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Dissipating and re-centring devices for portal-frame precast structures

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ABSTRACT

The seismic response of buildings not specifically designed to resist earthquake actions can be generally improved by allowing the structure to dissipate an appropriate amount of energy. The use of passive devices for improving the seismic performance of precast concrete structures is investigated herein. In industrial and commercial precast concrete buildings, these devices can be successfully applied at the beam-to-column connections of hinged portal-frames, in order to increase the connection degree of fixity and the dissipated energy during a seismic event. The specific aspects and efficiency of passive dissipation devices based on rotational friction with and without the addition of a re-centring device is analyzed herein. Such devices may be applied both to existing and new buildings; indeed, they are able to mitigate the inter-storey drift demand, to limit the damage at the column base and to reduce residual drifts.

A design procedure is developed in the paper for portal-frames implementing the investigated devices. A case study representing a single-storey precast concrete portal-frame is selected. The design procedure is applied to the case study, considering various devices configurations. The structural performance is assessed by means of non-linear time history analyses.

1. Introduction

Precast structures are widely recognized as being able to ensure several benefits such as the ability to cover large surfaces, by means of pre-stressed concrete beams, the high quality control of materials and elements, and the reduced construction time compared to traditional reinforced concrete (RC) structures. For the aforementioned reasons, such structures have been commonly adopted in the industrial and commercial sectors, where single-storey or few-storey buildings are characterized by a simple structural layout: cantilever columns pin-connected [1–3] to pre-stressed beams supporting pre-stressed roof elements. The columns are placed inside cup footings [4] or connected to the foundation by means of mechanical devices or grouted sleeves [5–7]. The energy dissipation capacity is generally provided by the development of plastic hinges at the base of the columns.

The beam-to-column connections are usually dry-assembled in place in order to speed up the erection sequence, leading to more flexible structures compared to cast in place RC connections. The building typology being investigated is characterized by a lower displacement ductility demand compared to traditional RC buildings, due to the inherent storey height; indeed, doubling the inter-storey height reduces by half the ductility demand. The lower value of the ductility demand leads to a design focused on controlling the lateral displacement demand rather than limiting the material strain.

Recent earthquakes in Italy have highlighted the vulnerability of precast structures not designed according to modern seismic codes [8–11]. The main vulnerabilities observed are related to inadequate horizontal load transfer mechanisms between precast members leading to the loss of support and consequent fall of both structural [11–14] and non-structural elements, as for instance cladding panels [15–17]. Additional loads in existing connections arise as a consequence of displacement incompatibility between adjacent elements due to the high flexibility of the considered structures. Such load increase could happen in the connections between beams and columns [18], between roof elements and supporting beams [19] and between cladding panels and supporting elements [15].

This paper focuses on the reduction of seismic lateral displacements and seismic damage in hinged portal-frames by providing additional beam-to-column connections, suitable for both new and existing buildings. This task can be achieved either with connections in emulation of cast-in-place RC structures [20–22] or with additional mechanical devices at the beam-to-column joint. The former solution involves formworks and additional castings with consequent increase of the erection time for new structures

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and operational difficulties in the case of existing buildings. The latter solution is fully compatible with the traditional construction sequence, indeed the additional devices are put in place at the end of the erection sequence. Consequently the solution is suitable also for existing buildings. The beam-to-column devices provide a source of additional damping to the system (i.e. dissipation of seismic energy) and a degree of fixity to the beam-to-column joint (i.e. increase of lateral stiffness).

Starting from solutions available in the literature [23,24], the paper investigates the most suitable arrangements for beam-to-column additional devices in order to be fully compatible with the seismic deformations arising in portal-frame structures. A design procedure is proposed and the suitability of the investigated devices is validated by means of non-linear time history analyses on a selected case study resembling a portal-frame of a precast industrial building. The paper considers the performance in the transverse direction of portal-frame structures; however, it is possible that additional devices could be applied in the longitudinal direction, for example between columns and gutter beams or between adjacent precast cladding panels [25].

2. Beam-to-column connection devices

In order to select the most suitable additional devices for beam-to-column joints of new and existing precast concrete structures, the following properties should be considered:

1. compatibility between the device and the considered hinged portal-frame static scheme;
2. assembling by means of dry post-installed connections;
3. avoid interference with floor activities, for instance by placing the devices at the side or underneath the main girders;
4. stable dissipation capacity;
5. easy substitution after an earthquake;
6. limited damage in the beams and in the columns as a consequence of the device installation, with the exception of plastic hinge formation at the base of the columns;
7. re-centring capacity if available.

Two devices are selected herein in accordance to the aforementioned properties. Such devices have different characteristics and they can be applied as single devices or as devices acting in parallel.

The first device, whose potential was previously investigated both analytically and through numerical analyses [24], is able to dissipate energy through the friction generated by the relative rotation of steel plates with interposed brass discs. The interposition of brass discs, softer than the connected steel plates, is necessary to guarantee smoothness during relative rotations. The energy dissipation increases the system damping and it is therefore beneficial especially in the case of seismic events which do not present “near field” characteristics, i.e. conditions in which the maximum deflection of the system is reached before fully engaging its dissipative capacity. Indeed, the maximum efficiency of a dissipation device is associated with a steady-state response, as evidenced by the concept of equivalent viscous damping [26].

Ideally, the adopted devices should be able to both dissipate energy and provide an appropriate degree of fixity at the beam-to-column joint in order to increase the system lateral stiffness. This could be accomplished by introducing a second elastic device able to limit the residual deformations as it is shown in the following. The two selected devices can be coupled and calibrated to dissipate a sufficient amount of energy, and to allow re-centring of the connection after an earthquake.

The optimal position of the devices, graphically represented in Fig. 1a, is selected to maximize their performance under a seismic event. A kinematic analysis has been carried out to check the compatibility between the investigated devices and the considered hinged portal-frame structural system. The position of the friction-rotation dissipation devices, shaded circles in Fig. 1a, is selected to obtain an articulated quadrilateral with the beam-to-column joint (hinges 1–4 in Fig. 1a) once the static friction load is overcome. This configuration does not significantly increase the lateral stiffness of the system. The position of the stiffening/re-centring device is selected to create a statically determinate triangle within the beam and column ends. This configuration is characterized by a high stiffening effect. It is worth noting that the proposed solution requires a mechanical connection at the beam-to-column joint. In buildings designed according to modern seismic codes, this connection is actually provided to transfer seismic actions among structural elements. In older buildings, as in the case of the precast industrial buildings damaged by the 2012 Emilia earthquake [8–11], horizontal loads may be transferred by friction. In such conditions, additional mechanical connections are required as retrofit measure to transfer seismic loads and to avoid out-of-plane failure of the reinforced concrete fork [11], even without the application of the additional devices investigated herein. U-shape steel profiles at the column sides may accomplish to this task (Fig. 1a). It is observed that the stiffening device could be substituted by friction-linear or other hysteretic systems to provide both energy dissipation and the stiffening of the beam-to-column joint. Finally, the investigated devices can be substituted by proprietary devices if available.

2.1. Energy dissipation (ED) device

The energy dissipation (ED) device considered herein can be applied in correspondence of the three hinges depicted in Fig. 1a. Such device dissipates energy through friction due to the relative rotation of its elements. In the present study, the application of sliding surfaces only at the bottom-right hinge of Fig. 1a is considered, the remaining hinges are free to rotate. The performance of the device is optimized by the insertion of brass discs as shown in Fig. 2. Other materials can be adopted. Brass discs are softer than the connected steel plates. This guarantees smoothness during relative rotations. In addition a small difference between static and dynamic coefficient of friction is observed, respectively 0.51 and 0.44 [27], which allows for stable and uniform hysteretic response.

Fig. 2 shows a possible solution to increase the system energy dissipation by increasing the device activation moment. This is accomplished by incrementing the number of sliding surfaces. The steel discs are fixed to the mounting frame by bolts placed in slotted holes. This detail is required to allow the whole transferring of the external tightening force to the brass discs; indeed eventual transverse displacements of the steel discs due to the tightening force are accommodated by the slotted holes. The setup shown in Fig. 2 allows for 4 sliding planes. Cup springs are provided on the main bolt for a better control of the tightening load acting on the brass discs.

The bending moment associated with the sliding of the brass surfaces in dynamic conditions is:

$$M = \int_{\rho=R_i}^{R_e} \int_{\theta=0}^{2\pi} \rho^2 \cdot \mu \cdot \frac{N}{\pi(R_e^2 - R_i^2)} \cdot d\rho d\theta = \frac{2}{3}\mu \cdot N \cdot \frac{R_e^3 - R_i^3}{R_e^2 - R_i^2} \qquad (1)$$

where μ is the dynamic coefficient of friction, N is the bolt pretension load and R_e, R_i are the external radius and internal radius of the brass disc respectively; ρ and θ are integration variables in the polar coordinate system. Table 1 shows the activation friction