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Beam-column joints in continuous RC frames: Comparison between cast-in-situ and precast solutions

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ABSTRACT

The use of precast reinforced concrete elements is rapidly increasing since this technique has several advantages over traditional cast-in-situ structural members such as lower manufacturing time and costs and a better quality control. Nevertheless, cast-in-situ solutions intrinsically allow building moment-resisting frames, a behavior that is usually hard to achieve using precast elements. In this paper a technical solution able to offer both high strength and ductility, simplicity of construction of the prefabricated elements and ease of assembly on site is presented. The solution realizes the continuity between beam and column by means of loop splices and cast-in-place concrete with steel fibers to improve the ductility of the concrete struts in the wet joint. The connection has been experimentally tested and compared to an analogous cast-in-situ one. The experimental results confirmed its good structural performances in terms of strength and ductility. Numerical investigations tuned on the basis of the experimental results allowed the improvement of the design to achieve reduced column damages for higher drift values while maintaining practically unchanged structural performances.

1. Introduction

Precast reinforced concrete techniques are increasingly replacing the cast-in-situ reinforced concrete solutions. This can be ascribed to the remarkable advantages that the prefabrication offers against traditional techniques such as the better quality of the components made in the workshop, the lower manufacturing costs, the possibility of realizing the precast components even in adverse weather conditions and the speed of construction. The cast-in-situ structures possess, however, the advantage of providing continuous frames intrinsically resistant to bending moment. This behavior should, instead, be specifically created in the prefabricated structures. Hence the choice of the right technology for the precast system is of major importance and the aim, for the designer, is to obtain a solution that is capable of obtaining the required performances in terms of load bearing capacity and ductility while minimizing construction manpower, time and costs. A number of technical solutions have been proposed for this purpose in the past, mainly focusing the attention on the load bearing capacity of the connection system. This study presents a technical solution able to offer both high strength and ductility in the plastic range, simplicity of construction of the prefabricated elements and ease of assembly on site. The comparison of cyclic tests with imposed displacements up to a drift ratio of 3.5% on a couple of external beam-column joints allowed verifying the structural behavior of the prefabricated solution. The results of the experimental tests showed a seismic performance of the prefabricated joint very similar to that of the 'twin' cast-in-place joint. A sophisticated arrangement of sensors has also allowed to analyze in detail the behavior of both technological solutions. Finally, FE analyses tuned on the results of the experimental tests have been used to improve the design of the precast joint moving the critical region outside the connection zone without reducing stiffness, strength and ductility of the joint.

2. Literature review on beam-column joint in precast structures

The first researches on beam-column joints have been carried out, obviously, with reference to cast-in-situ joints.

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Paulay et al. [1] were among the firsts to investigate the behavior of interior beam-column joints under seismic actions. They highlighted the existence of two shear resisting mechanisms, one involving joint shear reinforcement and the other the concrete strut. Based on extensive experimental results carried out in more than 15 years, Paulay [2] demonstrated the disposition of internal forces with diffuse diagonal cracking of the concrete core and that joint shear reinforcement is necessary to sustain a diagonal compression field rather than providing confinement to the compressed concrete in the joint core.

Later on, similar research efforts have been provided also for precast structures. In this case the importance of connection detailing for structures subjected to severe seismic action emerged since the beginning of the 90s and different technical solutions have been proposed for the beam-column joints.

A wide joint research project called PRESSS was carried out by researchers from the United States and Japan on the seismic design and performance of precast concrete structural systems [3]. The objectives of this program were the development of effective seismic structural systems for precast buildings and the preparation of seismic design recommendations for incorporation in the building codes. The attention of U.S. researchers was focused on ductile connections capable of protecting the precast elements against inelastic deformations by means of a capacity design while the Japanese program was concentrated on the strong-connection approach. The results of the research project were pointed out by Priestley et al. [4].

Restrepo et al. [5] tested six types of subassemblages of moment resisting frames located at the perimeter of buildings. Connections between the prefabricated elements were realized at beam midspan or at the beam-to-column joint region with cast-in-place concrete. The experimental results showed that the connection details can be successfully designed and constructed to emulate cast-in-place construction.

Priestley and MacRae [6] tested two ungrouted post-tensioned, precast concrete beam-column joint subassemblages under cyclic reversals of inelastic displacements to determine their seismic response. The test units were designed with greatly reduced beam and joint shear reinforcement compared with equivalent monolithic joints, but implementing a special spiral confinement of the beam plastic hinge regions. Both subassemblages performed well, with only minor cosmetic damage being recorded up to drift ratios of 3% or more. Energy absorption of the hysteretic response, though small, was larger than expected. A very low residual drift was observed after a severe earthquake. This is a characteristic of the unbonded prestressing system and is a significant advantage over conventional cast-in-place reinforced concrete construction, where very high residual drifts generally occur. It was concluded that satisfactory seismic performance can be expected from well-designed ungrouted precast, post-tensioned concrete frames.

Two full-scale beam-to-column connections of a precast concrete frame were designed, following the strong-column weak-beam concept, and tested by Alcocer et al. [7] under unidirectional and bi-directional cyclic loading. Conventional mild steel reinforcing bars, rather than welding or special bolts, were used to achieve beam continuity. Test results showed that the performance of both beam-column connections was roughly 80% of that expected from monolithic reinforced concrete constructions with a ductile behavior due to hoop yielding. Bar pullout and strength values were nearly constant up to drifts of 3.5%.

Korkmaz and Tankut [8] tested six 1/2.5 scaled beam-beam connection subassemblies under reversed cyclic loading. The first specimen was a monolithic one used as reference. The others were precast specimens composed of a middle precast beam placed between two cantilever beams connected to the columns. The connection between the precast elements region was obtained by lap splicing of the top reinforcement and welding between the steel plates anchored to the bottom of the middle and cantilever beams. Cast-in-situ concrete on the top of the beams completed the connection. The results of the tests allowed recognizing that this connection detail was not suitable for seismic use. Proper modifications to obtain significant performance improvements have been subsequently proposed and tested by the Authors.

A similar solution has been proposed also by Ong et al. [9] who used the DfD (Design for Disassembly) method to increase material reusability in the construction industry, allowing the reuse of the structural components after the decommissioning of the structure instead of their demolition and recycling of the resulting debris. Parastesh et al. [10] tested a new ductile moment-resisting beam-column connection capable of providing good structural integrity in the connections and reduced construction time. Their solution eliminated the need for formworks and welding and minimized cast-in-place concrete volume by realizing a discontinuity in the column filled by the cast-in-situ concrete.

A wide research project, SAFECAST [11,12], has been recently completed by the Joint Research Center of the European Commission. In this project a full-scale three-storey precast building was subjected to a series of pseudodynamic tests to evaluate the behavior of various parameters like the types of mechanical connections (traditional as well as innovative) and the presence or absence of shear walls along with the framed structure.

2.1. Classification of precast beam-column connections

Nowadays connections between precast beams and columns can be separated into three main classes: dry, hybrid and wet connections.

The mechanical connections made with steel elements and bolts belong to the dry class. Among these connections are those tested by Vidjeapriya and Jaya [13]. The Authors carried out tests on two types of simple mechanical 1/3 scale concrete beam-column connections realized with cleat angle with 1 or 2 stiffeners, subjected to reverse cyclic loading. The results of the tests were then compared with the performance of a reference monolithic beam-column connection. The Authors observed that ultimate load-carrying capacity of the monolithic specimen was superior to that of both precast specimens, while satisfactory behavior of the latter was found in terms of energy dissipation and ductility.

Hybrid connections are those where mechanical connections and cast in situ concrete are used at the same time. Hybrid connections have been tested by Choi et al. [14], Ong et al. [9]. Sometimes with the same term has been indicated a combination of mild steel and post-tensioning steel where the mild steel was used to dissipate energy by yielding and the post-tensioning steel was used to provide the shear resistance through friction developed at the beam-column joint [15].

Wet connections are generally made up of rebar splices and cast-in-situ concrete. Among the different types of rebar splices, very good mechanical properties have been shown by loop splice connections. Several studies showed that the mechanical behavior of this type of joint, if properly designed, can be considered similar to that of ordinary RC elements [16,17]. Moreover, the use of loop splice is also frequently used in practice to establish continuity between precast deck elements in steel-concrete composite bridges [18].

Since the beginning it was recognized the usefulness of steel fibers to develop ductile moment resisting wet connections designed to act as a plastic hinge during earthquakes [19]. High performance fiber reinforced cement composite (HPFRC) matrix was used to develop a high energy absorbing joint for precast/prestressed concrete structures in seismic zones reducing the amount of transverse reinforcement in the connection by using steel fibers