on the main findings obtained from tests on columns subjected to biaxial lateral loading (with constant and varying axial force) and under different test conditions; biaxial tests performed on global bare frame structures are also analysed. All relevant experimental works performed before 1996 are very well summarised in CEB (1996), and so the present section will focus on the main findings of the experimental studies and work performed after 1996.

Specimen geometries

Two types of column specimens were used in the cyclic biaxial tests described in the literature. The prototype test considering the column specimens fixed against rotation on both ends (Figure 6a) was used only in one study Takiguchi et al. (1980), while all the other studies report the use of the cantilever type (Figure 6b). Other test configurations can be used, namely, the double-ended cantilever with flexible-base and the hammerhead configurations Berry et al. (2004).

Double curvature specimens with rigid zones on top and bottom can be assumed as the best models to simulate a typical building column. However, due to many factors, most of the authors use the cantilever-type specimen. There are no known studies on the differences between these specimen configuration types.

The cantilever-type model assumes that the inflection point of a column is located at mid-height of the column and takes no damage. This can be considered to be true in columns governed by flexural behaviour, where the damage is concentrated in the so-called plastic hinge zones located at the column ends.

Regarding the column height and cross-section dimensions, many different sections have been tested as described in Table 1, where the main geometric characteristics of the columns are summarised. As previously mentioned, in most of the cases, the columns have a square cross-section, although there is no clear justification for a square section; mainly, it can be used due to the difficulties in developing the test set-up, the need to perform two uniaxial tests (one in each principal direction) and the new variable to analyse the differences in the stiffness and strength in each direction.

Displacement patterns

The behaviour of RC columns under cyclic behaviour is especially influenced by the geometric and mechanical characteristics of the column cross-sections and the *f* level of axial load. However, the displacement pattern can also influence the global behaviour, and in terms of biaxial bending forces, the displacement history and the way the biaxial forces are combined in two orthogonal

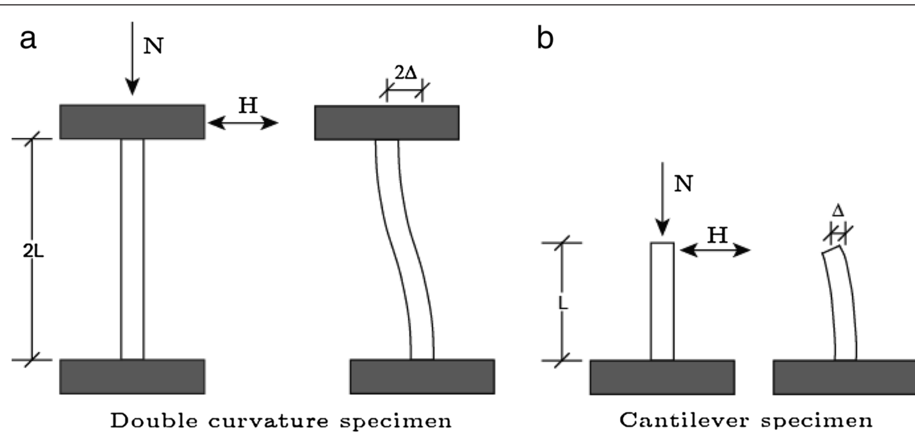

Figure 6 Column test configurations.

Table 1 Geometric characteristics of rectangular RC columns tested under biaxial loading (adapted and updated from CEB (1996))

Reference	Number of specimens	Length (mm)	Cross-section dimensions (b × h; mm)	Axial load
Takizawa and Aoyama (1976)	4	600	200 × 200	C
Otani et al. (1980)	4	1,372	305 × 305	C
Takiguchi et al. (1980)	5	250	150 × 150	C
Park et al. (1984)	1	1,600	400 × 400	C
Low and Moehle (1987)	2	546	127 × 165	C
	2	546	127 × 165	V
Li et al. (1988)	1	600	200 × 200	C
	4	600	200 × 200	V
Saatcioglou and Ozcebe (1989)	2	1,000	350 × 350	C
	1	1,000	350 × 350	V
Zahn et al. (1989)	2	1,600	400 × 400	C
Bousias et al. (1992)	9	1,500	250 × 250	C
	1	1,500	250 × 250	V
Kim and Lee (2000)	2	1,200	100 × 100	C
	4	1,200	200 × 100	C
Qiu et al. (2002)	6	900	200 × 200	C
Tsuno and Park (2004)	2	2,750	550 × 550	C
Bechtoula et al. (2005)	2	625	250 × 250	C
	1	1,200	560 × 560	C
	2	1,200	560 × 560	V
	2	625	242 × 242	V
	1	1,200	600 × 600	V
Kawashima et al. (2006)	6	1,750	400 × 400	C
Chang (2010b)	1	355	750 × 600	C
Rodrigues et al. (2013)	2	1,700	200 × 400	C
	5	1,700	300 × 300	C
	5	1,700	300 × 400	C
	5	1,700	300 × 500	C

C, constant axial load; V, variable axial load.

directions is a very important subject. This section will, therefore, review the displacement patterns used in published studies and will briefly analyse their influence on the column behaviour.

From the literature review, it was possible to describe several types of laws considered in displacement control biaxial tests. Bixial displacement patterns can be applied only along the x and y axes, illustrated in Figure 7 as L1 (unidirectional) and L2 (cruciform), creating a cruciform displacement pattern. Other configurations of displacement patterns have been used by different authors, namely: the diagonal cruciform (L3), the rhombus or diamond (L4), expanding square (L5), the square in each quadrant in the form of an eight (L6) and the circular (L7) or elliptical (L8). Some variations of the presented displacement patterns can be found in the literature.

The use of these (or other) displacement patterns is based on the main objectives of the performed biaxial tests: on one hand, the comparison between uniaxial and biaxial load paths, and on the other hand, the evaluation of the effect of the different biaxial displacement patterns in the column response. For example, in the study of Saatcioglou and Ozcebe (1989), similar hysteretic behaviour was found between uniaxial and diagonal load paths; however, for the elliptically shaped displacement pattern, an earlier progressive degradation of strength and stiffness was observed. In the studies of Li et al. (1988) and of Kawashima et al. (2006), based on the displacement path with the eight shape, a characteristic drop of the restoring force at zero displacement was observed. The biaxial loading history had a clear effect on the column response and can induce particular

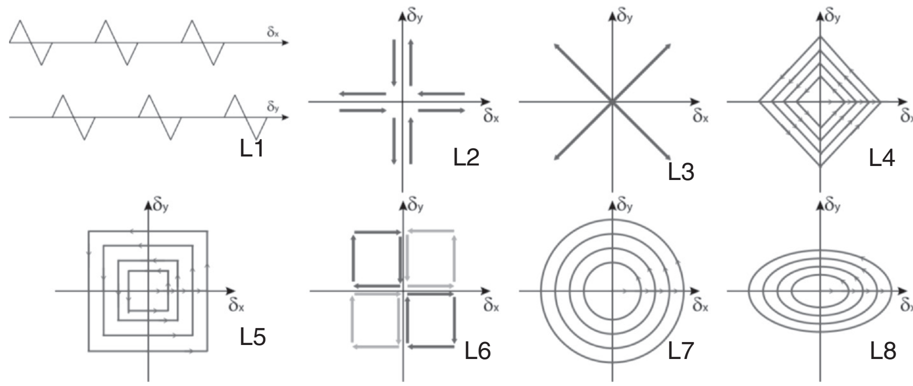

Figure 7 Load paths used by different authors.

effects as a result of the coupling between the two orthogonal directions.

Additionally, the experimental results are intended to be used in the development and calibration of mathematical models that represent the column behaviour, including the biaxial interaction. From the observation of the results, it is clear that the column behaviour is path-dependent and particularly the failure mode Taylor et al. (1996). This fact is even more relevant in the case of the biaxial loading, where the coupling effect between the axial and the two transversal directions is important. Similar tests tested with different loading paths present a very distinct damage evolution Rodrigues et al. (2013). Additional research on this topic should be conducted in order to correlate the load path with the failure mode. The presented displacement paths cannot be considered as representative of an earthquake displacement path; however, the intention of calibrating numerical models imposes the definition of simplified displacement paths with smooth increase of the peak displacements and with the repetition of each displacement level in order to capture the strength and stiffness degradation along the tests.

Behaviour of RC columns under biaxial bending with constant axial load

As stated before, the available test results for biaxial bending under constant axial load are not so extensive when compared to those for uniaxial bending, although they have been delivered over a period of almost 30 years. Contributions are summarised in Table 1. In general, most research findings agree that, additionally to the expected significant influence of axial loads on the hysteretic response of columns, the biaxial transversal load cycles are responsible for increasing the strength and stiffness degradation when compared to the uniaxial response. In addition, the failure mechanism of RC columns is found to be very dependent on the loading path/history and strongly affects both the ductile and energy dissipation capacity of the columns. On the other hand, there is some experimental evidence that plastic hinge zone lengths tend to be stable at around theoretical values and are not strongly affected by biaxial loading.

The CEB Report CEB (1996) includes the major findings of the experimental studies about biaxial flexure with constant axial load of RC columns until 1992. The major findings are summarised next. Observing the force path measured with the square displacement path, several authors (Takizawa and Aoyama 1976; Otani et al. 1980) have reported the expected elastoplastic behaviour of the RC columns, for which after yielding, the square force paths show a tendency to cluster into a single square.

Several authors (Takiguchi et al. 1980; Takizawa and Aoyama 1976; Otani et al. 1980; Bousias et al. 1992) reported a rotation of the measured force paths by about 10° to 20° with respect to the applied displacement path. This rotation occurs when the displacement in one direction is changed, while the displacement in the opposite direction is maintained at a practically constant level; the force required in this lateral direction consequently drops. The effect of this coupling on the hysteretic curves induces an almost vertical unloading branch, which increases the level of dissipated energy in each loop CEB (1996).

Saatcioglou and Ozcebe (1989) reported on the use of elliptical displacement paths with increasing ellipse amplitude, for which the force-displacement curves show an even more rounded shape characteristic of the phase lag between the resultant force and the imposed displacement vector. This fact is associated with the effect already reported for the square load paths. The increase in roundness of the force-displacement curves means that they are much wider when compared with the uniaxial response, thus increasing the energy dissipation due to the coupling between the two directions. For the circular load path, Bousias et al. (1992) have found similar results, concluding that the phase lag is almost constant at each deflection level, but increases with the deflection amplitude and at the test end, when failure is appearing.

Low and Moehle (1987) performed the first biaxial tests on columns with rectangular cross-sections. In the third test, besides the abrupt drop of the force at the beginning of the unloading branch, as also reported by other authors, a similar force drop under constant zero displacement was observed. This phenomenon is associated with the type of displacement path similar to L6 in Figure 7. This fact was also reported by Li et al. (1998).

Bousias et al. (1992) focused on the effect of load path. The examined load paths did not duplicate those of earlier researchers, but covered different transverse displacement-controlled paths. The study emphasised the significant coupling between the three loading directions. The strong coupling between the two transverse directions produced an apparent reduction in strength and stiffness in each of the two transverse directions when compared with the loading separately in each direction, but also increased the hysteretic energy dissipation. Despite the adverse effect on the structural response, some effects can be considered beneficial to the structural response, such as the increase of hysteretic energy dissipation.

Kawashima et al. (2006) studied the effect of bilateral excitation on the seismic performance of RC bridge columns with 1.35 m tall and 400 × 400 mm cross-section, using cyclic and hybrid loading tests. In the cyclic loading test, the columns were loaded unilaterally or bilaterally using diagonal, square, circular and elliptic displacement paths. For the hybrid loading cases, the ground accelerations of the Kobe and Northridge earthquakes were used. In the cyclic tests, the loading and unloading hysteresis curves are round near the peak displacements under the bilateral loading, which results from the interaction of restoring forces in two directions. Only the hysteresis at the first excursions, in each loading step, has a feature similar to that under the unilateral loading. This is because, under the circular-path loading, the column was first loaded only in the N direction in the first excursions at each loading step. Comparing to the strength of the column under bilateral hybrid loading, the strength of the column under bilateral cyclic loading is 14% to 23% and 15% to 35% smaller in NS and EW directions, respectively. Furthermore, the deterioration of the lateral restoring force is significant after 3% of drift, while deterioration did not occur until 6.3% peak drift under the bilateral hybrid loading. Flexural strength and ductility capacity of RC bridge columns with a square section significantly deteriorate under the bilateral excitation in comparison with unilateral excitation in both cyclic and hybrid loading tests. Failure of the columns under the cyclic loading test, for which the loading displacement was increased stepwise with three loading excursions at each loading step, is more extensive than the failure developed in the hybrid loading test. In fact, loading protocol is important, and it has to be carefully determined in the cyclic loading tests.

Qiu et al. (2002) tested seven specimens of RC column subjected to biaxial loading with different load paths. The interactions of biaxial deformation, under biaxial loads, were found to weaken the biaxial strength and the hysteretic energy dissipation capacity. According to the test result, although the accumulative hysteresis dissipation energy relates closely to the loading position and path length, the energy parameter of a specimen under biaxial load is apparently larger than that under unidirectional loading. The specimen damage under biaxial loading is greater than that under uniaxial loading, which agrees with the reduction of the plastic deformation capacity.

Tsuno and Park (2004) also performed cyclic bidirectional tests on two RC columns 2.75 m tall and with 550 × 550 mm cross-section. In this study, it was possible to conclude that the plastic hinge zone length tends towards theoretical values after some cyclic loadings and is not affected by bi-directional loading. The ultimate displacement of a column in a bi-directional cyclic loading is smaller than that of the same column subjected to the standard unidirectional loading pattern. Tsuno and Park, in agreement with Ohno and Nishioka (1984), state that the total dissipated energy until the ultimate state is achieved is approximately the same for biaxial and uniaxial conditions, meaning, the biaxial loading does not affect the total energy dissipation capacity of a column that reaches failure.

Chang (2010b) pseudo-dynamically tested two RC bridge columns at 2/5 reduced scale, and one identical column was also tested under biaxial cyclic horizontal load with constant axial load. The results showed that the distinct characteristics of biaxial hysteretic loops are rounded at corners and negative stiffness values. In addition, scatter plots of pseudo-dynamic results reveal that there is no bias in the orientations of the resultant flexural moments. Therefore, it seems appropriate to make a seismic design based on biaxial bending without bias in any specific direction. The complicated biaxial hysteretic loops confirm the difficulty of developing suitable load-displacement models for non-linear dynamic analysis. These pseudo-dynamic outputs, such as displacement and hysteretic responses, can be treated as references for analytical models proposed to simulate the load-displacement relationship. After comparing biaxial with uniaxial hysteretic loops for both cyclic loading and pseudo-dynamic tests, it is important to note that biaxial hysteretic loops show greater stiffness degradation and pinching during unloading. This reveals that damage caused in one direction weakens the seismic resistance in the other direction.

Bechtoula et al. (2005) tested eight large-scale and eight small-scale cantilever RC columns under various vertical and horizontal loading patterns. Square and circular, as well as unidirectional, horizontal displacement patterns were considered. The axial load was considered both as constant (moderate load and high load) and variable during the test. From the tests observation, it was clear that the bi-directional loading had a significant influence on the envelope curves as well as on the damage progress. The observed damage to large-scale columns was much more severe than that observed for the small-scale columns.

Finally, Rodrigues et al. (2013) and Rodrigues (2012) 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 (1) the initial column stiffness in both directions is not significantly affected by the biaxial load path, (2) 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% to 30% reduction of the maximum strength of the columns in their weak direction, *Y*, while reductions from 8% to 15% for the stronger direction, *X*; (3) the ultimate ductility is significantly reduced in columns subjected to biaxial load paths; (4) 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; (5) 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 Rodrigues et al. (2012a). (6) 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.

Behaviour of RC columns under biaxial bending with varying axial load

As widely known, from the axial load-bending interaction diagrams, it is possible to observe that both yielding and ultimate moments increase with the level of axial load until the balance point is achieved. Variation in the axial load during an earthquake can change the strength, stiffness and ultimate displacement capacity, as well as all the hysteretic properties of a RC section. Such variations can occur due to the vertical component of the seismic load, or in the external columns of the bottom storeys of RC frames, due to the overturning moments which increase the axial load on one side and decrease it on the opposite side. In fact, the variation in the axial force during the response cycle may significantly affect the inelastic response of the columns CEB (1996).

Due to testing difficulties, the number of RC column tested under bidirectional displacement with varying axial load is very reduced, and it is always associated with tests with constant axial load, as summarised in Table 1; thus, the few available results do not allow for solid conclusions to be drawn about coupling behaviour between biaxial bending and the varying axial force.

The early results of both Li et al. (1988) and Low and Moehle (1987) evidence similar effects of axial load variations on uniaxial and biaxial flexure. In particular, it was found that the axial load variation simultaneously, with the transverse forces and deformations, leads to stiffness and strength increase, while the strength degradation is larger for higher axial load, and also decreases when the axial load decreases.

The results obtained by Bousias et al. (1992) present a strong coupling between the axial and transverse directions. For the relatively low levels of compressive axial loads considered therein, deflections induce an axial extension which has a magnitude roughly proportional to their resultant vector. For lower compressive loads, the cycling of transverse forces or deflections causes a gradual shortening in the axial direction under the axial load alone, a ratcheting extension that rapidly turns into shortening when failure is imminent. As a result of axial/lateral forces coupling, the cycling of the axial force below the balance load causes a ratcheting increase in the deflection under constant transverse force.

Bechtoula et al. (2005) found that the axial load intensity had little effect on the envelope curve of the second cycle of the load-displacement plot for specimens under unidirectional horizontal load with constant or variable axial load. Equivalent viscous damping increased with the increase in axial load, and columns under variable axial load showed equivalent viscous damping values similar to those of columns under constant/moderate and constant/high axial loads.

Biaxial tests on global bare frame structures

The experimental study of the seismic response of RC frame structures is very important to understand the behaviour of RC buildings, since this inelastic response is dependent on each element and on the distribution and participation of each element in the global response. The available tests in singular elements or structural sub-assemblages give an important source of information for understanding the global structural behaviour; however, the available tests on concrete frame structures are very limited. Most of the tests performed on frame structures only focused on planar structures, or three-dimensional structures loaded along one single direction. However, it has been earlier recognised that three-dimensional behaviour may play an important role in the global behaviour of frame systems, in particular when the torsional response assumes significant importance due to in-plan irregular distribution of the strength and stiffness or mass. Therefore, only 3D model testing allows capturing the failures associated with the non-linear bidirectional flexure response CEB (1996).

Oliva and Clough (1987) tested a 7/10 scale model of a frame structure with two storeys and four rectangular columns by mounting it on a shaking table with its longitudinal principal axis at a 25°-angle relative to the axis of shaking table horizontal motion. The specimen was subjected to the N69W component of the 1952 Taft earthquake record, with increasing intensity motions.

From the frame behaviour observation, it was possible to find that the existence of simultaneous biaxial moments in the columns resulted in yielding, even though the moments along either of the column's principal axes were lower than uniaxial yield moments. The non-symmetrical structural stiffness distribution, relative to the loading direction, led to a global torsion in the frame response. The effect of the global torsional response on the frame corner columns and the varying axial load caused by the overturning moment were different from column to column. Thus, yielding of each column is reached for different steps, which influences the evolution of the overall lateral stiffness of the frame system, increasing the biaxial flexure demands in the corner columns.

From the analysis of column behaviour, it was observed that the response along the strong column axis, parallel to the frame longitudinal axis, exhibited readily identifiable yielding, and the column flexural response in the weak (or transverse) direction was significantly different from the cyclic flexural response normally seen in RC members without an obvious yield point even though the deformations were greater than those along the columns' strong axis. The yielding and damage induced by the strong axis motion resulted in a considerable decrease in the weak axis stiffness, with large deformations and low energy dissipation.

The SPEAR structure is a three-storey building representative of old constructions in southern European countries, without specific provisions for earthquake resistance Mola and Negro (2005). The structure is regular in elevation; the plan configuration is non-symmetric in two directions, with two-bay frames spanning from 3 to 6 m. There is a balcony, shifting the centre of the stiffness away from the centre of the mass. Eight columns have a square 250 × 250 mm cross-section, while one has a cross-section of 250 × 750 mm, which makes it much stiffer and stronger than the others along the Y direction. The test programme consisted of three different sets of pseudo-dynamic tests on the specimen in the original and in two different retrofitted configurations. Each set consisted of three tests at different PGA levels: 0.02, 0.15 and 0.20 g Molina et al. (2004). The Y direction, parallel to the strong column direction, was globally stronger. Thus, as expected, the levels of interstorey shear reached in this direction were larger, in agreement with the global value of the absorbed energy; on the contrary, much larger displacements were reached in the X direction on the second floor. These findings were confirmed by the time histories of the absorbed energy at each floor. The most affected level was the second level. The interstorey drifts at each storey were different for each of the nine columns of the specimen, due to torsional effects. The tests highlighted the strong effects of torsional irregularity on the column drifts, even for a limited level of plan eccentricity and relatively low levels of excitation Mola and Negro (2005).

Finally, it is worth referring that most of the testing campaigns available in the literature were developed, aiming to study the buildings response to three-dimensional loadings, so they were not particularly focused in the study of the biaxial behaviour of columns. So, the conclusions from those research projects regarding the analysis of the column response at local level are limited.

Conclusions

The response of RC columns is recognised as a very important topic that should be taken into consideration for building structures in earthquake-prone regions. The response of RC building columns to earthquake actions deals in general with three-dimensional responses, due to the random characteristics of the earthquake direction and to the building irregularities.

Experimental research 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 with the complexity of the experimental set-up, certainly justify this lacuna.

From the analysis of the available experimental work, it was possible to verify that, besides the expected significant influence of axial loads on the hysteretic response of columns, the bidirectional transversal load cycles are responsible for an increasing in the stiffness and strength degradation, when compared to the uniaxial response. In addition, the failure mechanism of RC columns is found to be very dependent on the loading path, which strongly affects both the ductility and energy dissipation capacity of the columns. On the other hand, there is some experimental evidence that plastic hinge lengths tend to be stable at around theoretical values and are not strongly affected by bidirectional loading. Based on the revision of the work done in the last years, many questions are still open in the field of the biaxial behaviour of RC columns, especially those related with the response dependency of the load paths. Thus, additional experimental tests are needed to be performed by imposing displacement paths representative of the displacements actually imposed by earthquakes.

Competing interest

The authors declare that they have no competing interests.

Authors' contributions

HR participated in the review of the experimental tests on RC column and structures. HV participated in the review behaviour of RC columns, in particular, the damages during recent earthquakes. AA participated in the review and discussions of the experimental studies presented. AC participated in the global revision and discussion of the review performed. All authors read and approved the final manuscript.

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