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Environmental impact reduction of precast multi-storey buildings by crescent-moon seismic dampers hidden in beam-column joints

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ABSTRACT: The growing demand of sustainable precast structures for multi-storey constructions is often driven by the optimisation of cross-sections and reinforcement volumes of the structural elements. The present paper describes a real building recently designed and assembled with the installation of crescent-moon hysteretic dampers in the beam-column joints, recently proposed and patented. The joint continuity allows for an optimisation of the lateral load resisting system, reducing the size of the columns with respect to the classical precast frame structural arrangement with hinged joints, whilst protecting columns and beams from the large actions deriving from the classical moment-resisting cast-in-situ or partially precast technological solutions. After the complete detailed design of the case study building employing the 3 solutions described above, the precast dissipative one being designed with dynamic non-linear analysis, the results of an environmental impact analysis are compared and discussed, confirming a reduced environmental impact for the dissipative solution, with respect to both precast with hinged beam-column joints and moment-resisting cast-in-situ alternatives.

1 INTRODUCTION

The demand of precast structures for the construction of multi-storey buildings is growing, mainly due to the advantages offered by pre-stressing technology, speed of assemblage, robust performance, quality checks, etc. The most economical and typical beam-to-column joints in such buildings are hinged, which however makes the structure not always compatible with the requirements of drift limitation and reasonable column cross-sections. This issue becomes critical in zones of medium/high seismicity. Moreover, the adoption of wall panel or coupled wall/frame structures often results not compatible with architectural requirements. In typical cast-in-situ concrete frames, the stiffness and resistance of the spatial frame structure relies on moment-resisting beam-to-column joints. Such a solution is accompanied by large bending moments insisting on the joints, both in static and seismic load combinations. Indeed, combining this with the capacity design principle of strong column/weak beam for ductile seismic design, the dimensions of the elements also typically become large.

Emulative precast structures with wet-completed full moment-resisting joints typically become too complex if spans larger than the usual for cast-in-situ structures are employed. Recently, dry-assembled precast frame structures with hinged joints adaptable to clamped after dead loads are transferred was proposed by Dal Lago et al. (2018) thanks to the late activation of mechanical couplers, thus optimising the bending moment insisting on the joints.

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This paper presents an alternative solution consisting in equipping the beam-to-column joints with crescent-moon steel hysteretic dissipative devices with elastic-plastic behaviour, allowing to control the degree of rotational stiffness of the joints, whilst thresholding the moments after yielding of the devices is attained. Such devices are conceived as structural seismic fuses, to be replaced after possible heavy use after strong earthquakes. This detail was recently proposed and patented by Manini Prefabbricati S.p.A. with deposit No. 102019000025459.

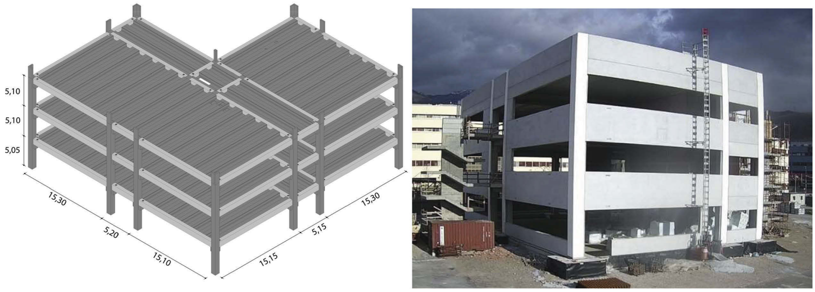
The efficacy of this joint is shown through a real case study building located in an Italian university campus, designed following dynamic non-linear analysis. An axonometric view and a picture of the case-study building made by 3 floors for a total height of 15 m and a total built surface near 3.000 m², are shown in Figure 1. The optimisation of the cross-sections of structural elements attained thanks to the proposed joint is also accompanied by enhanced environmental sustainability, typically mined for reinforced concrete structures by the components of reinforcing/insert steel and cement.

The main strategies currently tackled to reduce the environmental impact of structures can be essentially framed in two. The first strategy, object of wide research activities in the last decades, consists in partially or totally replacing the most impacting components with green alternative ones, such as sulfoaluminate cement instead of Portland (Coppola et al. 2018), or composite material rebars instead of steel (Dal Lago et al. 2017). Such replacements, on the basis of the current knowledge, are generally accompanied with a reduction of the structural performance and/or cost competitiveness of the structure. The second strategy, less extensively tackled in literature, consists in reducing the consumption of material volume, following the adoption of sophisticated technologies (e.g. pre-stressing and highly-technological moulds for precast structures) associated with a process of structural optimisation.

Recent research (Bonamente et al. 2014, Lamperti Tornaghi et al. 2018, Abey & Anand 2019, Wang et al. 2020, Baldograni et al. 2022, Dal Lago et al. 2022b, Nagireddi et al. 2022) demonstrated that precast structures, although employing more performing and impacting materials with respect to traditional cast-in-situ concrete structures, allow for a strong reduction of total volume of material employed for the construction, which results prevailing in the sustainability balance, and much more efficient than replacing cement or steel with green alternative materials (Baldograni et al. 2022, Dal Lago et al. 2022b). Such a balance tends to even more pend towards precast structures if analysing the sustainability in the framework of a Life-Cycle Analysis (LCA – Rodrigues et al. 2018), where additional factors contribute, including higher durability due to the adoption of high-quality concrete, absence of cracks in service due to pre-stressing, demountability, enhanced resilience, etc. Counter-balancing effect include the consumptions of precast production plants, and the transportation of the elements.

With the aim to quantify the advantages of the proposed dissipative solution in terms of environmental sustainability, the same structure was designed according to the following solutions:

1. precast frame with beam-to-column joints equipped with dampers;
2. precast frame with hinged beam-to-column joints;
3. cast-in-situ frame with moment-resisting beam-to-column joints.



(a) (b)

Figure 1. Structure at study: (a) axonometric view with main structural elements and geometry; (b) picture of the building near completion.

The present paper tackles the sustainability analysis with reference to the prime material consumption only, leaving to further publications currently ongoing extensions of the research in terms of wider LCA.

2 DESIGN OF THE STRUCTURAL FRAMES

2.1 *Precast frame with beam-to-column joints equipped with dampers*

Due to the highly non-linear and dissipative behaviour of the hysteretic crescent-moon dampers, and to the difficult framing of such original system in the classical seismic force-based design with response spectrum analysis, non-linear dynamic analysis was employed to check the previously proportioned structural members. The Finite Element Method (FEM) numerical model employed to this aim, shown in Figure 2, is made with linear beam elements for all frame members, since all non-linearities are expected to be concentrated in the joints. In particular, the column base was equipped with non-linear spring elements to which moment-rotation bi-linear diagrams were attributed (Figure 3), and the beam-to-column joints were modelled with a saddle combination of rigid links and non-linear spring elements provided with Bouc-Wen hysteretic behaviour calibrated on the basis of experimental qualification tests (Figure 4). The floor decks, made with adjacent pre-stressed elements making a double-flat hollow cross-section (similarly to the one described in Dal Lago et al. 2022a) after steel sheets are placed in the open central core of the elements and in-situ concrete topping is cast, were modelled with semi-rigid diaphragm, simulating the effective in-plane floor stiffness. Cladding panels were introduced as masses without stiffness, thanks to the adoption of special sliding connectors decoupling their motion from that of the frame (Toniolo & Dal Lago 2017).

Design resistance was considered for concrete class C45/55, rebars mild steel grade B450C, and 7w-strand pre-stressing steel fp1860.

The design process followed these steps: (a) evaluation of the structural performance under first-phase static loads without dissipative devices; (b) activation of the dissipative devices; (c) application of second-phase static loads; (d) non-linear dynamic time history analysis for different hazard scenarios encompassing limit states of Operability (OLS), Damage (DLS), Life-Safety (LSLS), and Collapse (CLS).

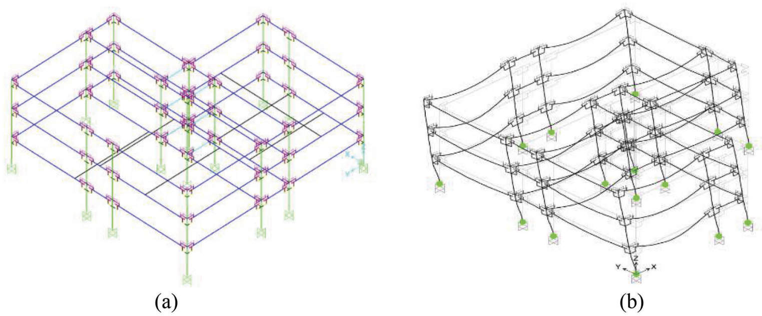


Figure 2. Deformed shape and activated plastic hinges (green dots) at the end of one of the dynamic NL analyses at collapse limit state.

For each limit state, the response under 7 triplettes (X,Y,Z) of artificially-generated EC8-spectrum-compatible accelerograms was evaluated (EN 1998-3:2005). The stationary part of the accelerograms was assumed to be 10s long. The pseudo-stationary time window of the accelerograms followed a 2s time interval with accelerations of increasing amplitude starting from zero, and was set to be followed by a tail of 13 s with accelerations of decreasing amplitude. Thus, the whole duration of a single ground motion is 25 s. The mean of the maximum values evaluated through the 7 triplettes for each limit state was considered for the checks.

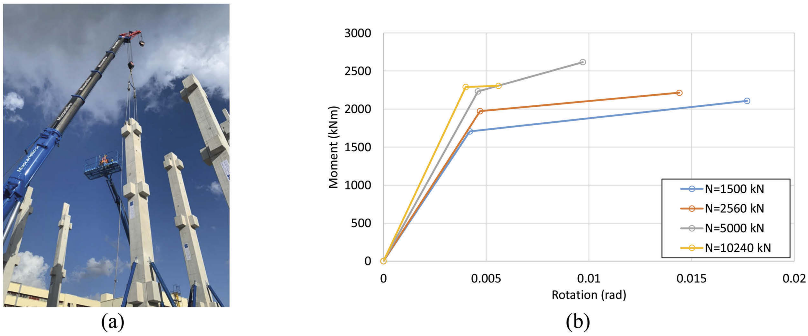


Figure 3. Column elements: (a) picture during assemblage; (b) bi-linear moment-rotation curves attributed to the base spring.

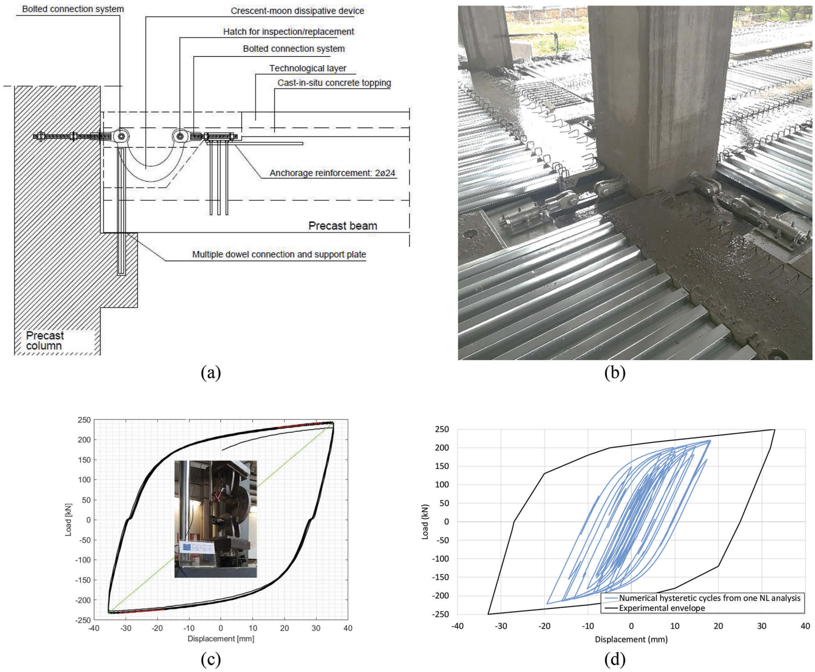


Figure 4. Dissipative beam-column joint with hidden crescent-moon hysteretic dampers: (a) schematic description; (b) picture from real building; (c) experimental hysteresis of crescent-moon damper; (d) non-linear force-displacement diagram attributed to spring elements in the model.

Figure 2b shows the deformed shape of the frame structure and the activation of the column base plastic hinges after an analysis related to CLS. The exemplificative hysteretic response of a crescent-moon device under the same analysis is shown in Figure 4d.

On the basis of the analysis results, it was observed that the column base attained a minimum capacity over demand ratio (C/D) of 2.39, evaluated based on the ultimate rotation capacity. Critical for the design resulted indeed the interstorey drift of the last storey in OLS, equal to 0.331% versus a maximum value which, according to the class of use III of the building, was equal to 0.333%.

In order to synthetically estimate the hysteretic contribution of the dissipaters, acting in parallel with the contribution of the column bases, further analyses were run assuming a perfect elastic response of the dissipative devices considering an equivalent secant stiffness associated to the mean local device displacement obtained in the first series of NLTHA for each LS.

The comparison with the first series of analyses allows to compute the reduction factor β associated with the displacement reduction due to the hysteresis of the dissipative crescent-moon devices. The spectral demand reduction due to the added dissipation effect may be expressed in terms of added equivalent viscous damping (e.g. within the capacity spectrum method – Dal Lago & Molina 2018) or by increasing the force reduction (behaviour) factor q (e.g. within the force-based design method – EN 1998-3:2005), within the assumption of equivalent anelastic displacement for flexible structures. Considering Eq. (1):

$$q_D = \beta \times q_{lim} \tag{1}$$

where

q_{lim} is the limit behaviour factor in the context of modal analysis with response spectrum, assumed equal to 2.0 for the considered case study;

q_D is the behaviour factor to be attributed to the presence of the dissipative devices.

The value of the behaviour factor of the dissipative structure q_D is calculated as 2.56 following a β coefficient of 1.28 for LSLS, and as 2.78 following a β coefficient of 1.39 for CLS, respectively. It is highlighted that the above values are directly referred to the case study analysis, based on a conservative limit behaviour factor assumed in the design phase, where even at CLS the full deformation capacity of frame structure and dissipative devices was far to be attained, and hence these values could potentially be extended.

With the aim to validate the estimation carried out with the above method, further linear dynamic analyses with response spectrum were carried out utilising a CLS spectrum and adopting the behaviour factor q_D determined as above. The total base shear obtained in the two main directions (3009 kN and 2934 kN in X and Y directions, respectively) resulted close to the peak values of the NLTHA (3121 kN and 3321 kN in X and Y directions, respectively).

The contribution of the proposed dissipative joint led to large benefits in the proportioning of the column cross-section, which was set to be square with 80 cm of side, assumed constant along the height. The bending moment transmitted by the joint, thresholded by yielding of the hysteretic dissipative devices, attained a maximum contained in 189 kNm at LSLS. Hence, the partial continuity of beams and columns did not lead to additional reinforcement for all frame members in seismic load combinations with respect to that calculated for gravity load combinations, and the typical details requested to ensure ductility around beam ends for typical cast-in-situ members resulted indeed not necessary.

The foundations were made with footing RC plates supported on 4 piles of diameter 0.60 m and length of 20 m.

2.2 *Precast frame with hinged beam-to-column joints*

Within this solution, representative of the typical precast solution for this typology of buildings, the design was carried out assuming columns cantilevering from their clamped base and perfectly hinged beam-column joints. Since this structural typology is framed in the current normative, a traditional design process was carried out following modal analysis with response spectrum on the basis of a force reduction (behaviour) factor q equal to 2.0.

Figure 5 shows the envelope of bending moments on the columns in direction X. A maximum base bending moment per single column of 2879 kNm was evaluated at LSLS. This led to the adoption of square cross-sections of side 1.10 m.

The foundations were evaluated to be similar to the previous case.

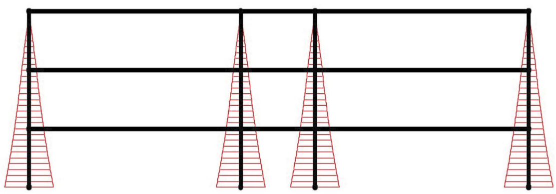


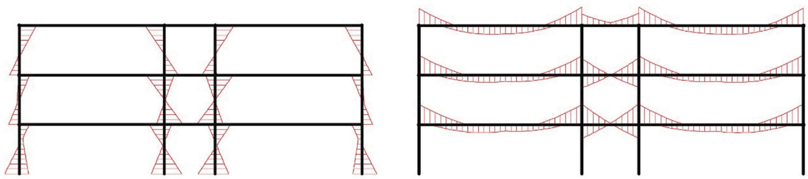
Figure 5. Precast frame with hinged beam-to-column joints: envelope of bending moments on columns.

2.3 *Cast-in-situ frame with moment-resisting beam-to-column joints*

The design of the cast-in-situ frame was carried out assuming a traditional "shear-type" frame structure, on the basis of modal analysis with response spectrum assuming a force reduction (behaviour) coefficient equal to 2.76. Figure 6 shows the resulting bending moment envelopes on both column and beam elements.

Maximum bending moments equal to 3317 kNm and 3634 kNm were evaluated at LSLS for individual column and beam members, respectively. This led the cross-sections to be designed as square with side of 1.20 m and T-shaped with height of 1.40 m and thickness of 0.60 m for column and beam members, respectively.

Foundations were designed to be very similar to the previous cases, except for a slight increase of pile length to 22.5 m.



(a) (b)

Figure 6. Cast-in-situ frame with moment resisting beam-to-column joints: envelope of bending moments on (a) columns; (b) beams.

3 ENVIRONMENTAL IMPACT ANALYSIS

The environmental impact of the structural organism of the case study building designed according to the 3 different technological solutions described above is analysed with reference to the contribution of primary structural materials. In order to quantify environmental impact, reference was made to the ponderation indexes of Global Warming Potential (GWP) relative to the different materials employed, and to their single components. Such indexes have been taken from Environmental Product Declarations (EPD) spontaneously issued on a voluntary basis by Italian producers (where present) following the procedure described in EN:15804:2012+A2:2019 and UNI EN ISO 14025:2010. Global indexes (sum of items A+B+C) were considered, since mostly relevant to quantify the impact deriving from the use of primary structural materials.

The GWP values utilised in the computation are reported in Table 1 expressed in terms of equivalent carbon dioxide ($eqCO_2$) referred either to unity of mass or volume of material. The summation of the concrete components for different concrete grades were evaluated based on actual mix designs employed by Manini Prefabbricati S.p.A.

On the basis of the complete quantity list of materials employed for each designed solution, the balance of environmental sustainability was evaluated, as synthetically reported in Figure 7. It is noted that the impact of about 600 tons of $eqCO_2$ related to the foundations is practically equivalent for all solutions, with slight increase in the case of the cast-in-situ frame due to the longer piles employed.

Differently, it can be observed a relevant difference related to the superstructure, ranging in between 835 and 1100 tons of $eqCO_2$. Referred to the built surface of the building, these values range in between 278 and 367 $kgeqCO_2/m^2$. The results shown in Table 2 demonstrate that the more sustainable solution is the proposed one with dissipative beam-to-column joints, where the additional impact related to the physical steel devices and anchorage systems is more than balanced by the reduction of concrete and reinforcement in columns with respect to the traditional precast solution with hinged beam-to-column joints (+12% of $eqCO_2$), and in both columns and beams with respect to the cast-in-situ frame (+31% of $eqCO_2$).

Table 1. GWP weighted indexes for the different materials and composites employed.

MATERIAL	DENSITY (ton/m^3)	GWP (kg Co_2 eq/ton)	GWP (kg Co_2 eq/m^3)
CEMENT CEM I 52,5 R	3.15	910	2866.5
CEMENT CEM IV 32,5 N	3.15	588	1852.2
AGGREGATES	1.5	20.7	31.1
SUPERPLASTICISER	1.1	1888	2076.8
WATER	1	-	-
LEAN CONCRETE C12/15	1.8	109	196.7
CONCRETE C25/30	2.4	116	279.4
CONCRETE C28/35	2.4	122	293.6
CONCRETE C32/40	2.4	162	388.8
CONCRETE C40/50	2.4	167	401.8
CONCRETE C45/55	2.4	226	542.2
POLYSTYRENE	0.02	5436	108.72
INSERT STEEL	7.85	1130	8870.5
REBAR STEEL B450	7.85	924	7253.4
STRAND fy1860	7.85	2530	19860.5

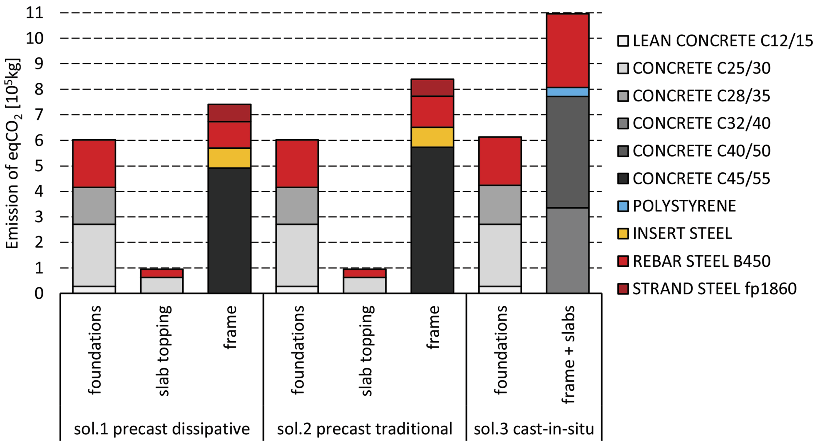


Figure 7. Equivalent CO_2 emission for the different structural components of each solution.

Table 2. Total equivalent CO_2 emission for the different structural solutions analysed.

Emission of eqCO_2 for the superstructure [10^5 kg]		
sol.1 precast dissipative	8.35	-
sol.2 precast traditional	9.34	(+11.9%)
sol.3 cast-in-situ	10.96	(+31.3%)

4 CONCLUSIONS

The non-linear time history analysis of the real case study building provided with semi-rigid beam-column joints with dissipative crescent-moon hysteretic dissipaters installed showed a seismic behaviour characterised by a good balance between the requisites of (a) limitation of drift, and (b) member strength according to the different limit states analysed. This behaviour is associated with the hysteretic added damping provided to the structural assembly by the dissipators through flexural stiffening, energy dissipation, and thresholding of the actions on the frame structures after attainment of yielding. The alternative design of the same building with either ordinary precast with hinged beam-column joints or traditional cast-in-situ with clamped joints, led to larger cross-sections and reinforcement volume. The environmental impact analysis of the 3 alternative solutions classified the precast dissipative one as the more sustainable due to the following reasons: with respect to the ordinary precast, the contribution of the metallic dampers and their anchoring systems more than balanced the larger column cross-section of the ordinary precast solution, with 12% equivalent CO_2 emission less for the super-structure; with respect to the traditional cast-in-situ solution, the contribution of the use of more performing though impacting materials much more than balanced the larger volumes of concrete and reinforcement of the less optimised traditional cast-in-situ solution, with 31% equivalent CO2 emission less for the superstructure. It is currently under development an extension of the environmental impact analysis herein presented which includes factors other than the consumption of prime materials, following a more general LCA approach.

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