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Seismic design and performance of dry-assembled precast structures with adaptable joints

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ABSTRACT

Previous research projects and post-earthquake field observation showed that dry-assembled precast frame structures with hinged beams and cantilever columns restrained at their base, if correctly designed and detailed, can attain good seismic performance, mainly due to their flexibility and robustness. Their seismic design is often conditioned by the need of reducing their flexibility by increasing the cross-section of the columns, which, due to minimum reinforcement requirements, results in their over-strengthening. High flexibility may also induce displacement compatibility issues with non-structural elements. The paper concerns the proposal of an innovative enhanced structural frame system, based on the adaptation of hinged beam-column joints into rigid through the activation of special mechanical connection devices performed after the installation of the slab. While keeping all the benefits of the dry prefabrication, the resulting moment-resisting frame is provided with enhanced redundancy and stiffness. A design comparison among three precast frames with similar geometries and different static schemes shows how the joint adaptation can be exploited to optimise the structure by modifying the distribution of bending moment. The results of dynamic non-linear analyses on a three-storey precast structure with adaptable joints tested as a part of the SAFECAST research programme show the seismic performance of this system through different static schemes, and the comparison with the experimental results provides information about the validity of the models and the effectiveness of the technological solutions employed.

1. Introduction

Dry-assembled precast frame structures with hinged beams and cantilever columns restrained at their base are extensively used in Europe and in several other regions of the globe mainly for single-storey or low-rise multi-storey either industrial or commercial buildings.

Wet-assembled partially precast structures are designed to emulate cast-in-situ concrete structures with rigid connections through in-situ concrete pouring of the joints, usually provided with rebars that protrude from the precast members. On the contrary, dry-assembled precast structures are connected by mechanical devices avoiding in-situ concrete pouring. Conventionally, dry-assembled joints also include semi-dry connections, which need in-situ casting of a small volume of special mortar for completion. Dry-assembled precast frame structures maximise the benefits of the prefabricated construction technique. Typical structural layouts and details of this type of structures are available in [1,2].

Over the last two decades an extensive research activity aimed at investigating the seismic behaviour of precast concrete frame structures [3] allowed a good knowledge of the seismic behaviour of precast systems to be consolidated and contributed to the achievement of outstanding realisations in terms of both quality and reliability [4]. The results from both analytical and full-scale experimental investigations showed that these precast systems (I) are characterised by an intrinsic large flexibility coming from their peculiar traditional static scheme with hinged beam-column joints [3,5–7]; (II) can provide comparable energy dissipation capacity/seismic performance as cast-in-situ systems if the connections are properly designed and drift limitations and other minimum requirements provided by structural standards are respected [3,8]; however, (III) quite often the flexibility limitation requirements govern, resulting into larger column cross-sections than those strictly needed to resist the seismic forces for the assumed global ductility level [6]; in such case, (IV) minimum reinforcement requirements impose large over-strength in the columns, so that (V) while the structures possess adequate safety levels, they often behave elastically or in the range of low ductility even under the ultimate design seismic action, not fully exploiting the energy dissipation resources of the column [6,9].

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This raises the problem of the capacity of the connections, in particular for multi-storey buildings [10], and the compatibility of displacements with possible interacting non-structural members, for instance the cladding panels [11–15], which caused quite extensive failures in the last strong earthquakes which hit Southern Europe [16–18]. A systematic framing of the design of precast structures including the in-plane effect of cladding panels supported by extensive experimental activity was addressed in the Safecladding project [19–25].

The seismic performance of these structures may also be influenced by the diaphragm effectiveness, since roofs often have spaced members and skylight openings. In this case, the diaphragm effect relies on the structural behaviour of the roof connections [26].

In the current European design practice [27], the key design parameters are often (i) the inter-storey drift sensitivity coefficient θ, defined as the ratio between vertical and horizontal loads at a storey divided by the inter-storey drift ratio ($\theta = P_{tot}\, d_r \,/\, V_{tot}\, h$), at Ultimate Limit State (ULS), or (ii) the drift limitation at Drift Limitation State (DLS), rather than (iii) the column base strength at ULS. To be noted that, in traditional multi-storey precast structures with hinged beam-column joints, the column strength is not influenced by the capacity design, since the beams are not part of the lateral load resisting system.

Several structural solutions were proposed to limit the flexibility of typical dry-assembled precast frame structures while keeping their dry assemblage, mainly focusing on the addition of bracers like dry-assembled precast walls [28] or diagonal metallic devices [29–31] or on the less effective introduction of rotational dissipative devices in the beam-column joints [32,33]. Solutions concerning rigid beam-column connections have been mainly developed involving in situ concrete pouring [34]. Alternative dry approaches concern “hybrid” structural arrangements based on the use of precast dry-assembled rocking frames with unbonded post-tensioning giving an elastic restoring action coupled with metallic connection devices providing dissipation of energy and hysteretic damping [35]. The use of re-centring unbonded strands and dissipative connections is the basis of the Precast Seismic Structural System (PreSSS), to which a large experimental campaign was devoted at the end of the 1990s and further [36]. Despite the results showed a large ductility associated to a low-moderate damage of the concrete components, the diffusion of this construction system in practice found difficulties, mainly due to its complexity.

Within the present paper, an innovative solution to reduce the flexibility of dry-assembled precast frame structures and improve their seismic performance is proposed, based on the adaptation of selected nodes of the frame from hinged into rigid using mechanical devices that couple the reinforcement of columns and beams avoiding any in-situ concrete pouring (Precast Structure with Adaptable Joints [37]).

2. Precast Structures with Adaptable Joints (PSAJ)

A unique structural system with variable structural configuration was conceived with beam-column and/or floor-to-beam hinged joints during assemblage, which can be adapted into rigid in selected positions, potentially turning dry-assembled precast frames into highly dissipative and redundant structures with increased stiffness.

The freedom of selection of the joints to be adapted into rigid opens wide possibilities to the structural designer. Few seismic resisting frames may be selected in a structural arrangement, leaving the others with hinged beam-column joints for gravity load bearing only. By providing a rigid diaphragm to ensure the collaboration of the stiffer bracing frames with the gravity load bearing ones, relevant saving of material may be obtained.

The joint adaptation into rigid may be designed, as an alternative, only at selected floors, for instance the first floor or the roof. This may provide a solution to the frequent design cases in which one or few floors are subjected to a much larger gravity load, if compared with the others, due to several reasons (a different use, need of installation or circulation of heavy machines, interruption of columns, etc). If adopting hinged beam-column joints at those floors, the column size and reinforcement would not be affected by the capacity design related to the deep beams needed to sustain the load, which could lead to a remarkable reduction of the column cross-section and a general structural rationalisation. Even if geometrically regular in elevation and plan, structures with non-regular distribution of adapted joints may turn into irregular.

The joint adaptation is particularly interesting for pre-stressed concrete beams/slabs. If the horizontal members are supported on corbels and connected as hinges (i.e. with dowels), the dead loads give a simply supported moment distribution. All nodes are not then stressed by moment due to the dead loads, while those nodes adapted into rigid will be stressed by the additional live gravity loads and by the lateral loads (wind or earthquake) only. If, for instance, the live loads were approximately equal to the dead, the precast joint would be designed for a maximum moment equal to half of that of a cast-in-situ. This assumption is correct only if the beam does not tend to rotate in time at its ends due to creep effects, which may be obtained through a proper design of the pre-stressing. Fig. 1a shows the bending effects of dead loads on beams, where it is assumed that all dead loads are applied during the assemblage of the structure, and Fig. 1b shows the effects of the application of horizontal loads. The envelope at the lower side of the beams (Fig. 1c), considered also inverting the horizontal load direction, provides an almost constant positive bending moment profile along the beams, which may result in an optimal exploitation of the pre-stressing tendons.

From a practical point of view, the joint adaptation described above can be obtained by assembling the structure according to the following phases: (a) installation of the beam with hinged joint; (b) installation of the slab elements with hinged joints; (c) activation of beam-column mechanical reinforcement couplers; (d) filling of the construction joint.

In the framework of a highly industrialised precast concrete manufacturing [38], the elements can be transported to the construction site already provided with the dead non-structural technologic layers. In

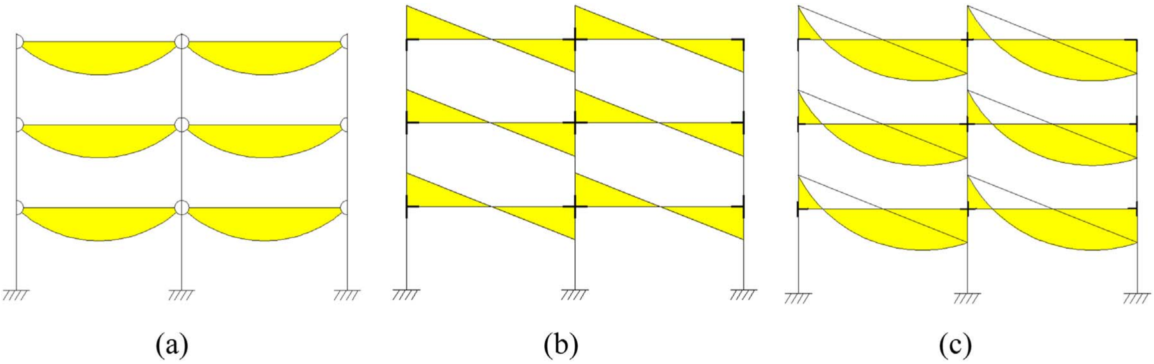

Fig. 1. Bending moment distribution along the beams: (a) dead loads, (b) horizontal loads, (c) envelope combination of both.