EXPERIMENTAL STUDY ON PRECAST BEAM-COLUMN CONNECTIONS USING GROUTED SLEEVES AND THREADED COUPLERS

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Abstract

The experience of past strong earthquakes in advanced seismic engineering countries showed that the beam-column joints represent the most sensitive component of precast structures. Beam-column joints able to provide full bending moment continuity are necessary in precast concrete structures to increase the lateral stiffness, strength and redundancy. In Romania, the intermediate depth Vrancea earthquakes generate large lateral displacements of structures. Stiffer structures are necessary to accommodate the serviceability requirements under large lateral displacements. A suitable way to increase the lateral stiffness of the precast structures while preserving the cross-sectional dimensions of columns is the use of rigid beam-columns joints.

In this paper, some results of an experimental testing program on rigid beam-column joints are presented. In this program, the continuity of the longitudinal reinforcement from precast beams to the beam-column joints is achieved using grouted sleeves and threaded bar couplers. Four precast beam specimens were tested under cyclic bending and shear using a quasi-static loading protocol. The obtained results were compared to the behavior of a reference “monolithic” specimen. All the specimens have the same geometrical properties. The beams were 2000 mm long and had a cross sectional area of 300 mm x 400 mm. They were embedded in an anchorage bulb of 900 mm x 500 mm x 500 mm. The specimens were tested in an upright position as vertical cantilevers with no axial load. Experimental data was digitally acquired using displacement transducers and strain gauges.

The tests results showed that the jointing solution has suitable strength and proper hysteretic behavior.

The jointing solution was developed by design department of the precast construction company Bauelemente SRL, in accordance with the available construction technology for precast building with large openings. This solution is currently being applied to assemble precast buildings in Romania.

The structural testing was carried out using the equipment donated by Japanese Government through the Japanese International Cooperation Agency within the Technical Cooperation Project for Seismic Risk Reduction in Romania. This generous support is deeply acknowledged.

Keywords: precast concrete, experimental testing, emulative connections, grouted sleeves, threaded couplers

1. Introduction

In advanced earthquake engineering stiffer, stronger and more ductile structures are required to comply with the continuously increased seismic design requirements. In case of precast structures, the use of rigid beam-columns joints is necessary to attain the necessary lateral stiffness and strength.

The high lateral displacement demand caused by the intermediate depth Vrancea earthquakes in Romania generates the need for rigid beam-column joints in precast concrete structures. There are worldwide detailing solutions to achieve the continuity of the longitudinal reinforcement in the joint area. The applicability of these solutions should be analyzed considering the available technologies, materials and workers skills at a given site.

To be able to use a given jointing solution for beams and columns at a given site, the following requirements should be considered:

- to be installed at most by 2 workers;
- to necessitate little or no formwork and limited volumes of fresh concrete or mortar;
- to require limited time for installation;
- to allow rigid connections in both horizontal directions;
- to allow the transfer of the full bending moment from the beam to the joint;
- to assure a stable hysteretic behaviour at full loading reversals;
- to allow the formation of the plastic hinges in beams and columns with the joints responding in the elastic range.

One jointing solution for beams and columns with full moment continuity for precast structures with monolithic slabs is presented in Figure 1. This solution was conceived by SC Bauelemente SRL, one of the largest precast companies in Romania.

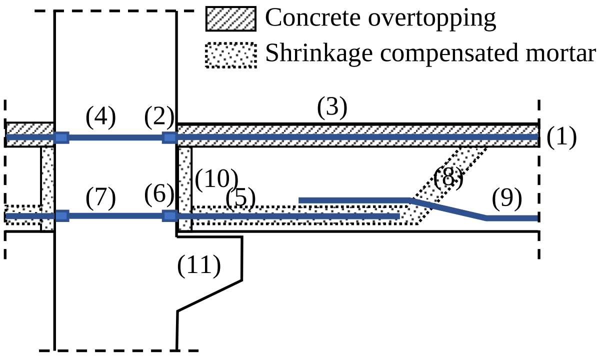

Fig. 1 – Schematic representation of the jointing solution [1]

The top longitudinal reinforcing bars (1) are sited in the layer of monolithic concrete (3) and jointed with the rebars crossing the precast column (4) using threaded mechanical couplers (2). These are previously installed in the precast column.

The bottom longitudinal rebars are jointed using a two steps solution:

- horizontal starter bars (5) are connected to the rebars crossing the precast column (7) using mechanical threaded couplers (6) which were previously installed in the column;
- the starter bars (5) are connected to the precast beam bottom rebars (9) using grouted sleeve connections (8), outside the plastic hinge of the beam – corrugated steel sleeves are inserted into the beam before casting of concrete and shrinkage compensated mortar is injected to achieve the continuity of the reinforcement.

To get a full contact between the precast beam and the precast column, a 15 cm layer of shrinkage compensated mortar (10) is casted at the interface. The minimum thickness of the mortar layer is determined based on technological conditions i.e. to allow screwing of the bottom starter bars into the threaded couplers.

In the case of beams that transfer large shear forces, corbels (11) can be provided in the columns to favor the full and safe transfer of the shear force from the beam to the columns. These corbels are useful as well during the construction, serving as temporary support for the beams.

The advantages of this system are:

- is an emulative connection with full transfer of the forces from the beam to the column;
- allows the full connection of the precast beams with limited length monolithic areas;
- is cost effective;
- can be installed with locally available materials and technology;
- requires commonly trained workers;
- simulates common details from monolithic frame structures which are trusted by designers of concrete structures in seismic areas.

The optimal hysteretic behavior and the emulative characteristic of the corrugated steel grouted sleeves connections was previously demonstrated by the authors [2, 3].

2. Experimental testing program

An experimental testing program on precast beam-column joints has been carried out to determine the hysteretic behavior of beam-columns joints. The experimental testing program was performed by the Seismic Risk Assessment Center (CERS) in the Technical University of Civil Engineering of Bucharest in cooperation with SC Bauelemente SRL. 5 precast specimens have been tested under full lateral deformation reversal cycles.

Each specimen was T shaped and consisted of a beam embedded in an anchorage zone. The total length of the specimen was 2500 mm. The beam length was 2000 mm and the anchorage bulb width was 500 mm. Cross section of the beam was 400 mm x 300 mm, with the longer side parallel to the direction of loading. The overall dimensions of the anchorage bulb were 900 mm x 500 mm x 500 mm.

Concrete class C50/60 [4] was used for all specimens. Deformed steel rebars with S500 quality steel, ductility class C according to SR EN 1992-1-1:2004 [4], were used. The expected characteristic yield strength is 500 MPa and the design strength is 435 MPa [4].

The testing specimens were built by jointing two prefabricated pieces (the anchorage bulb and the beam) using the solution previously described. These elements are subsequently called in this paper as “precast specimens”. A reference specimen was built as a monolithic beam-joint assemblage with continuous beam longitudinal rebars directly anchored in the bulb.

The differences between the precast specimens were given by the longitudinal reinforcement solution, in terms of the tensioned reinforcement percentage and the rebars diameters and by the presence of the corbel used for the direct transfer of the reaction force from the beam.

The longitudinal reinforcement solutions for the tested specimens were established in order to have similar reinforcement percentages with those of the beams used in real prefabricated structures with monolithic RC plate. A percentage of 0.86% was adopted for the top reinforcement while for the bottom rebars the longitudinal percentage was only 0.42%. This substantial difference is because the prefabricated beams that are the subject of this experimental study have large openings and, consequently, the moments from gravitational loads are relatively large compared to those from seismic loads. Thus, in the relevant seismic design combination, there is a substantial difference between the positive and negative bending moments in the section adjacent to the column. So, the specimens BAU1, BAU2 and BAU3 were reinforced with 3 rebars D20 at the top, in the monolithic zone, and 3 rebars D14 at the bottom side of the beam. Hence, the effective longitudinal reinforcement coefficients are higher than the minimal values prescribed by the European and Romanian seismic design standards [5,7]. The specimen BAU4 was symmetrically reinforced with a longitudinal reinforcement of 3D14 on both sides, scaling the real pattern of a secondary beam in precast structure with rigid joints (subjected only to horizontal loads)

Currently, however, due to the large bending moments that develop near the column, the prefabricated beams that are the subject of this study are reinforced with large diameter rebars (for example, 25 mm or 28 mm). However, scaling the specimens implies the use of smaller rebars (14 mm). And, given the relatively high concrete strength, the use of smaller rebars may alter the cyclic behavior of the tested beams. Therefore, the fifth specimen (BAU 5) has been introduced in the test program. Having a symmetrical reinforcement of 2 D25 mm on both sides, this specimen was designed to assess the influence of the rebar diameter on the hysteretic behavior of the tested elements.

The transverse reinforcement was made with D8 mm perimeter stirrups spaced at 50 mm in the critical zone near the bulb and at the opposite end, while the spacing between stirrups in the middle zone of the beam was 150 mm. Thus, the percentage of transverse reinforcement in the critical zone is 0.67% and 0.22% in the current zone. These are common values for the prefabricated beams that are the subject of this study. Deformed steel bars with S500 quality steel, ductility class C according to SR EN 1992-1-1:2004 [4], were also used for transversal reinforcement.

The reinforcement layout of the specimen BAU3 is shown in Figure 2.

In order to assess the influence of the corbel on the hysteretic behavior of the beams in the critical zone, the specimen BAU2 was constructed with a short corbel located at the intersection between the bulb and the beam.

The distinctive characteristics of the tested specimens are presented in Table 1.

Table 1 – Characteristics of the specimens

Name	**Type**	**ρ (-)**	**ρ % (+)**	**Top rebars (mm)**	**Bottom rebars (mm)**	**Cantilevers**
BAU1	Monolithic	0,86%	0,42%	3D20	3D14	No
BAU2	Precast	0,86%	0,42%	3D20	3D14	Yes
BAU3	Precast	0,86%	0,42%	3D20	3D14	No
BAU4	Precast	0,42%	0,42%	3D14	3D14	No
BAU5	Precast	0,89%	0,89%	2D25	2D25	No

For each specimen, the test was conducted in the plane generated by the longitudinal axes of the beam and the supporting bulb. Out-of-plane displacements were restricted by the testing equipment. Transverse displacements were applied at the free end of the beam, while the rotation of the anchorage bulb was restricted. The specimens were tested in the upright position, with the anchorage bulb at the bottom. The general loading scheme is shown in Figure 3.

Quasi-static displacement-based control was used to apply cycles of transverse displacements reversals. The loading speed was low and did not generate significant inertia forces. The beam was not axially loaded during the test. The transversal force was applied using two horizontal 100tf hydraulic jacks. The loading protocol included a cycle for a general rotation of 0.0025 rad followed by two cycles for each maximum rotation of 0.005 rad, 0.01 rad, 0.02 rad, 0.03 rad and 0.04 rad. The upper limit value of 0.04 rad for the maximum rotation was imposed by the technical constraints of the testing equipment corresponding to the maximum stroke of the horizontal hydraulic jacks. The loading protocol was established in accordance with international practice [6].

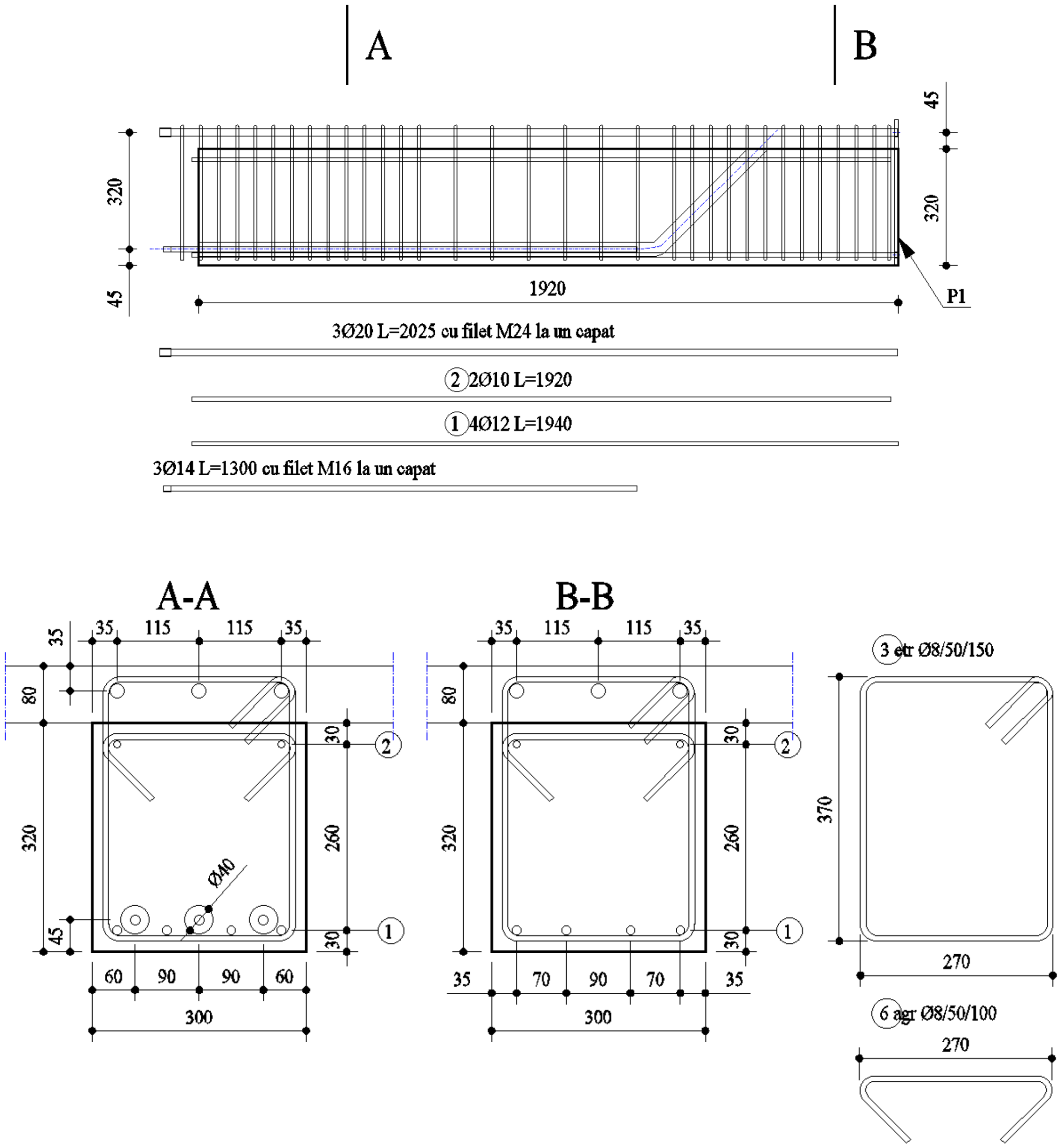

Fig. 2 – Specimen BAU3 – detailing solution [1]

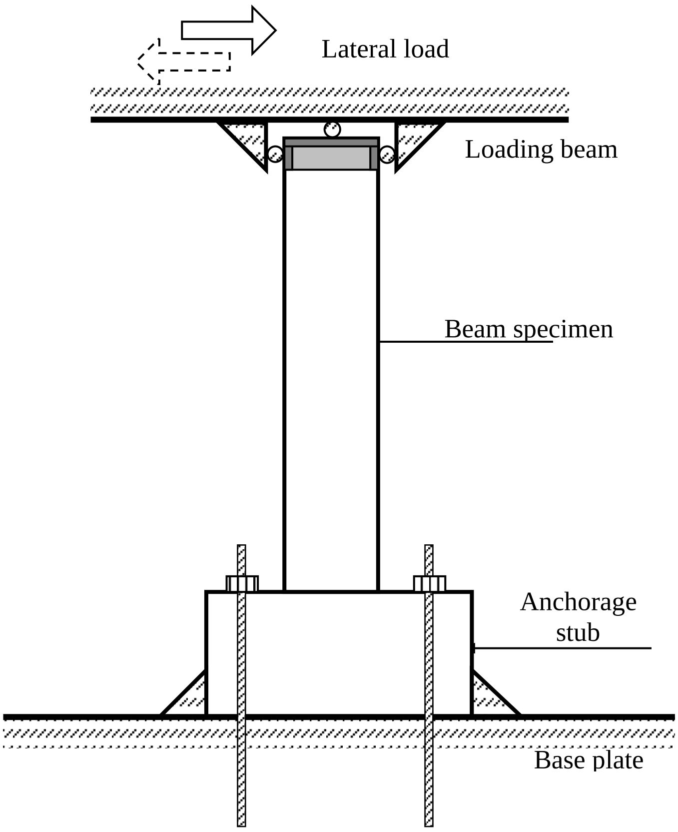

Fig. 3 – Loading system [1]

Fig. 4 – Reaction frame [1]

The experimental tests were performed using the reaction framework of the Seismic Risk Assessment Center of the Technical University of Civil Engineering of Bucharest (Figure 4). The testing equipment has computerized loading control and data acquisition systems. It was donated by the Japan International Cooperation Agency (JICA) within the Romanian-Japanese seismic risk reduction project.

The forces were measured using load cells installed on the ends of the hydraulic jacks. The displacements were recorded through digital transducers. In order to determine the deformations in the steel bars, strain gauges were installed on both the longitudinal rebars and on the stirrups. All measurements during the tests were monitored and stored using an automatic data acquisition system.

2. Preliminary results

The reference specimen BAU1 was subjected to loading cycles, according to the adopted loading protocol, up to a rotation value of 0.03 rad. Subsequently, the loading was carried out on a semi-cycle until the rotation of 0.04 rad (4%). Then, the test was interrupted due to some limitations of the testing equipment. There was no failure of the specimen. The damage state is moderate (Figure 5, a). The recorded hysteretic response is stable (Figure 6, a).

The precast specimen BAU2 had a stable hysteretic behavior up to ± 3% loading cycles (Figure 6, b). The recorded strength capacities were similar to the reference specimen. Within the first loading cycle to -4% there was a tensile fracture of a D14 mm diameter rebar. The mechanical threaded couplers ensured the transfer of the efforts between the longitudinal rebars.

The precast specimen BAU3 showed a stable hysteretic behavior up to ± 3% (Figure 6, c). The recorded hysteretic loops are close to those of the reference element. During the first loading cycle towards -0.04 rad, all the rebars with D14 mm diameter failed successively in tension and the loading was stopped. The observed damaged state was similar to specimen BAU2, (Figure 5, c).

For precast specimen BAU4, the expected hysteretic behavior was recorded until complete loading cycles were performed at ± 0.01 rad (Figure 6, d). During the second loading cycle to +0.02 rad, one longitudinal rebar D14 mm slipped from the threaded coupler. In this case, two wide-open cracks were observed at the interfaces between the mortar layer and the prefabricated elements (Figure 5, d).

For specimen BAU5, the stable hysteretic behavior was observed throughout the test, until both loading cycles at 0.04 rad were completed (Figure 6, e). The response of the element was governed mainly by the bending moment and, secondarily, by the shear force. There was no significant strength degradation. The stiffness degradation was within acceptable limits. The hysteretic loops are symmetrical, but there was a pronounced slipping caused by the absence of the axial compressive force. At -0.04 rad, the degradation state is moderate (Figure 5, e).

Apart from the element BAU4, all tested specimens exhibited a stable hysteretic response at ±3% loading cycles. However, tensile failure of the rebars due to the localized plastic deformations is not suitable for seismic applications. It is necessary to take appropriate measures to increase the length where the longitudinal bars are severely yielding, thus reducing the average elongation. Such measures may consist in suppressing locally the bond of concrete to rebars. Likewise, the use of large diameter rebars favors a progressive bond failure near the crack allowing the steel bars to yield also in the zones near the section with maximum bending moment.

The specimen BAU5 responded optimally to cyclic loading without significant strength degradation for the ± 0.04 rad loading cycles. The moderate damage state observed at the end of the test shows that the solution adopted for this specimen is appropriate for seismic applications with significant plastic rotation requirements. This stable hysteretic behavior of the prefabricated elements reinforced with large diameter rebars has also been validated by experimental studies in the same laboratory [2].

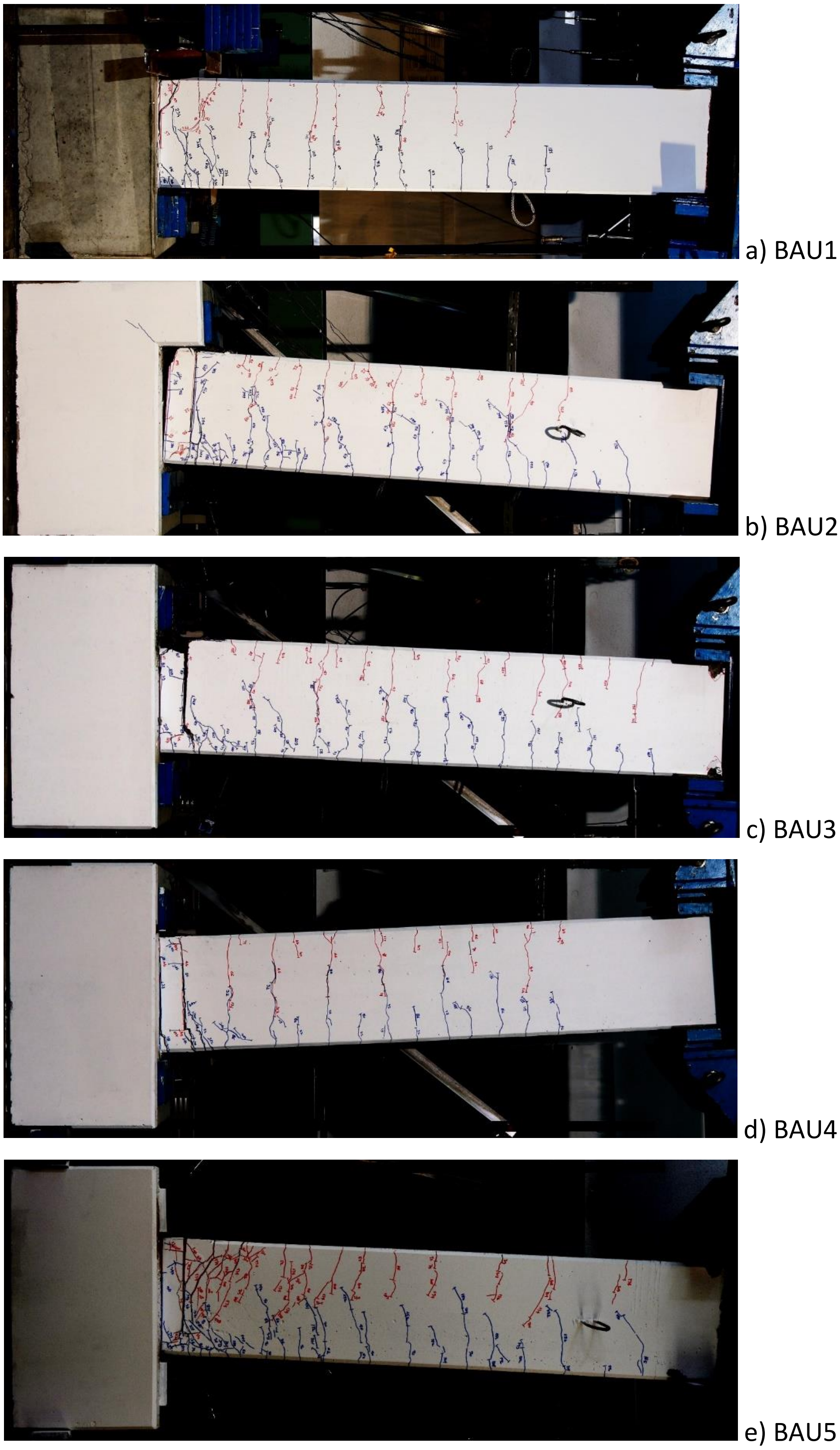

Fig. 5 – Damage state of the specimens at maximum lateral displacement

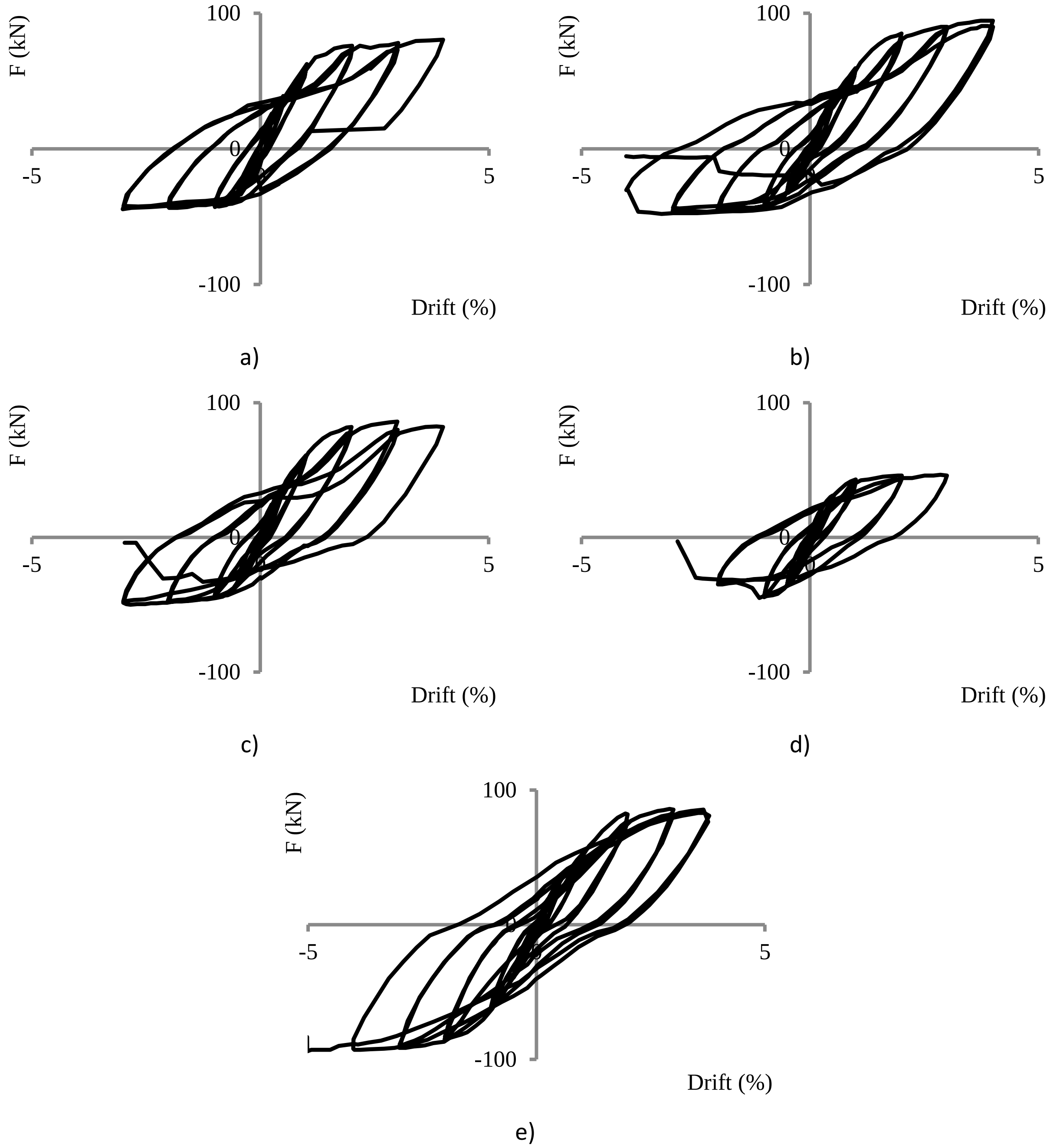

Fig. 5 – Hysteretic force-displacement response

5. Conclusions

Creating rigid joints between prefabricated beams and columns is a necessity of the prefabricated industry and a challenge for structural engineers. The experience of previous earthquakes in countries with advanced seismic engineering shows that the joints between beams and columns can represent the weak link of the prefabricated structures when subjected to strong seismic actions. The high displacement requirements associated to earthquakes from the Vrancea source require structures with high lateral stiffness. Creating rigid joints allows maintaining the dimensions of the precasted elements within acceptable limits. Therefore, the structural engineers and the companies in the prefabricated industry must develop solutions for beam-column joints complying with the specific functional requirements, the locally available technologies and the particular rotation demands caused by the medium depth earthquakes from the Vrancea source.

Experimental testing programs on locally developed solutions for rigid beam-column joints is a necessary approach and a helpful resource to evaluate their hysteretic behavior.

From the preliminary analysis of the experimental data recorded in this study, the following conclusions can be drawn:

(a) The proposed solution for the rigid joint used in this study allowed the prefabricated specimens to achieve the same stiffness and strength under horizontal loading cycles as those of the monolithic element.

(b) A distributed cracking was observed for the monolithic element. Normal and inclined cracks appeared with openings that gradually decreased as the cracks were further away from the fixed end of the specimen.

(c) In the case of the prefabricated specimens, the bending cracks were mostly concentrated at the interface between the prefabricated parts (beam and bulb) and the mortar layer.

(d) When small diameter rebars were used the longitudinal reinforcement failed in tension because the steel bars yielded only in the two wide-opened cracks developed under and above the mortar layer, allowing the rigid joint to fail at a relatively small rotation.

(e) The behavior of the prefabricated specimen was fundamentally changed when large diameter rebars were used. The thicker steel bars were more compatible with the high strength concrete which is largely used in the prefabricated industry and allowed the plastic deformations to extend beyond the mortar layer.

(f) The use of grouted sleeve connections allows for a proper overlapping of the longitudinal steel bars subjected to cycles of post-elastic deformations.

(g) The mechanical couplers used in this study had the ability to transfer the forces between the longitudinal rebars even to high values of the plastic rotations of the beams associated with the design for DCH ductility class as defined in EN 1998-1.

(h) The adequate connection between the concrete overtopping and the prefabricated beam was able to provide a monolithic behavior for the tested elements.

(i) The corbel used for the direct transfer of the shear force did not significantly change the response of the rigid connection for rotations lower than 0.03 rad.

This paper describes the preliminary results of an experimental testing program on rigid beam-column joints. The results and conclusions will be published after analyzing all the recorded data.

5. Acknowledgements

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