EXPERIMENTAL INVESTIGATION ON RC EXTERIOR WIDE BEAM-COLUMN CONNECTIONS SUBJECTED TO CYCLIC LOADING

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ABSTRACT :

In countries of the Mediterranean area, such as Spain or Italy, it has been a very common practice to use reinforced concrete moment-resisting frames (RCMRF) with wide beam-column connections as the main structural system for resisting lateral seismic loads. Past research has unveiled the vulnerability of this type of system to earthquakes. Especially problematic are the exterior wide beam-column connections. This paper presents preliminary experimental results of a bigger research project aimed at evaluating the vulnerability of the RCMRF with wide beam-column connections built in Spain during the 1970s, 1980s and 1990s, and to develop innovative seismic upgrading strategies based on the use of hysteretic energy dissipators. To this end, two 3/5 scale test models representative of exterior subassemblages in a prototype six-story building were subjected to gravity-load levels typical of those acting during an earthquake, and quasi-static cyclic lateral loads until failure. The specimens exhibited a “strong column-weak beam” type of flexural yielding mechanism. The average drift ratios at first yielding of the wide beam longitudinal reinforcement and at failure were 2.2% and 4.5%, respectively.

KEYWORDS: exterior connection, wide beam, seismic performance, cyclic test.

1. INTRODUCTION

In countries of the moderate-seismicity Mediterranean area, such as Spain or Italy, it has been a very common practice to use reinforced concrete moment-resisting frames (RCMRF) with wide beam-column connections as the main structural system for resisting lateral seismic loads. Even now, they are extensively used despite insufficient information as to how they behave under severe earthquake loading. Past research has unveiled the vulnerability of this type of system to earthquakes due to its large lateral flexibility, low energy dissipation capacity and the deficient transmission of bending moments from beams to columns. The safety of these buildings in the event of a severe earthquake is very questionable.

The exterior connections of this type of frame are especially problematic. One typical characteristic of the exterior connections built in the Mediterranean area is that the depth of the spandrel beam equals the depth of the wide beam, and the former is not designed for torsion. Thus, the longitudinal wide beam reinforcement steel passing outside the column core is not properly anchored, and it can not develop its full capacity because it is limited by the torsion failure of the spandrel beam. In this study, two 3/5 scale test models representative of exterior wide beam-column connections were subjected to gravity and cyclic lateral loading until collapse. The specimens represent critical parts of a prototype structure with six storeys and four bays, typical of a residential building constructed over ten years ago in the southern part of Spain (Granada region), where the design peak ground acceleration (PGA) according to current seismic code (NCSE, 2002) is 0.24*g* (*g*: gravity acceleration). This paper presents the preliminary results of the tests.

This work is just part of a more comprehensive research project funded by the Spanish Government (Ministry of Education), aimed at evaluating the vulnerability of existing RCMRF with wide beam-column connections, so as to eventually develop innovative seismic upgrading strategies based on the use of hysteretic energy dissipators.

2. DESCRIPTION OF THE EXPERIMENTS

2.1. Prototype building

A prototype structure with six storeys, four bays and four spans was designed following usual construction practices in Spain during the 1970s, 1980s and 1990s. It reproduces features common to this type of structure: (a) the width of the transverse beams is equal to that of the columns; (b) the slab is constructed with one-way joists carried by the wide beams, non-structural clay elements are placed between the joists, and a concrete topping 4cm thick is added; (c) all members have the same depth (typically 25-30cm); and (d) the transverse beams are lightly reinforced. The prototype building is shown in Fig. 1.

The prototype structure was located in the highest earthquake-prone area of Spain (the province of Granada, southern Spain). The design gravity loading consisted of the plate self-weight, plus 1kN/m^2 superimposed dead load and 3kN/m^2 live load. The design earthquake entailed a triangular distribution of lateral forces. The base shear normalized by the total building weight was 0.14, as prescribed by earlier Spanish seismic code (PDS-1, 1974). The design yield stress of the reinforcement was 400MPa, and the concrete compressive strength 17.5MPa. The prototype was designed as an ordinary moment-resisting frame, following earlier Spanish Concrete Code (EH-90, 1990). Non-ductile details and common construction practices used over ten years ago in Spain were employed. Accordingly, the transverse beams were not designed for carrying torsion, but simply for sustaining their self-weight plus the dead load of the exterior walls. As a result, minimum longitudinal and shear reinforcement was required in the zones of the transverse beams adjacent to the columns.

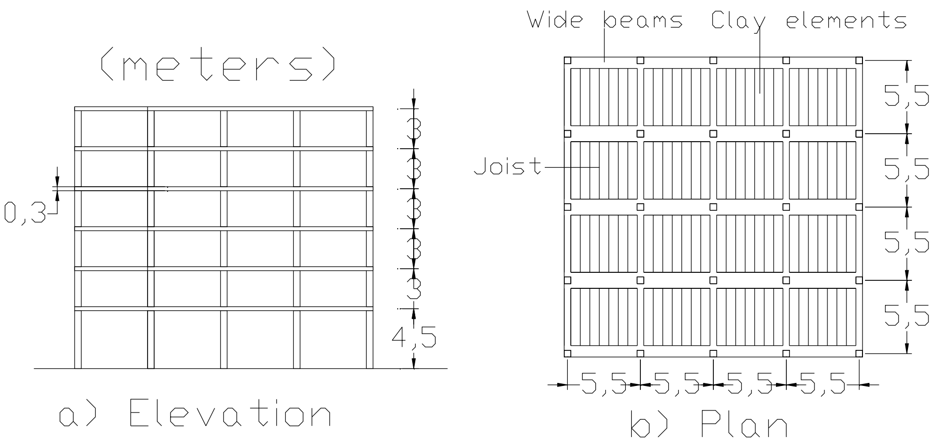

Fig. 1: Prototype building

2.2. Test specimen

From the prototype structure, two exterior wide beam-column connections were selected: one from the second storey and the other from the fifth storey of the building. Points of inflection in the prototype structure under lateral loading were assumed to be located at mid span and mid-storey height. From the selected connections, the corresponding test models, herein designated as EL and EU, were derived by applying a scaling factor of 3/5 for geometry. The test models were prepared in the laboratory. The average yield stress of the steel was 404MPa, and the concrete compressive strength 24.9MPa. The overall geometry and reinforcing details are shown in Figs. 2 and 3, respectively. The width of the beam in specimen EL exceeds the limit set by the current Spanish seismic code (NSCE, 2002) but remains within that established by code ACI-318-99 (ACI, 2005). The beam width of specimen EU coincides with the limit set by the current Spanish seismic code (NCSE, 2002).

The spandrel beams of specimens EL and EU had equal depth (18 cm) but different widths (12 cm for specimen EL and 9 cm for specimen EU). Also different was the spacing of the spandrel beam's transverse torsion reinforcement, which was set to 4.5 cm in specimen EL and 7.8 cm in specimen EU. The spacing of 7.8 cm is the maximum (after scaling) allowed by earlier Spanish Concrete Code (EH-90, 1990), and it is larger than the maximum permitted by code ACI-318-05 (ACI, 2005) to ensure the development of the ultimate torsional strength of the beam, to prevent excessive loss of torsional stiffness after cracking, and to control crack widths.

2.3. Loading apparatus and history
Figure 4 shows the test setup. Gravity loading was simulated by the combination of wide beam self-weight, sand bags of total weight 40kN placed on the beam, and an axial force applied to the columns by means of two post-tensioned rods, whose value was 214 kN on specimen EL and 37 kN on specimen EU. The sand bags were positioned so that scaled shear and moments in the beam at the column face were similar to those acting in the prototype building for the combined gravity and earthquake load.

The load history consisted of several sets of three cycles of forced horizontal displacements at the top of the column. The amplitude of the cycles was made constant within each set but increased every consecutive set of cycles following the sequence 0.5δ_y, 0.75δ_y, 1.0δ_y, 2δ_y, 3δ_y, 4δ_y and so on, up to a drift ratio of 8%, the maximum available stroke of the actuator. Here, δ_y denotes the yield displacement (drift ratio) predicted using a model proposed in the literature (Benavent-Climent, 2002), which gave δ_y =2.5% for specimen EL and δ_y=1.4% for EU.

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.

3. TEST RESULTS

3.1. Overall response
The overall response in terms of the load displacement curve, Q-δ, is shown in Figs. 5 and 6. Both specimens exhibited severe pinching of the hysteresis loops and early degradation of the overall lateral strength. No sign of joint shear failure was observed. Both specimens behaved as a strong column-weak beam mechanism. Columns remained in the elastic range with minor cracking.

Yielding of the beam longitudinal bars started from the axis of the column and extended progressively to the outer bars. First yielding of the wide beam longitudinal bars was observed at drift ratios of 2.4% and 1.9% in the positive and negative domains, respectively, for specimen EL; and 3.1% and 1.4% in specimen EU. The outermost bars never yielded, but larger strains were measured in specimen EL than in specimen EU. The capacity of the connection was limited by the flexural yielding of the longitudinal bars anchored within the column width.

The maximum lateral load, Q_{max}, was attained at drift-ratios of about 4% in specimen EL and 3% in specimen EU. Soon after attaining Q_{max}, a sudden strength reduction was observed which determined the failure of the connection. Failure was assumed to occur when the strength came below 0.75Q_{max}, which is considered in the literature (Scribner and Wight, 1980) to mark the limit of the "usable" capacity of the member. This drop in strength was due to the development of severe torsion cracks in the spandrel beams. The corresponding ultimate drift capacities in the positive and negative loading domains were 4.9% and 5.1%, respectively, for specimen EL; and 4.6% and 3.6% for EU.

3.2. Cracking process
Flexural cracks formed in both specimens across the full width of the beam when the drift ratio was below 0.5%. As noted above, the development of severe torsion cracks in the spandrel beams determined the failure of the connection. The sequence of cracking patterns is shown in Figs. 7 and 8.

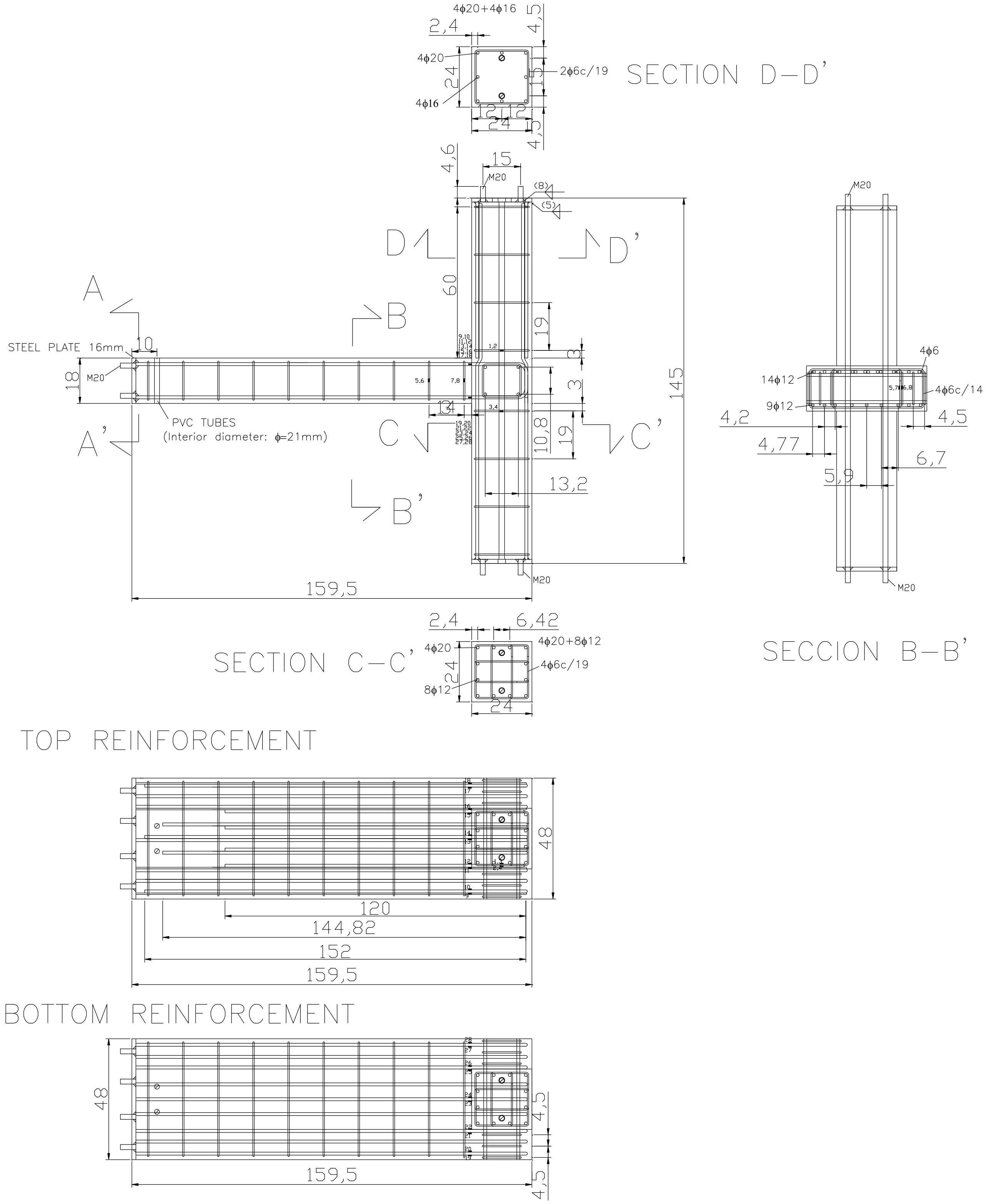

Fig. 2: Test specimen EL

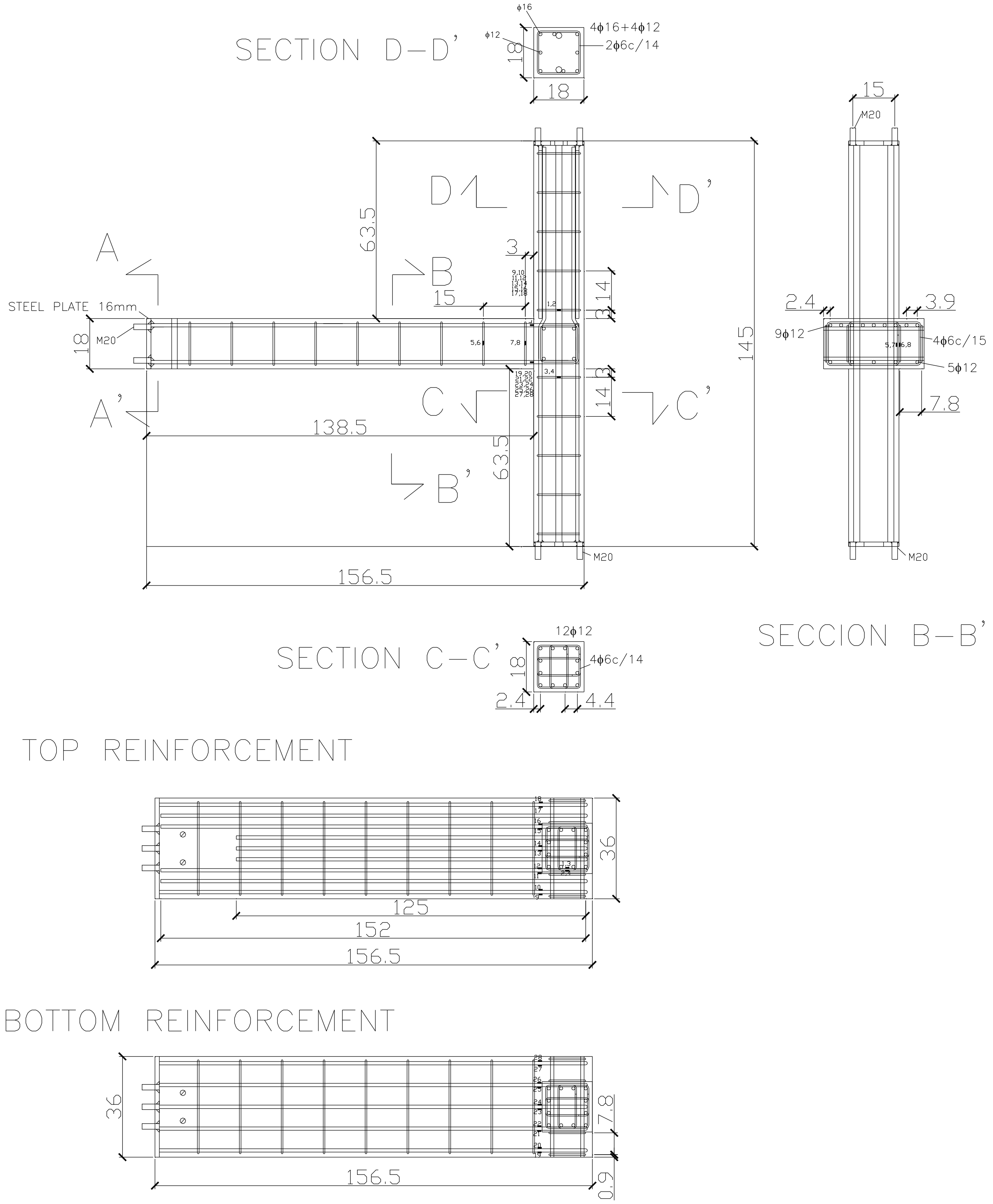

Fig. 3: Test specimen EU

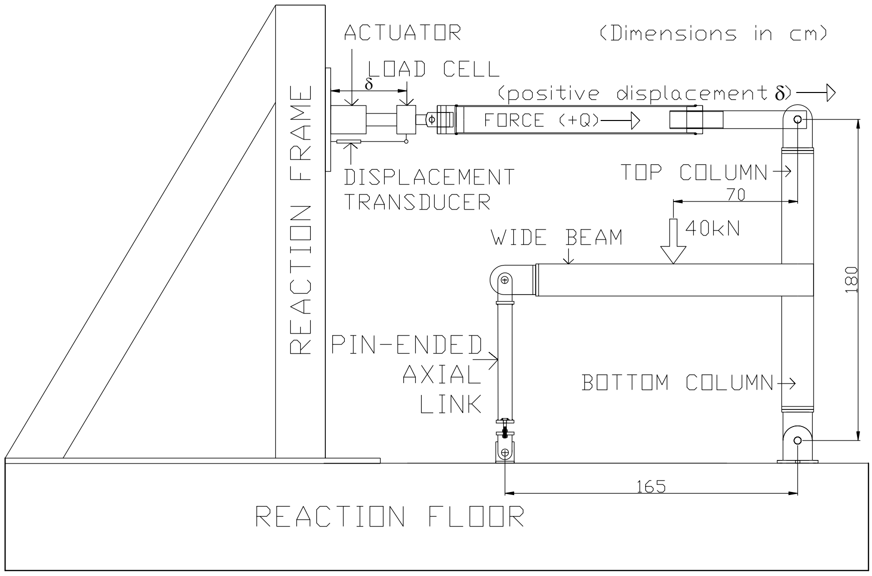

Fig. 4: Test set up

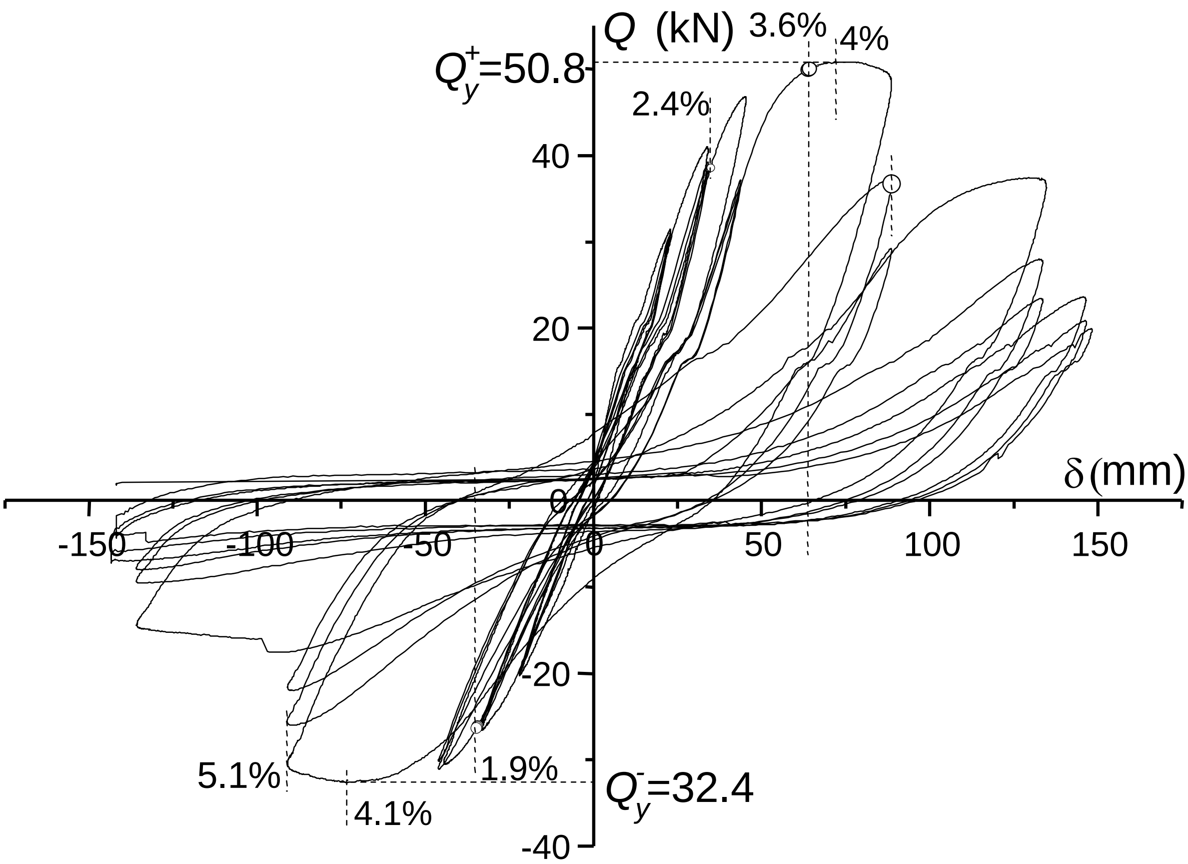

Fig. 5: Load-displacement curve of specimen EL

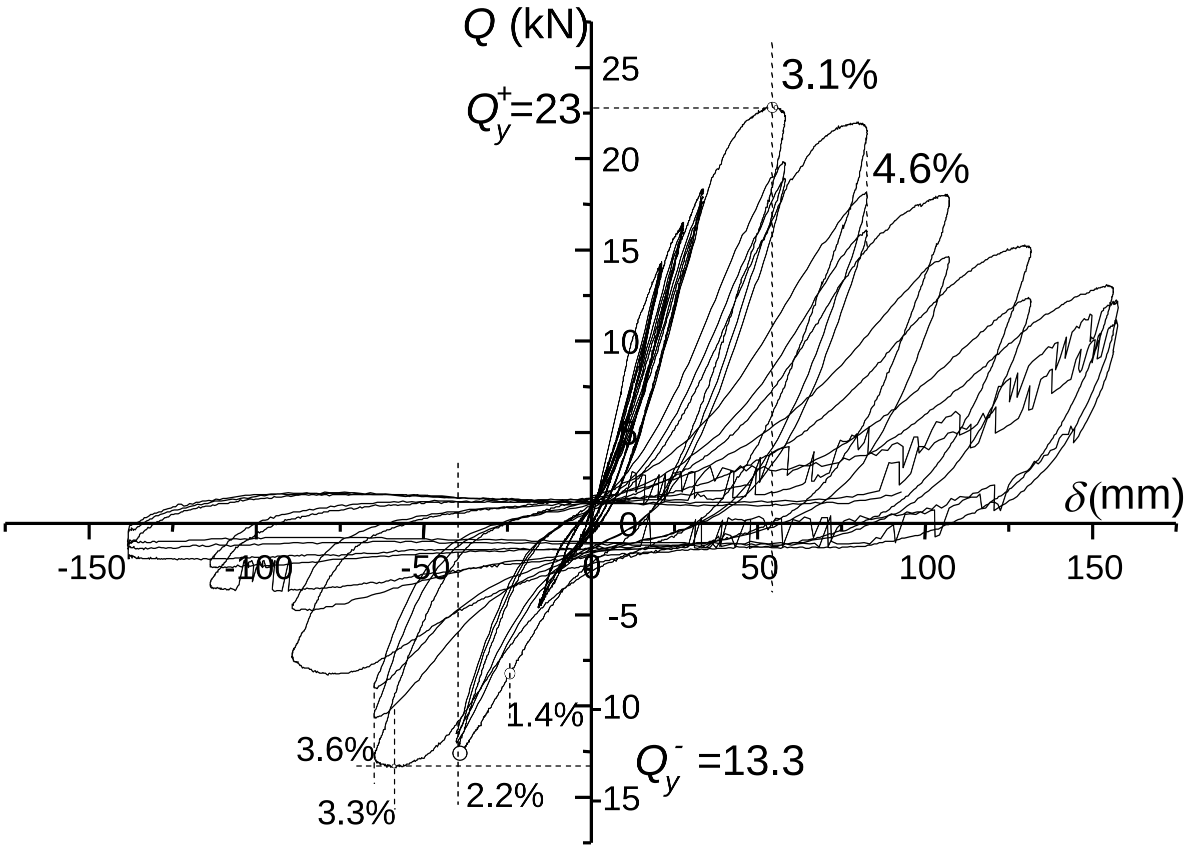

Fig. 6: Load-displacement curve of specimen EU

4. CONCLUSIONS

This paper presents the preliminary results of an experimental study conducted to investigate the seismic behavior of existing exterior RC wide beam-column connections designed according to construction practices in Spain during the 1970s, 1980s and 1990s. Two specimens with shallow spandrel beams lightly reinforced for torsion were subjected to moderate levels of gravity loading and quasi-static lateral cyclic loads until failure. First yielding of the wide beam longitudinal bars was observed at an average drift of about 2.2% of the storey height, and the ultimate drift ratio was about 4.5%. The failure of the connection was due to the development of severe torsion cracks in the spandrel beams (torsion members).

ACKNOWLEDGEMENTS

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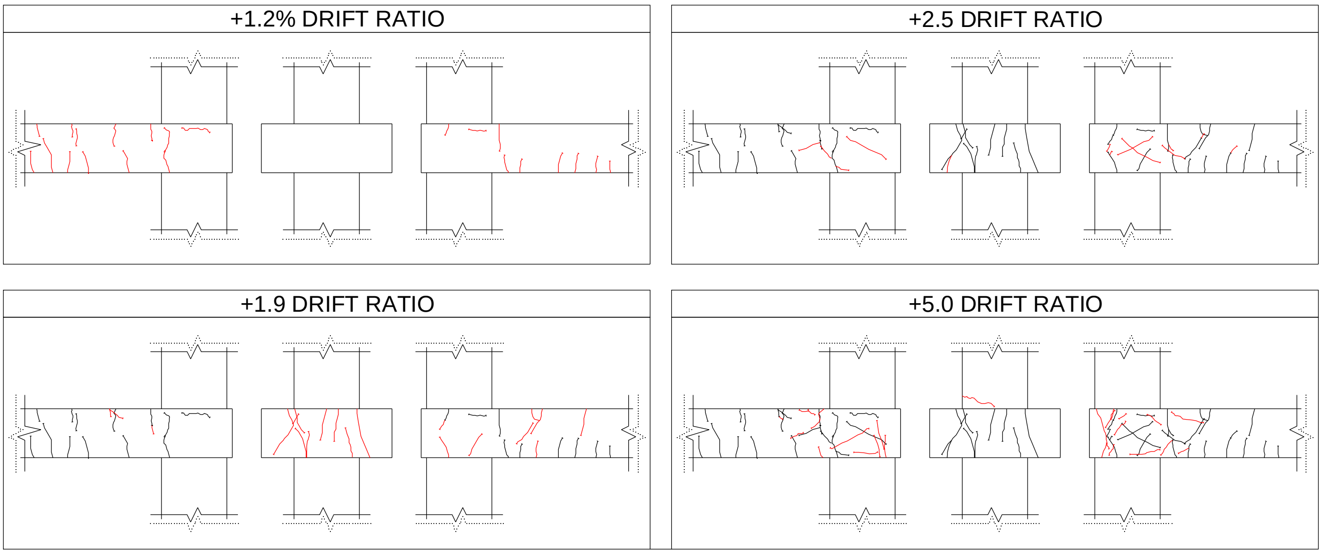

Fig. 7: Cracking pattern of specimen EL for different drift ratios

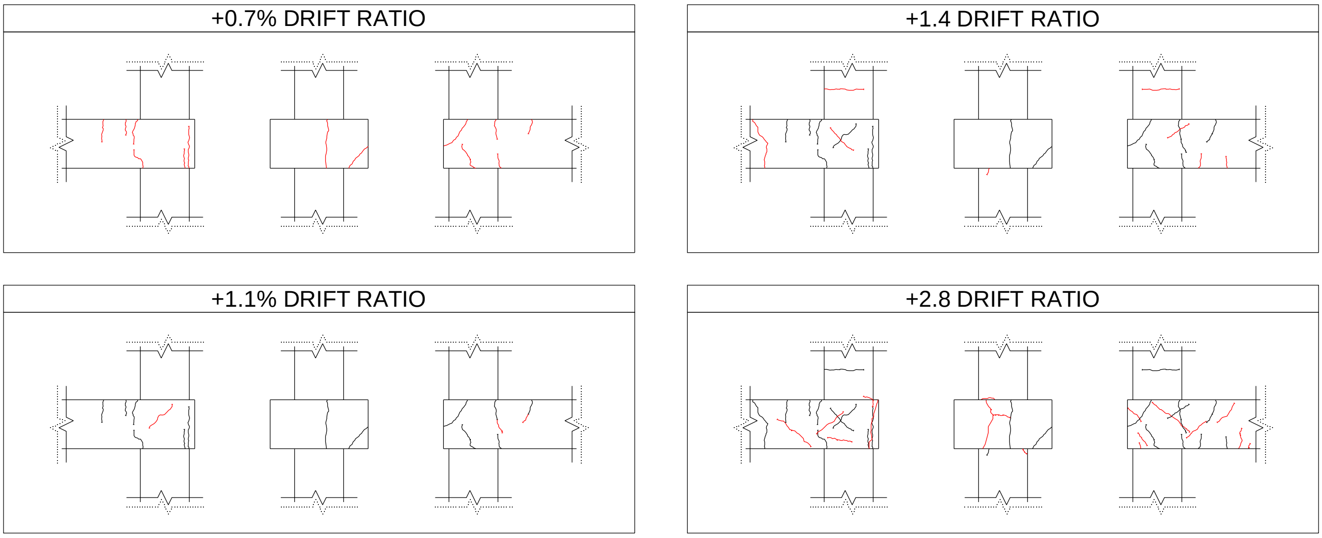

Fig. 8: Cracking pattern of specimen EU for different drift ratios

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