CYCLIC TEST ON RC EXTERIOR CONNECTIONS IN EXISTING WAFFLE-FLAT-PLATE STRUCTURES

A. Benavent-Climent[1], X. Cahís[2] and A. Catalán[3]

[1]*Associate Professor Dept. Structural Mechanics, University of Granada, Polytechnical Bld, Granada, Spain*
[2]*Associate Professor Dept. Mechanical Engineering, University of Girona,Campus of Montilivi, Girona, Spain*
[3]*Associate Professor Dept. of Construction, University of Oviedo Campus of Viesques, Gijón, Spain,*
Email: benavent@ugr.es

ABSTRACT :

In the moderate-seismicity southern European countries it is very common to use the reinforced concrete waffle flat-plate structure as a main system for resisting lateral earthquake loads. Field investigations on the damage suffered by this type of structures under past earthquakes and experimental research have raised serious concerns about their safety in a severe seismic event. The exterior connections of this type of structural system are especially problematic, because very often the longitudinal wide beam reinforcement steel that extends passing outside the column core is not properly anchored, and the torsion failure of the plate's edge limits the capacity of this reinforcement. This paper experimentally investigates the seismic behavior of exterior connections in reinforced concrete waffle flat-plate structures subjected to moderate gravity-load levels such as those acting during an earthquake. A 3/5 scale test model representative of an exterior connection in a prototype six-storey building was subjected to gravity and cyclic loading until failure. First yielding was observed at 1% drift ratio. The maximum strength occurred at 3.3% drift ratio and the ultimate displacement capacity was 5.5%.

KEYWORDS: exterior connection, waffle flat-plate, seismic performance, cyclic test.

1. INTRODUCTION

In moderate-seismicity southern European countries such as Spain, Portugal and Italy, the use of reinforced concrete waffle-flat-plate structures as the main system for resisting lateral earthquake loads is very common. In the case of Spain, many structures of this type were built during the 1970s, 1980s, and 1990s according to earlier seismic codes (PDS-1, 1974) that required relatively small lateral strength in comparison to the current code (NCSE, 2002), and which did not contain any provision for attaining ductility. Field investigations on the damage suffered by older non-ductile waffle-flat-plate structures subjected to past earthquakes (i.e. Mexico) and experimental research (Rodriguez et al., 1995) have raised serious concerns about their safety in the event of a severe earthquake. Past research focused on the non-ductile waffle flat-plate structure built according to US construction practices. However, research data characterizing the hysteretic behavior, lateral drift and ultimate energy dissipation capacities of existing waffle flat-plate systems built according to past construction practices in the moderate-seismicity Mediterranean area are very rare. The exterior connections of this type of structural system are especially problematic, because very often the longitudinal wide beam reinforcement steel extending outside the column core is not properly anchored, and the torsion failure of the plate's edge limits the capacity of this reinforcement.

This paper presents preliminary results of an experimental investigation aimed at clarifying the seismic behavior of exterior connections in reinforced concrete (RC) waffle-flat-plate structures subjected to moderate gravity-load levels similar to those acting during an earthquake. To this end, a 3/5 scale test model representative of an exterior connection in a prototype six-storey building was subjected to gravity and cyclic loading until failure. This work is part of a larger ongoing research project funded by the Spanish Government (Ministry of Construction), whose final goal is to evaluate the vulnerability of older non-ductile waffle flat-plate structures built in the Mediterranean area, and to develop innovative seismic upgrading strategies based on the use of hysteretic energy dissipators.

2. DESCRIPTION OF THE EXPERIMENT

2.1. Prototype building

The prototype structure consists on a six-storey, three-span and three bay building designed following the usual construction practice in Spain during the 1970s, 1980s and 1990s. It reproduces common features of this type of structure in Spain: (a) there are neither braces nor structural walls; (b) the bottom part of the plate is an orthogonal grid of ribs; (c) a solid zone is left around the columns; (d) there is a concrete topping 40-50mm thick lightly reinforced with a steel mesh; and (e) punching shear reinforcement consisting of closed hoops is provided. Figure 1 shows the plan and elevation of the prototype building.

The prototype structure was located in the highest earthquake-prone area of Spain (the province of Granada, southern Spain). The design gravity loading on each floor consisted of the plate self-weight, plus 1kPa superimposed dead load and 3kPa live load. The design earthquake was represented by a triangular distribution of lateral forces. The base shear coefficient was 0.11, as prescribed by earlier Spanish seismic code (PDS-1, 1974). The adopted compressive strength for concrete was 17.5MPa, and the yield stress of reinforcement 400MPa. The prototype structure was designed following former Spanish Concrete code (EH-90, 1990).

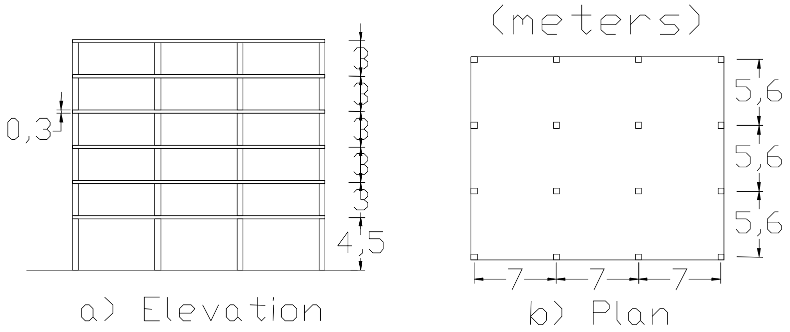

Fig. 1: Prototype building

2.2. Test specimen

From the prototype building one exterior waffle flat-plate-column connection was selected from the third storey. The width of the selected portion of the plate, measured perpendicularly to the direction of loading, coincided with the width of a column strip as defined by code ACI 318-05 (ACI, 2005). It was also equal to the width of the solid zone of the plate around the column (2.8m). Points of inflection in the prototype structure under lateral loading were assumed to be located at mid span and mid-storey height. Applying similitude requirements, the test model was defined from the selected connection. The test model was prepared in the laboratory. The scale factor chosen for linear dimensions was 3/5.. The average yield stress f_s of the material tests conducted for reinforcement (deformed steel bars) was 405MPa, and the concrete compressive strength was 19.4MPa. The overall geometry and reinforcing details of the test model are shown in Fig. 2.

2.3. Loading apparatus and history

Figure 3 shows the test setup. Gravity loading was simulated by the combination of plate self-weight and sand bags with a total weight of 20kN placed on the plate. Additionally, an axial force of 287kN was applied to the columns by means of two post-tensioned rods. The positioning and weight of the sand bags were set so that scaled shear and moment in the plate at the column face would be similar to those caused by gravity loading during an earthquake. After applying the gravity loading, the test model was subjected to cycles of incremental amplitude up to a drift ratio of 6.6%, as shown in Fig. 4.

2.4. Instrumentation

A load cell and displacement transducers were installed on the actuator, to measure the overall horizontal force Q applied to the top of the upper column and the corresponding overall horizontal displacement, δ. The strain in the reinforcing steel was measured with gauges prior to casting the concrete. Photographs were taken and detailed visual inspections and drawings were made of the concrete cracks.

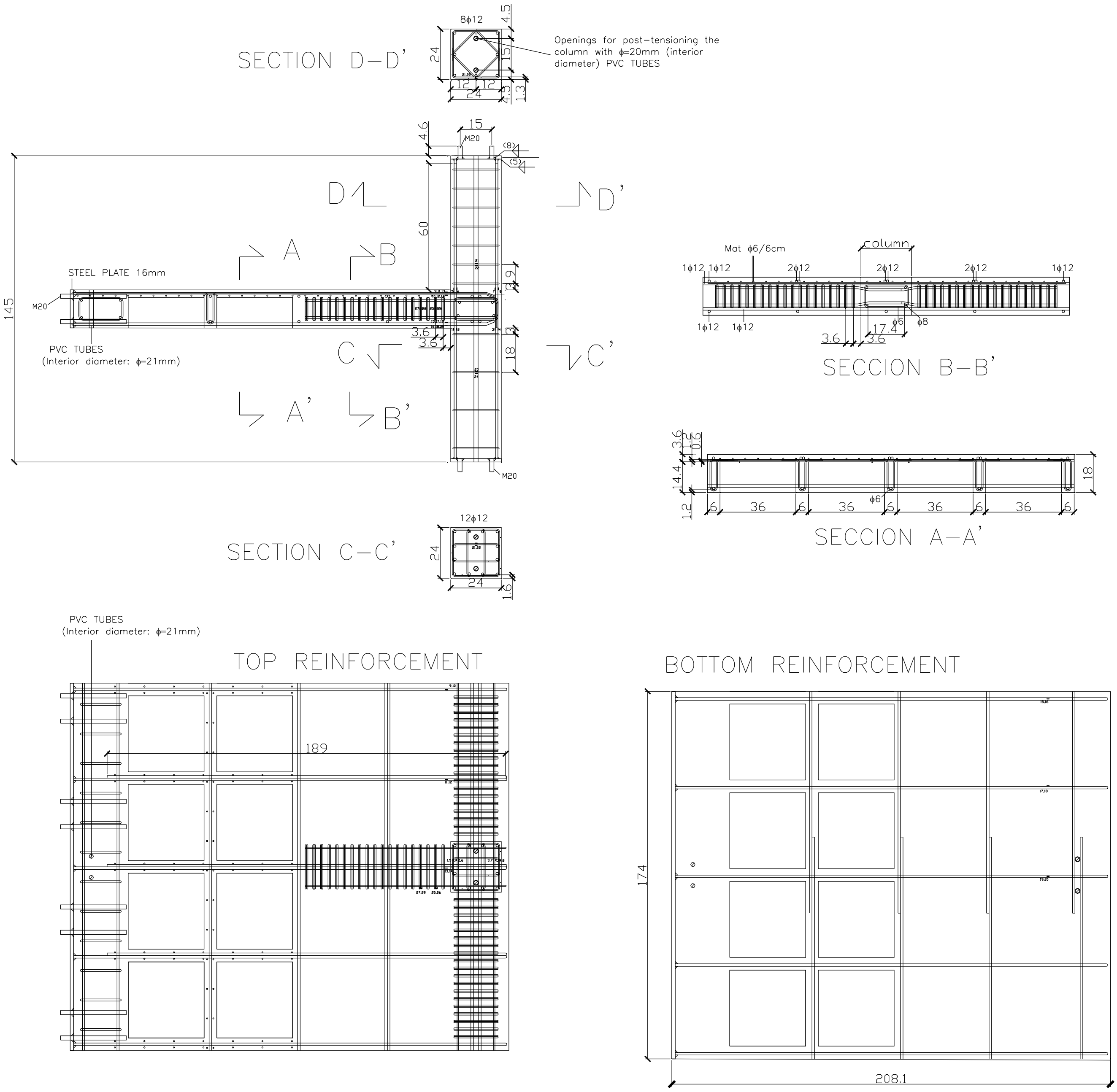

Fig. 2: Test specimen

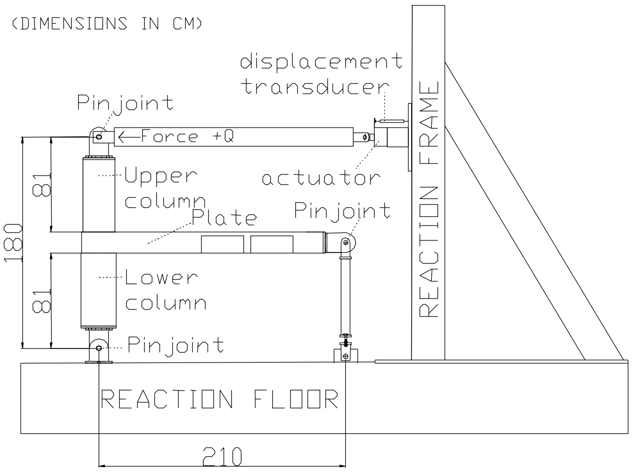

Fig. 3: Test set up

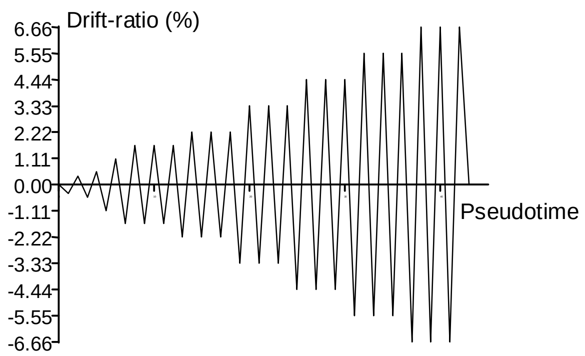

Fig. 4: Loading set up

3. TEST RESULTS

3.1. Overall response

The load displacement relationship, Q-δ, obtained from the test is shown in Fig. 5. The overall response was characterized by severe pinching on the hysteresis loops and early degradation of the lateral strength of the connection. Typical features of this type of system were corroborated by the test: high flexibility and limited energy dissipation capacity. The columns remained elastic with minor cracking. The typical punching failure involving pyramidal inclined cracking in the plate around the joint did not occur, most probably because of the existence of punching shear reinforcement and the relatively low levels of gravity load. The waffle flat plate-column connection behaved as a “strong column-weak plate” mechanism. The torsional yield moment of the torsional members limited the flexural strength of the plate, and governed the capacity of the subassemblage.

3.2. Cracking process

First flexural cracks were observed perpendicular to the direction of loading over the full width of the plate. Typical diagonal torsion cracks from the side of the column to the slab edge were also observed in the torsion members at early stages of the test. These torsion cracks controlled the behavior of the connection throughout the loading history. At approximately 1% driftratio, the first yielding occurred in the bar located at the bottom part of the plate, anchored in the column width. Yielding of other plates´ longitudinal bars began in the column axis and extended progressively, but in no case reached the outermost bars. When the peak lateral forces Q_y were attained at about 3.3% drift ratio, wide torsion cracks of about 1.2mm wide appeared in the torsional members adjacent to the columns, while the width of the flexural cracks across the plate remained below 0.1mm. The cyclic displacement continued beyond the 3.3% drift ratio, and failure occurred at 5.5% drift-ratio. Failure was assumed to occur when the specimen entered the strength degradation path and the strength dropped below $0.8Q_y$. The crack pattern at failure was characterized by a severe widening, up to a width of approximately 8mm for the diagonal cracks on the torsional members. The cracking process is shown in Fig. 6.

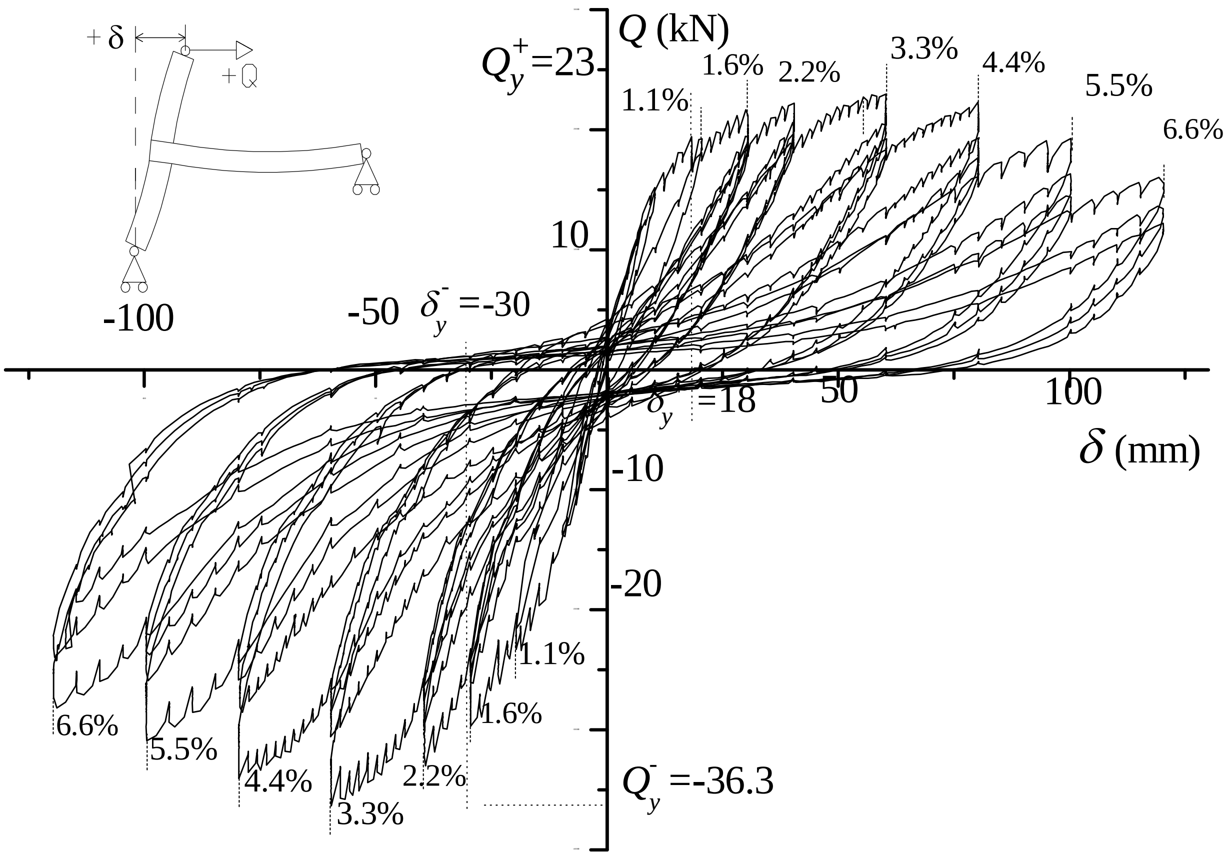

Fig. 5: Overall lateral force-displacement relationship

4. CONCLUSIONS

This paper presents the preliminary results of an experimental study aimed at investigating the seismic behavior of exterior waffleflat-plate column connections subjected to lateral seismic loads. The research is focused on typical buildings constructed in Spain during the 1970s, 1980s, and 1990s, and designed according to earlier seismic codes. A 3/5 scale test model representative of an exterior connection in a prototype six-story building was subjected to gravity and cyclic loading until failure. The load displacement curve was characterized by severe pinching on the hysteresis loops and early degradation of the lateral strength. Typical punching failure was not observed. The waffle flat-plate-column connection behaved as a "strong column-weak plate" mechanism. The torsional behavior of the torsional members governed the capacity of the subassemblage. First yielding was observed at 1% drift ratio. Maximum strength occurred at 3.3% drift ratio and the ultimate displacement capacity was 5.5%.

ACKNOWLEDGEMENTS

This investigation has been funded by the Spanish Ministry of Construction. National Program of Construction I+D+i 2004-2007 (project number 2004/39).

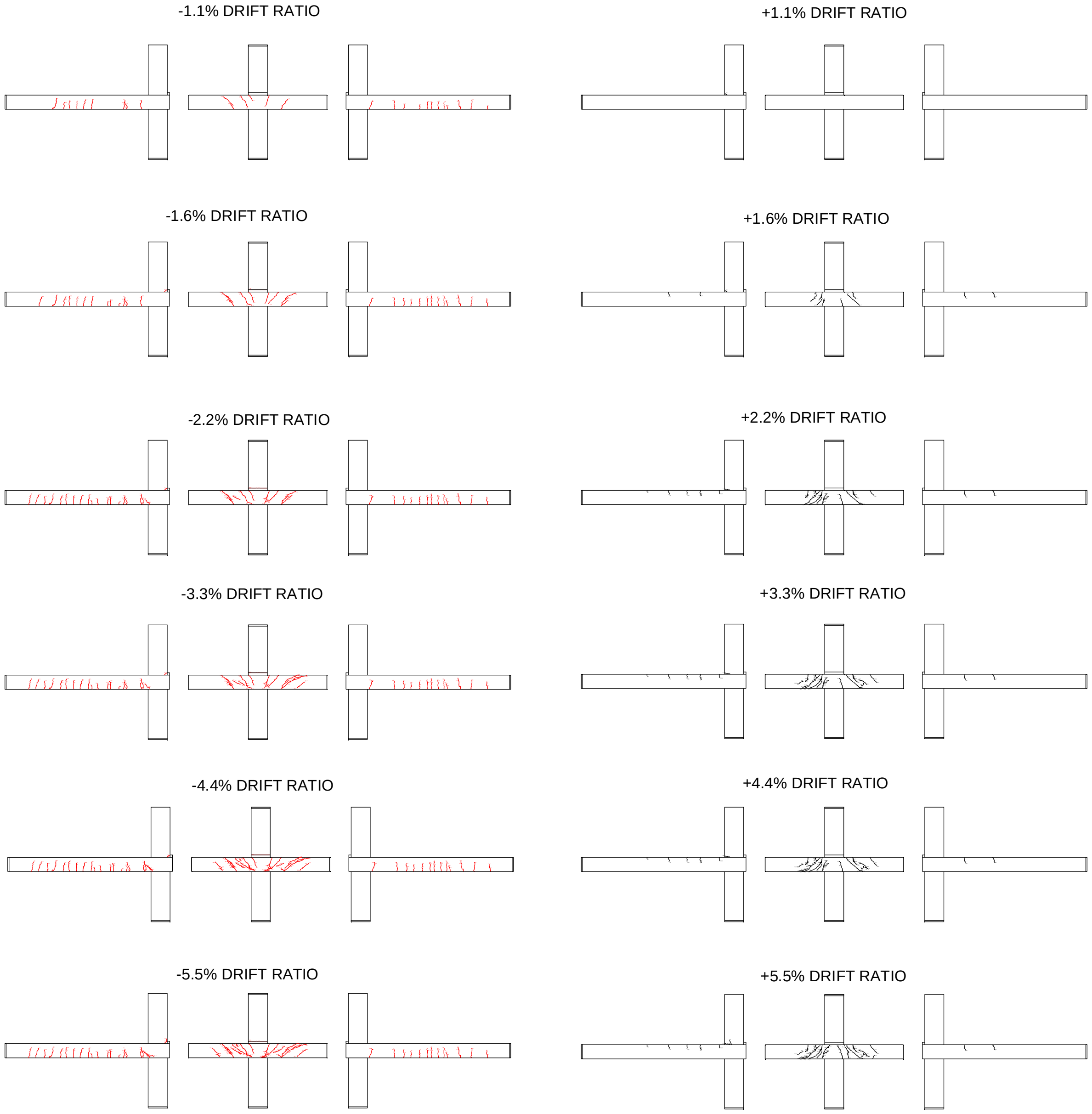

Fig. 6: Cracking process

REFERENCES

ACI Committee 318 (2005) Building code requirements for reinforced concrete, American Concrete Institute, USA.

Committee for the development of seismic codes. Norma Sismorresistente PDS-1 Parte A, Madrid: Spanish Ministry of Construction, 1974.

Committee for the development of seismic codes. Norma de Construcción Sismorresistente NCSE-02, Madrid: Spanish Ministry of Construction, 2002.

Concrete Committee. Instrucción para el proyecto y ejecución de obras de hormigón en masa o armado EH-90, Madrid: Spanish Ministry of Construction, 1990.

Rodriguez, M. E., Santiago, S. and Meli, R. (1995). Seismic load tests on two-story waffle-flat-plate structure. *Journal of Structural Engineering* **121:9**, 1287-1293.