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Experimental and numerical investigation of the static performance of innovative prefabricated high-strength composite columns

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ABSTRACT

An innovative high-performance precast beam-to-column joint for multi-storey framed structures is introduced. The proposed solution consists of coupling between Composite Steel Truss Concrete (CSTC) beams with a concrete base and High-Strength Concrete (HSC) columns. This paper focuses mainly on the static performance of prefabricated HSC columns, including experimental and numerical investigations. The finite element model of the structural system is calibrated on experimental static testing evidence. On the basis of the data collected, the finite element model is used to evaluate the strength domain of members and optimize the related coupling system between columns. Aiming to limit time-consuming analyses and provide practical rules for design, an analytical simplified procedure is introduced to compute the assembly's strength domain. An analytical approach is adopted to estimate the reference design strength for the considered composite columns, accounting for the partial safety factor imposed by codes and allowing for estimation of the limit on the number of storeys for frames adopting the proposed precast technology.

1. Introduction

The use of prefabricated concrete components and their related coupling systems in seismic engineering constitutes a subject of wide and deep interest among researchers, practitioners and manufacturers all over the world. As demonstrated by a large number of studies conducted in numerous countries, especially in Japan, New Zealand and the United States since the early 1980s and, in relatively more recent times, in Italy.

The reference layout for traditional precast structures is the 1- to 3-storey gravity-resisting frames assembled by monolithic columns fixed at the base and free at the top, with pinned beams resting on corbels, sometimes strengthened with a shear panel.

In the mentioned countries, both academia and research have provided viable alternatives to this typical precast layout. Proposed solutions range from an emulative approach, namely, moment-resisting frames assembled with trough monolithic precast elements joined together with cast-in-place concrete, to a dry-connection approach, namely, frame connection based on a rocking effect, joined together through tendons or damping devices [1–7].

Cast-in-place emulative technology is mainly developed in New Zealand and Japan during the 80s and consists of a capacity-design-approach applied to precast structures. Connections are designed to restore the performance of the equivalent monolithic system [8]. Details of different types of connections have been discussed extensively by Park [9] and FIB Bulletin 43 [10] and more recently by Bhatt and Kirk [11], Seckin and Fu [12], and French et al. [13,14].

Opposite to emulative is the dry joint precast approach, which consists of a moving inelastic response from members to connections. These are detailed to be weaker than the precast elements and are intended for locations of inelastic deformations [15]. As consequence, the precast members should not be detailed for ductility and should remain elastic during seismic action. A major advantage of a dry-jointed connection system is the reduction of scheduling conflicts between construction phases related to in-place concrete casting and strengthening. This is just a finishing phase and is not required to get structural strength and stability during the assembly process.

Conversely, in Italy and more generally in Europe, the typical precast skeleton structure has long been adopted, and this same solution is still widely adopted at present [16]. Considerable research effort in Europe has been devoted in the last decade to investigation of the seismic performance of those types of industrial buildings, as tested by

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the project PRECAST STRUCTURES EC8, which concluded in early 2007 after 4 years of activity. The project SAFECAST, aiming to design dry connections between members and study their contributions to the structural global behaviour [17–19].

A key issue of research on precast concrete still remains, that is, the possibility of applying the typical benefits of the pre-fabrication in areas characterized by medium to high seismic intensity. Not only to low-rise industrial or commercial structures but also to multi-storey frames for public and strategic buildings, such as schools, hospitals and many others, as well as to high-rise residential premises [20,21].

The research activity presented in this paper aims to provide a positive contribution to this topic through the proposal of an innovative hybrid high-performance precast beam-to-column joint for multi-storey framed structures, characterized by a modular assembly process that is less dependent on the construction phases.

To verify the effectiveness of the proposed precast technology, the conducted research activity consists of two complementary approaches. First is an experimental phase that aims to improve knowledge of the behaviour and resisting mechanisms of the joint, owing to an innovative layout and a lack of analogous reference experiences from the literature. Afterwards, a numerical and analytical study phase, to evaluate the components' strength domains, optimizes structural components and defines the design rules.

This paper focuses on the static performance of the system. Both the experimental and numerical results reported address evaluating the static axial capability of High Strength Concrete (HSC) columns.

2. Description of the system

The major advantage of dry-jointed connection systems over monolithic ones is the reduction of scheduling conflicts between construction phases related to in-place concrete casting and strengthening. This is just a finishing phase and is not required to obtain structural strength and stability during the assembly process. Hence, the challenge faced during the design phase of the new precast system consisted of making the assembly process less dependent on the construction phases than typical emulative precast technologies, taking inspiration from the dry-jointed system approach, without surrendering ease of assembly and structural performance.

Fig. 1 shows the manufacturing process of high strength composite columns. Concrete columns are made by centrifuged HSC class C75/90, casted through a process that leads to the typical ovoid section. HSC allows for high bearing capacity with limited overall section dimensions (330 by 550 mm) and consequent maximization of the commercial or saleable space. The precast process of these members is highly standardized and automated, thus containing manufacturing costs, though the base materials are of high quality. As a first step, the single-storey column-skeleton is assembled by welding two end-flanges (steel grade S355) at both ends on 8 longitudinal rebars (steel grade B450) (Fig. 1a–d) and coiling up ϕ6 stirrups to complete the reinforcement cage (Fig. 1e).

Short column elements are easier to transport, handle and raise. The best compromise is found in the adoption of single- or double-storey columns (Fig. 2), with voids at the inter-storey level. Such portions of the column are referred to as Steel Core Joints (SCJs) and allow beams to rest in the temporary phase. Bolted connections at the two ends of the column provide structural continuity for the vertical columns and complete the layout of the presented precast columns. Moreover, all horizontal flanges present a central hole (120 mm in diameter) designed for the HSC centrifuged casting process, which is later performed on formwork specifically designed for this purpose (Fig. 3).

The horizontal structural element of the proposed joint is constituted by a Steel Truss Concrete (CSCT) beam with a concrete base. Such a precast solution is introduced in Italy in the 1970s, while it is currently widely adopted and is spreading rapidly even outside Italian borders. Moreover, the Italian Superior Work Council has recently released specific instructions for the design of these components, which are fully comparable to steel-concrete composite elements, removing any limitations for their employment in seismic regions [22]. Among the benefits provided by CSTC beam technology, some are here recalled: high bearing capacity, high mounting speed thanks to unpropped erection, and limited costs owing to a high prefabrication level. Furthermore, as a concrete base section is adopted for CSTC beams, good fire strength is also provided.

On-site column assembly of CSCT beams is straightforward: the asymmetrical layout of vertical steel plates belonging to SCJs enables convenient beam accommodation (Fig. 4), drastically reducing construction tolerance issues and increasing construction speed. During the temporary phase, CSCT beams rest in a simple support scheme without the need for temporary scaffolding (Fig. 5a). To restore beams' longitudinal continuity through the joint, specifically designed lateral Steel Lattice Girders (SLGs, highlighted in red[1] in Fig. 5b) are finally provided. Finally after placement of the floor slabs (Fig. 5c), the concrete is casted to make the assembly monolithic (Fig. 5d).

The proposed precast system can be classified as a hybrid solution since it adopts both wet and dry connection approaches: cast-in-place concrete to provide structural continuity to the horizontal beams and dry bolted-joints for the columns. This strategy guarantees the overall ease of construction with reduced tolerance problems and self-bearing capacity during construction phases, with a consequent reduction of scheduling conflicts between construction phases and favourable consequent economic impacts on construction time and costs. Fig. 6 shows one parking garage where this type of prefabricated high-strength composite column is used. The authors have also investigated the cyclic behaviour of CSTC beams connected by HSC columns through experimental and numerical simulation methods [23]. The results showed that, despite the absence of lateral reinforcement, the beam-to-column joint specimens showed an acceptable ductility.

The proposed joint layout appears extremely tidy, avoiding reinforcement congestion typical of reinforced concrete frames or other precast solutions; the modularity of the precast components allows a low-storey frame to be assembled with the same ease as a taller one.

The total self-bearing capacity and mounting ease of the proposed solution make rapid all-weather erection possible, even by unskilled labours, contributing to the final cost reductions. The quality of the adopted materials and smartness of the final joint layout make this solution suited not only to multi-storey industrial or commercial structures and multi-storey parking garages but also to multi-storey frames for municipal facilities and strategic building, such as schools, hospitals and many others, and even high-rise residential structures in areas of medium to high seismic intensity. Despite the high quality of the base materials, the final cost is comparable to that of equivalent RC structures thanks to the high automation level during the manufacturing precast process and the on-site mounting ease.

3. Experimental tests

3.1. Test specimen design

The innovative layout of the presented precast system and the lack of similar reference experiences in the literature required experimental tests to appraise the resisting mechanisms of the proposed HSC system. It is very important to investigate the response of the joint in all the phases and particularly understand the contribution of each structural element to the joint response. A detailed finite element model simulation performed at the beginning of the research confirmed that it was necessary to understand better the flow of vertical forces between the concrete column and the steel flanges of the joint, and that a great

[1] For interpretation of color in Figs. 5 and 21, the reader is referred to the web version of this article.