16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3854 (Abstract ID)

Registration Code: S-O1474037940

EXPERIMENTAL TESTING OF COLUMNS SUBJECTED TO BIAXIAL HORIZONTAL LOADING AND CONSTANT/VARIABLE AXIAL LOAD – AN INNOVATIVE SETUP

A. Arêde[(1)], P. Rocha[(2)], P. Delgado[(3)], H. Rodrigues[(4)], A. Furtado[(5)], N. Vila-Pouca[(6)], A.A. Costa[(7)], A. Costa[(8)], R. Delgado[(9)], H. Varum[(10)], N. Pinto[(11)]

[(1)] *Associated Professor, CONSTRUCT – Faculty of Engineering of University of Porto, Portugal, aarede@fe.up.pt*
[(2)] *Senior Lecturer, Superior School of Technology and Management of Polytechnic Institute of Viana do Castelo, procha@estg.ipvc.pt*
[(3)] *Senior Lecturer, Superior School of Technology and Management of Polytechnic Institute of Viana do Castelo, pdelgado@estg.ipvc.pt*
[(4)] *Senior Lecturer, RISCO, School of Technology and Management, Polytechnic Institute of Leiria, Portugal, hugo.f.rodrigues@ipleiria.pt*
[(5)] *Researcher, CONSTRUCT – Faculty of Engineering of University of Porto, Portugal, afurtado@fe.up.pt*
[(6)] *Auxiliar Professor, CONSTRUCT – Faculty of Engineering of University of Porto, Portugal, nvp@fe.up.pt*
[(7)] *Senior Lecturer, CONSTRUCT, Polytechnic Institute of Porto, Portugal, alc@isep.ipp.pt*
[(8)] *Full Professor, RISCO – University of Aveiro, Portugal, agc@ua.pt*
[(9)] *Full Professor, CONSTRUCT – Faculty of Engineering of University of Porto, Portugal, rdelgado@fe.up.pt*
[(10)] *Full Professor, CONSTRUCT – Faculty of Engineering of University of Porto, Portugal, hvarum@fe.up.pt*
[(11)] *Researcher, CONSTRUCT – Faculty of Engineering of University of Porto, Portugal, npinto@fe.up.pt*

Abstract

Over the last years, there has been increasing interest on experimental testing to support better understanding of structural behaviour under earthquake loading, with emphasis on numerical model calibration, development of efficient techniques for seismic protection and/or resilience improvement of structures. A significant number of experimental studies have been carried out during the last years concerning to the characterization of the columns (reinforced concrete or steel) behaviour when subjected to cyclic loadings. However, the experimental tests of columns under cyclic uniaxial and biaxial bending is one of the hardest and complex to reproduce in laboratory, since this tests should contemplate current actions simultaneous simultaneously.

There is many column test models proposed by different authors, differing in aspects such as the fixation of the specimens, the application of the horizontal or of the axial load and in the measurement of the displacements and the extensions. Nevertheless, the application of the axial load is probably the most critical and distinguish issue in this type of experimental tests, not only by the difficulty of the test implementation, but mostly because this particular issue influence significantly the columns response during the tests, namely in terms of strength, stiffness, ductility and energy dissipation capacity. For this, along present manuscript a brief state-of-art of columns experimental test setups will be described, and will be compared with the test setup developed and implemented in the Laboratory of Earthquake and Structural Engineering (LESE) of the Faculty of Engineering of the University of Porto (Portugal). Aspects related to the load control and application, fixation of the specimens, instrumentation of the test control system will be discussed along the manuscript.

Keywords: Experimental testing, Biaxial cyclic loading, constant and variable axial load, test setup, load control

1. Introduction

The study of the reinforced concrete (RC) elements subjected to axial loadings combined with cyclic biaxial flexure is recognized as a very important topic regarding the RC structures behaviour in seismic prone regions. The importance of this topic is justified due to the fact that the seismic action that reach the structures did not occur only in one direction, and otherwise the structural response of the existing buildings is tridimensional due to the seismic action direction and to the structural irregularities. Thus, the effect of the biaxial loading on a RC element accelerates their stiffness and strength degradation during a cyclic action. 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 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 and, therefore, most of them focus only on the uniaxial behaviour of these elements. Columns are studied with non-zero axial force under uniaxial or biaxial bending and also tested with constant or variable axial load. In the case of slender elements, the behaviour is governed by flexure but, depending on the cross-section geometry and the already mentioned 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 the view of the present study, it is important to perform a retrospective review of experimental [1-3].
Different models of experimental tests of RC columns were proposed by different authors, varying namely on the fixation of the specimens, application of the horizontal and the axial forces and on the measurement of the displacements and stresses. Nonetheless, the strategy to apply the axial load is, probably, the most critical deciding factor, not only because of the difficulty of the implementation in the experimental tests as easily be shown below, but mainly because it is a factor that has the greatest influence in the columns behaviour, especially in their: strength, stiffness, ductility and energy dissipation capacity. Despite the amount of experimental results clearly be insufficient during the last 30 years, many researchers have made important contributions to the advancement of knowledge in this field, as can be seen in the state of the art collected by Takizawa e Aoyama, 1976 [4]; Otani et al., 1980 [5]; [6] Bousias et al., 1992 [7]; Kim e Lee (2000) [8]; Qiu et al., 2002 [9], Tsuno e Park, 2004 [10], Nishida e Unjoh, 2004 [11], Umemura e Ichinose, 2004 [12], Kawashima et al., 2006 [13], Li et al., 2008 [14], Acun, 2010 [15] e Rodrigues, 2010 [16].

2. Experimental tests configurations

2.1 Introduction

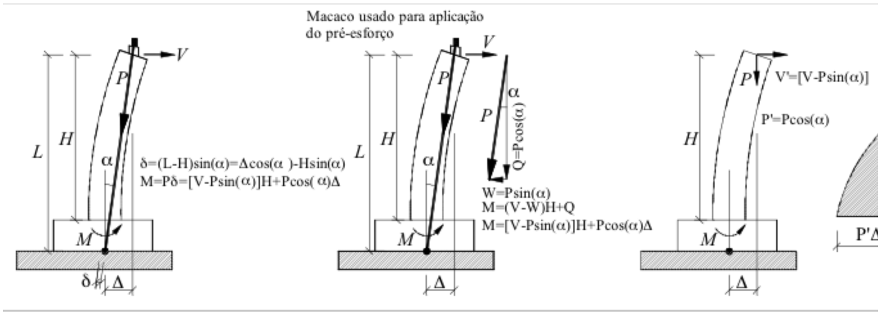
From the set of studies analyzed it appears that the experimental work described in the literature, which aim to simulate the cyclical behavior of RC columns, can be divided into two major groups: i) with constant axial load; and ii) variable axial load.

2.2 Application of the axial load through pre-stresses rods

In this type of test setup, the axial load is applied by means of external tie rods labeled base (strong floor, foundation block or other element that ensures proper fixation) and the upper end of the specimen where the prestressing is applied on the specimen. In this context, the lashing of the rods is of particular importance, since, typically, limits its use to study of RC columns attached to the strong floor or, more generally, the cantilevered columns.

As can be seen in Fig. 1, in this scheme the verticality and direction of load applied through the prestressed tie rods varies depending on the horizontal displacement of the top of the columns-induced cyclic horizontal actions. Because of this effect, the force, which is to be vertical, will tilt a certain angle and its application point will deviate from the base alignment. The test configurations that use the application of the axial load through prestressed rods not correctly simulate the P-Δ effect, as occurs in structures subjected to seismic action. However, this does not mean that you cannot correct the results obtained in order to eliminate the effect produced by the tilt of the load.

Regarding the application of axial load through the use of prestressed tie rods, these may be articulated at one end (the labeled base) or both (bi-articulated rods) to thereby prevent bending stresses to install the risers. The axial load is applied, generally by means of hydraulic jacks which allow to fix the constant traction effort that is to be installed in the rods. However, this effort on the risers can also be applied using a hydraulic actuator which allows varying the axial force to install the samples during the course of the cyclic tests.



a) b) c)

Fig. 1 – Application of the axial load through pre-stressed tie rods [1].

2.3 Application of the axial load through hydraulic actuators

This axial load application approach is performed by a hydraulic actuator fixed to the head of the column, where the action is applied, and reacts at the other end against a vertical reaction structure. In this group of application of axial load type, the large differences between the configurations adopted by different authors consulted are due mainly to the way it is fixing the actuator performed either at the end of the action as in the reaction and the structure chosen for reaction vertical (Fig 2).

Regarding the fixation of the actuator (through labeled systems, downlights, or roller, applied indifferently to their ends), it should not be neglected the influence of the axial action of the slope may have in reading the results of test. Another advantage of this axial load of the configuration application is to allow the possibility of controlling the actuator so that during the test the load level can vary depending on a charging law.

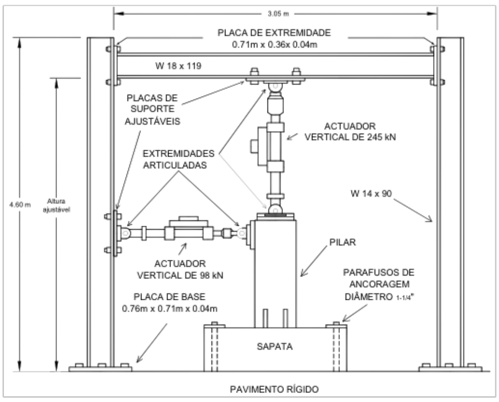


Fig. 2 – Application of the axial load through hydraulic actuator [2].

2.4 Application of the axial load through weights

The application of the axial load through weights, consists of placing on the head of the columns of a volume of material with a mass that produces a weight equal to the desired load. The two ways to materialize this procedure are: i) using steel plates that will overlaying up to the desired level of effort; ii) providing for the specimens themselves are built with a volume of the same material dimensioned so that their weight constitutes the axial load.

In the case of steel plates, must be met stability during the test and as far as possible they should be positioned so as to reduce the deviation between the center of gravity and vertical sample axis in its section where it is applied the horizontal actuator. Only in this way will be attenuated parasite variations efforts and may actually be simulated, and calculated directly, the effect of P Δ. This solution has a serious limitation when subject to be tested pillars high levels of axial force

2.5 Application of the axial load through mechanisms

The use of mechanisms for the axial load application is usually weighted in cases where only offers small capacity actuators and whether to extend this action through a system of levers. Given the complexity of the schemes adopted by some authors, were also included in this group, the test configurations that use arms in L for side loading, with or without the pantograph type systems (device used to transfer pictures and It can also be set to run enlargements and reductions in desired proportions) which are designed to simulate without pillar head rotation test cases (deformed with double curvature).

2.6 Final considerations

After the presentation of the different axial load application approaches in this section, it can be summarized the advantages and disadvantages of each one in (Table 1):

Table 1 – Comparison of the main characteristics of the axial load applications approaches (adapted from [3, 4]).

Axial load application approaches	**Advantages**	**Disadvantages**
Pre-stressed tie rods (between the base and the head of the specimen)	- Inexpensive solution; - Execution facility; - Allow the study of the cyclic behaviour under certain axial load	- Risk of improper interpretation of the results (P δ effects) - Not allow axial cyclic loading
Hidraulic actuator (reacting against a vertical reaction structure)	- Possibility of adjustment of the axial load during the experimental test; - Possibility of the axial cyclic loading;	Risk of part of the horizontal force be mobilized by the stiffness of the reaction vertical structure; Connection between the actuator and the head of the specimen
Weights (applied on the head of the specimens)	- Simplicity - Absolute rigorous for the desired simulation	Handle large loads both before the test and when possible occur of collapse of the system
Mechanisms (indirect application of the vertical loading)	- Low capacity of the hydraulic equipment's; - Possibility of proportional axial loading	Complex axial load application procedure; No possibility of variable axial load

3. LESE Experimental test setup configuration

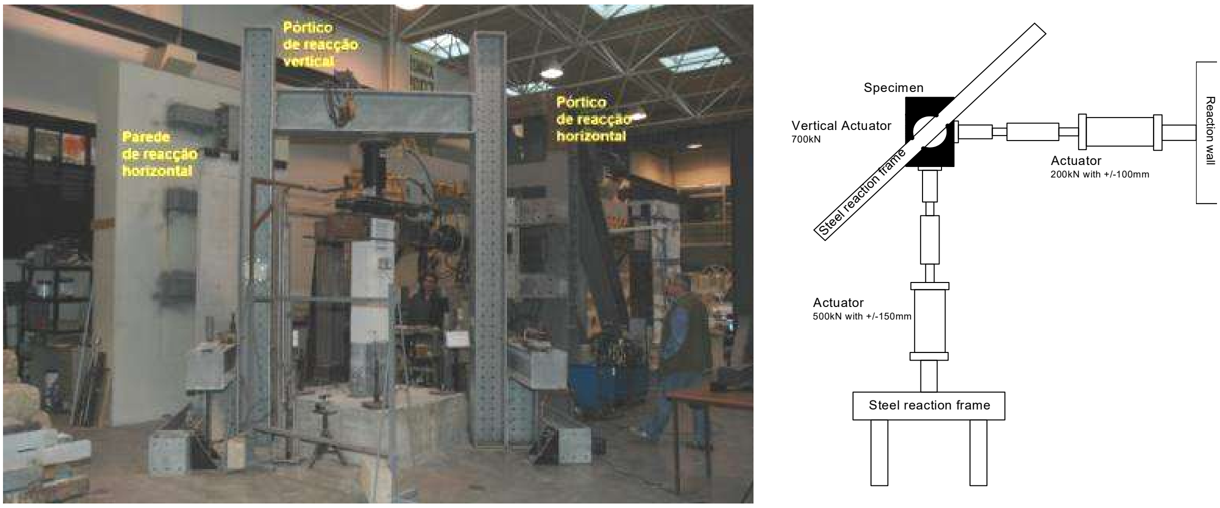
3.1 Introduction

The installed test configuration in the Laboratory of Earthquake and Structural Engineering- LESE is designed to allow the testing of full-scale RC columns of buildings (and bridges have been performed at 1: 4) which can be applied simultaneously, a controlled axial load and two actions orthogonal cyclic horizontal (intensity and variable and independent sense each other).

In comparison with other test configurations, it should be noted that the greatest advantage of this assay system is the possibility of performing biaxial tests on RC columns, by applying the bidirectional horizontal actions associated with an axial force independent variable of the remaining actions applied in a vertical line remains unchanged, and therefore no interference in the results the effect of the variation of its point of application and direction over the test (P effect δ). Indeed, it was the objective of simultaneous achievement of these three conditions led to the development of test configuration installed in LESE impossible to achieve in any of the other mentioned in the previous section.

3.2 Test setup description

The experimental test setup includes a vertical 700kN capacity actuator was used to apply the axial load and 2 horizontal independent actuators to apply the lateral load paths on the columns (one with a capacity of 500kN with +/-150mm stroke and the other with a capacity of 200kN and +/-100mm stroke). The reaction system for the three actuators is composed by 2 steel reaction frames and a concrete reaction wall form the (Fig.3). The column specimens and the reaction frames were fixed to the strong floor of the laboratory with prestressed steel bars to avoid sliding or overturning of the specimen during testing, or sliding of the reaction frame.



a) b)

Fig. 3 – Test setup of biaxial horizontal loading combined with axial loading on RC columns at the LESE Laboratory: a) General view of the test setup; and b) schematic layout of the tests setup.

Since the axial load actuator remains in the same position during the test while the column specimen laterally deflects, a sliding device is used (placed between the top-column and the actuator), which was built to minimise spurious friction effects. This device is composed by two sliding steel plates that exist between the top column section and the actuator. However, with the main purpose of to measure these small friction forces, load cells in the two horizontal directions were connected to the upper plate (that is expected not to displace laterally) and the corresponding measured forces were subtracted from the forces read by the load cells of the horizontal actuators.

3.3 Axial loading application

The vertical load is applied by means of a hydraulic actuator interposed between the beam of the gantry vertical reaction and the head of the column (Fig. 4). At this stage of development of the test configuration, as well as if you want the vertical force is maintained constant, it was intended to be complied with, among others, three key assumptions: i) allow the pillar of head movements in two orthogonal directions; ii) maintain unchanged the vertical application of the axial force; and iii) applying a constant vertical load (in this system development phase).

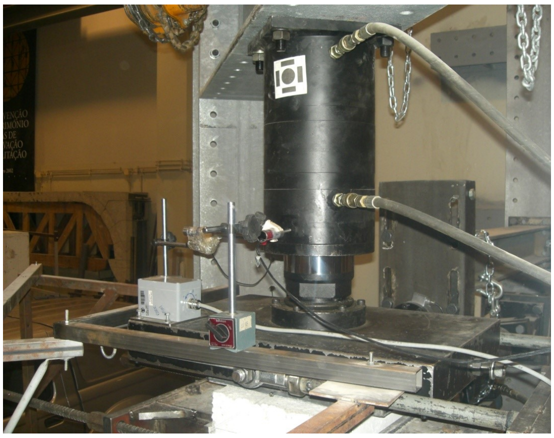


Fig. 4 – General view of the axial load application.

With this purpose it was opted a sliding device made of two metal plates with good crush resistance and low friction between the contact faces. To this end, it was placed in a finish surface contact consisting of a thin plate of stainless steel and the other comprising predominantly a mixed solution teflon. As can be seen by observing Fig.4 the lower plate rests directly on the top of the column (with interposition of a lead sheet to increase friction and to accommodate any irregularities); the upper plate rests on the bottom plate and receiving the vertical load of the actuator by means of a spherical cap which abuts the piston of the actuator to allow rotation of the top pillar (maximum rotation 8%). To maintain unchanged the load from the vertical, the top plate is also connected externally to prevent any horizontal movement, properly instrumented to measure the force mobilized between the two plates and thereby correct the horizontal force applied to the abutment during the test.

During the test the pressure of the hydraulic oil should be kept constant in the upper chamber of the actuator, to ensure that the axial force applied does not vary significantly.

3.4 Axial loading application control

This test configuration is designed so that the axial force applied on the specimen was constant throughout the test. When searching for justification for the initial results obtained with this assay system, it was found that the amount of force applied by the vertical actuator could not be constant as intended, or the reading of the manometer and pressure existing transducer in the chamber the oil pump could not be correct. Made some additional tests, we came to the conclusion that despite the system design point in the opposite direction, the company that manufactured the equipment put a check valve in the intake circuit. As a consequence, the piston of the vertical actuator was unable to adjust the vertical movements induced by the geometric effect of the horizontal displacement of the test piece

(Fig. 5). In other words, the increase of oil pressure in the chamber of the vertical actuator, and thus an increase in the axial force results from the fact that the point of application of the vertical force being fixed to the plant and the deformation of the pillar (obtained by imposing horizontal displacements) force the piston vertical actuator to retreat. However, as the pressure gauges are located in the pump chamber and the check valve (improperly installed), the oil isolated in the upper chamber of the actuator, it was not possible to detect this fault directly via the installed instrumentation.

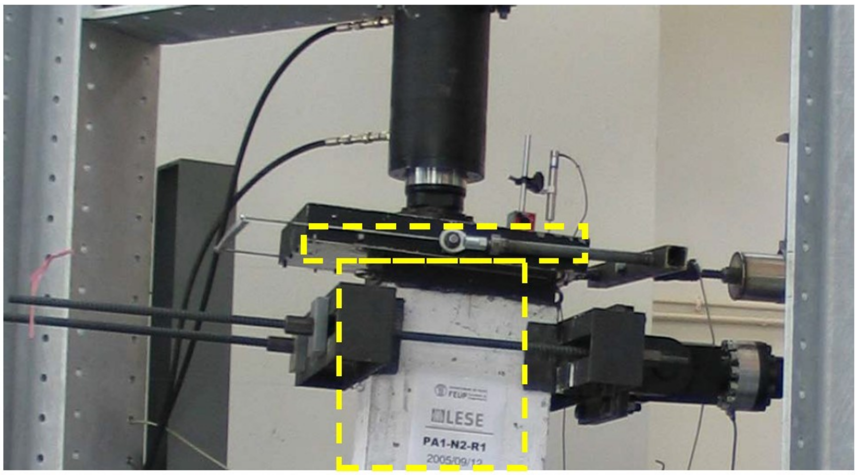


Fig. 5 – Geometric effect of the horizontal displacements of the specimens.

3.5 Acquisition system and load control

The movements of the horizontal actuator were operated by National Control System Instruments (NI) consists of a PXI chassis, controlled by a computer program with routines written in LabVIEW, designed specifically to meet the defined requirements. Data acquisition was also supported by another PXI system equipped with card acquisition and signal conditioning, which allows the direct reading of data from strain gauges, load cells, LVDTs or other any amplified analog devices or digital sensors, and the data acquisition software also developed in LabVIEW. For a better understanding of the functioning of the whole, we present an outline in Fig. 6, where, in addition to the control systems (including hydraulic pumps and actuators) and acquisition are depicted three main electrical panel in good overall performance - A supply and signal conditioning ; the other connected to the control; and another connected to the acquisition - as well as the indication of the direction of information flow of information between all system components.

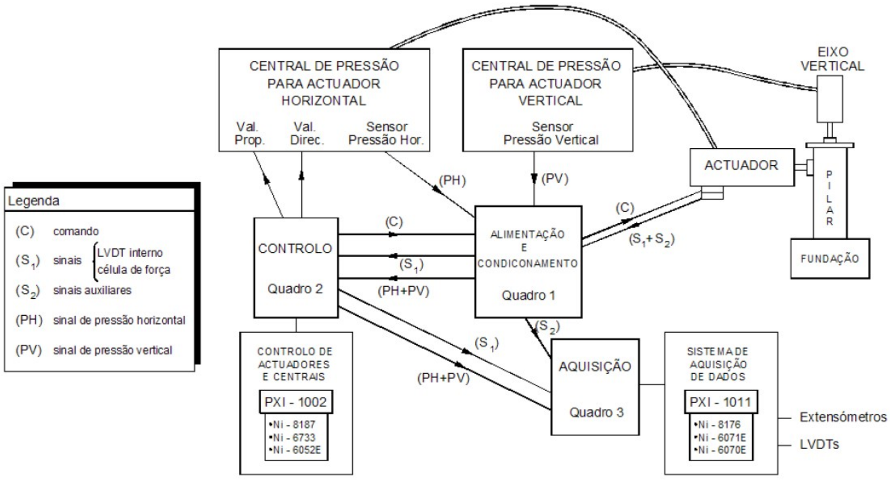


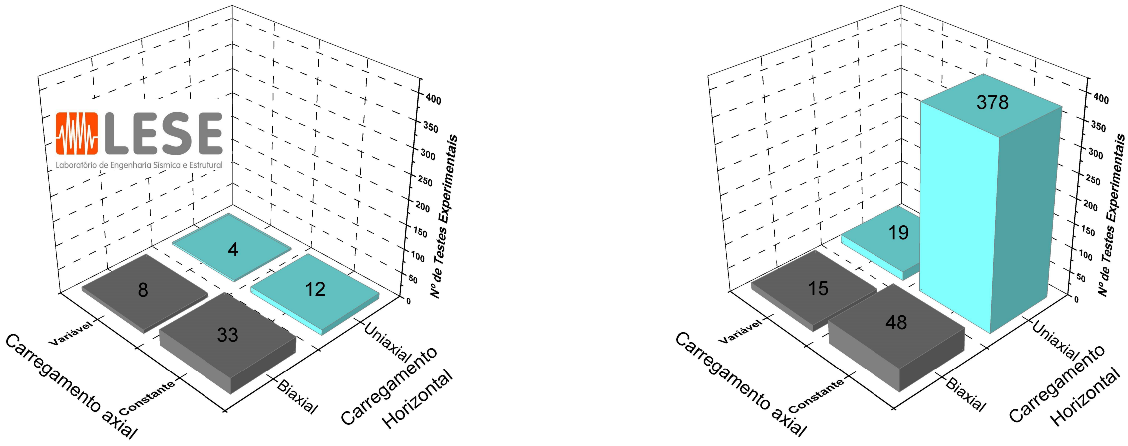
Fig. 6 – Schematic layout of the load and acquisition system.

These tables allow for greater reliability and organization in the various links between the control systems and procurement, central pressure and actuators. In addition they are also represented the hydraulic connections between the central oil pressure, vertical and horizontal, and the respective hydraulic actuators, carried out by normal-pressure hoses in such systems (up to 350 bar, about). The idealized system and implemented in LESE that allows the simultaneous application of a vertical load and one or two orthogonal horizontal cyclic loads (magnitude and varying direction), proved reliable and versatile in test composite structural elements subject to bending or deviated. Up to now have been tried with good results, full scale building columns and bridges with a scale of 1: 4.

The major novelty of this assay configuration is of the axial load application system via sliding plates and which gives the particularity of maintaining the axial load in a fixed vertical position. Because there is no experience in this type of device, it was necessary to make a series of preliminary tests that allow to know all the forces transmitted through the system. To this end it has been mounted an articulated steel column base (which transmits only axial loads), and thus not interfere with the value of the horizontal load applied. Thus, after playing operation of the set and evaluating the level of forces involved in friction and displacement in the vertical gantry, it was possible to calibrate all system components.

3.6 State of the art of the experimental tests performed in the LESE laboratory

During the last decade it has been carried out an extensive test campaign of RC columns subjected to uniaxial and biaxial horizontal loading combined with constant or varied axial force. They were tested in all so far 56 columns with different geometrical sections, of which 40 were subjected to biaxial flexural tests and the other 46 uniaxial bending. Of the 56 columns tested in total were tested 42 original, 8 and 6 repaired after being tested previously. The LESE laboratory has contributed significantly to the increase of the database available in the international literature on the biaxial bending tests combined with constant and variable axial force which resulted in an increase of 41% and 35% respectively. Already with regard to uniaxial bending tests combined with constant and variable axial force's contribution LESE has resulted in increased database by 5% and 23% respectively. In Fig. 7 we can observe the state of the art test reinforced concrete pillars made in recent years in LESE Laboratory and literature.



a) b)

Fig. 7 – State of the art of RC columns experimental tests: a) Lese Laboratory; b) Literature [5].

Conclusions

This manuscript presents an idealized and implemented system LESE laboratory that allows the study of the behavior of reinforced concrete columns of buildings or bridges with a scale of 1: 4 subject to bending flexure combined with constant or variable axial load. Given the complexity of this type of testing due to the combination of numerous actuators setup presented here showed excellent results resulting in a significant contribution to the scientific community with a large number of experimental trials in recent years.

Acknowledgements

The authors would like to acknowledge the technicians of the LESE laboratory, Mr. Valdemar Luis and Mr. Nuno Pinto for their support in the experiments reported in this paper.

References

[1] A. Esmaeily-Ghasemabadi and Y. Xiao, "Seismic Behavior of Bridge Columns Subjected to Various Loading Patterns," Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley PEER Report 2002/15, December 2002 2002.

[2] W. Kim, A. A. El, and R. N. White, "Small-Scale Modeling Techniques for Reinforced Concrete Structures Subjected to Seismic Loads," NCEER-88-0041, Buffalo, N.Y. : National Center for Earthquake Engineering Research, Technical report1988.

[3] V. Rodrigues, "Reforço Sísmico de Pilares de Betão Aarmado - Análise e Avaliação Experimental," Tese de Mestrado, DEC - FEUP, Universidade do Porto, Porto, 2005.

[4] P. Rocha, "Reforço e reparação de pilares de edifícios de betão armado em zonas sísmicas," Departamento de Engenharia Civil da Faculdade de Engenharia Universidade do Porto, Porto, 2011.

[5] H. Rodrigues, H. Varum, A. Arêde, and A. G. Costa, "Behaviour of reinforced concrete column under biaxial cyclic loading—state of the art," *International Journal of Advanced Structural Engineering,* vol. 5, pp. 1-12, 2013.