COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27 May 2015

SEISMIC PERFORMANCE OF INNOVATIVE STEEL AND CONCRETE HYBRID COUPLED SHEAR WALLS

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Keywords: Coupled shear walls, Nonlinear finite element models, Performance-based design, Seismic design, Steel and concrete hybrid structures, Steel dissipative links.

Abstract. *Steel and concrete hybrid systems are obtained through a combination in series of steel elements and reinforced concrete elements with the aim of exploiting at their best the potentialities of each material. This concept differentiates steel and concrete hybrid structures from steel and concrete composite structures, where steel and concrete are working in parallel in the same structural element, e.g. concrete filled hollows steel columns and steel profiles embedded in reinforced concrete elements. In this work the seismic behaviour of an innovative hybrid coupled shear wall (HCSW) system, developed in the European research project INNO-HYCO (INNOvative HYbrid and COmposite steel-concrete structural solutions for building in seismic area), is investigated. Such earthquake resistant solution is composed by a reinforced concrete wall coupled to steel side columns by means of steel links with the objective to exploit both the stiffness of reinforced concrete wall, necessary to limit building damage under low-intensity earthquakes, and the ductility of steel links, necessary to dissipate energy under medium- and high-intensity earthquakes. The seismic behaviour of the system is assessed through multi-record nonlinear incremental dynamic analysis (IDA). For this purpose, first a set of realistic case studies is designed, then a finite element model is developed into the platform OpenSees and validated through comparisons against experimental tests including local and global responses quantities. The outcomes of the numerical analyses show that the proposed innovative system is actually able to effectively dissipate the energy through the activation of the inelastic behaviour of the steel links before yielding in the reinforced concrete wall.*

1 INTRODUCTION

Recent advances in the field of structural engineering were more that ever oriented towards economically and technically efficient as well as sustainable solutions. Specific attention was given to structural systems capable of offering significant advantages in terms of seismic protection through the structural fuse concept, i.e. the dissipation of seismic energy is concentrated only in sacrificial elements in order to preserve the integrity of the primary load-resisting structural components and to allow a rapid repair even after major earthquakes. Many systems were developed following this concept, and, among them, steel and concrete hybrid structures, i.e. combination in series of steel elements and reinforced concrete (RC) elements, appear to be a rather promising a competitive solution both in structural and economical terms. During the 2010-2013 European research project INNO-HYCO [1] innovative seismic-resistant steel concrete hybrid systems obtained by coupling RC elements with steel elements were developed. Although these systems were subjected to extensive numerical and experimental studies, more investigations are indeed required in order to gain more insight into their seismic performance and consequently produce better performing designs.

The objective of this work is to investigate the seismic behaviour of an innovative hybrid coupled shear wall (HCSW) system developed in the INNO-HYCO project by means of the analysis and assessment of its ductile behaviour, an indispensable step towards the possible use in real applications. The investigated solution is composed by a RC wall coupled to two steel side columns by means of steel links. Such a structural system was conceived with the objective to exploit both the stiffness of RC wall, necessary to limit building damage under low-intensity earthquakes, and the ductility (necessary to dissipate energy under medium- and high-intensity earthquakes) and replaceability of steel links, necessary to easily repair the seismic-resistant components of the structure when damaged after seismic events. In order to analyse the seismic performance of the innovative hybrid systems, a parametric analysis was performed on a set of realistic case studies. The benchmark cases are characterised by a gravity-load resistant steel structure in which the HCSW solution is employed as bracing system. The seismic behaviour of the system is assessed through multi-record nonlinear incremental dynamic analysis (IDA). For this purpose, a finite element fibre-based model is developed into the platform OpenSees and validated through comparisons against experimental tests including local and global responses quantities. In the performed parametric study, global and local engineering demand parameters are monitored in order to obtain a thorough description of the failure mechanisms of the system. The outcomes of this study constitute a contribution for the optimal design selection of the propose innovative HCSW system and a for further possible researches on steel and concrete hybrid systems.

2 DESIGN OF INNOVATIVE COUPLED WALL SYSTEMS

2.1 Resisting mechanism of the system and design procedure

Horizontal actions in the HCSW system generate the forces and moments highlighted in Figure 1. A significant part of the overturning moment is resisted by means an axial compression – tension couple N_c exerted by the two lateral side columns while almost of the all horizontal shear and only a fraction of the overturning moment are sustained by the RC wall (V_w and M_w respectively). The axial forces at the base of the side columns N_c are the summation of the shear forces in the links $V_{link,i}$ (i = 1, …, n_{links}) with n_{links} the number of links for each column (typically equal to the number of storeys). A parameter significantly influencing the structural behaviour of the considered HCSW is the coupling ratio CR [2], defined as the ratio between the base moment resisted by the lateral columns M_c and the total overturning moment M_c+M_w.

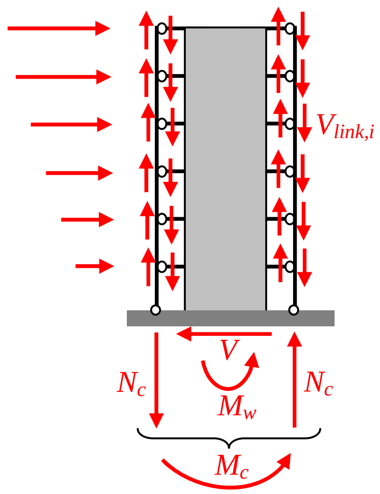

Figure 1: Resisting mechanism of the innovative hybrid coupled shear wall

The procedure adopted in this work for the design of the case studies was developed during the INNO-HYCO research project [1] and takes inspiration from the ASCE recommendations [2] for conventional hybrid coupled shear walls [3].

2.2 Benchmark cases selected and design results

The case studies were defined starting from the plant configuration reported in Figure 2, taken from [1]. The benchmark case is a residential building located in Camerino, Italy, (elevation 670 m). The building was designed as a steel frame with pinned beam-to-column joints resisting to the gravity loads connected to two HCSW systems for each direction as the only horizontal resisting structural elements. The case studies were obtained by varying the number of levels (from 4 to 12 with increasing of 2) and the coupling ratio CR (from 0.40 to 0.80 with increasing of 0.10) for a total of 25 cases. For each case study the gravity resistant system and the innovative earthquake resistant systems, highlighted in Figure 2, were designed following the Eurocode 3 [5] and Eurocode 8 [6] prescriptions. Regarding to the HCSW systems, concrete C30 (f_{ck} = 30 MPa) and reinforcements B450C (f_{yk} = 450 MPa) were used for the wall designed by selecting an aspect ratio (ratio between the overall height and base of the wall h_w/l_w) equal to 10 and a thickness b_w of 0.36 m for each case. The design of the longitudinal reinforcements was performed in order to maximize the wall flexural capacity. For this objective the Eurocode 8 [6] DCM rules (geometric percentage ratio in the confined edges just below 4%) were used. Selecting commercial IPE profiles in order to guarantee short links, according to the Eurocode 8 [6] classification for links used in eccentrically braced frames, the design results summarized in the Table 1 are obtained. Further results can be found in [4].

No. levels	Wall	CR 0.40		CR 0.60		CR 0.80	
	$b_w \times l_w$ [m]	Section	length [mm]	Section	length [mm]	Section	length [mm]
4	0.36×1.40	IPE140	140	IPE220	225	IPE360	360
6	0.36×2.10	IPE140	140	IPE200	200	IPE360	360
8	0.36×2.80	IPE120	120	IPE200	200	IPE360	360
10	0.36×3.50	IPE120	120	IPE200	200	IPE360	360
12	0.36×4.20	IPE120	120	IPE200	200	IPE360	360

Table 1: Design results of the RC wall and the dissipative links.

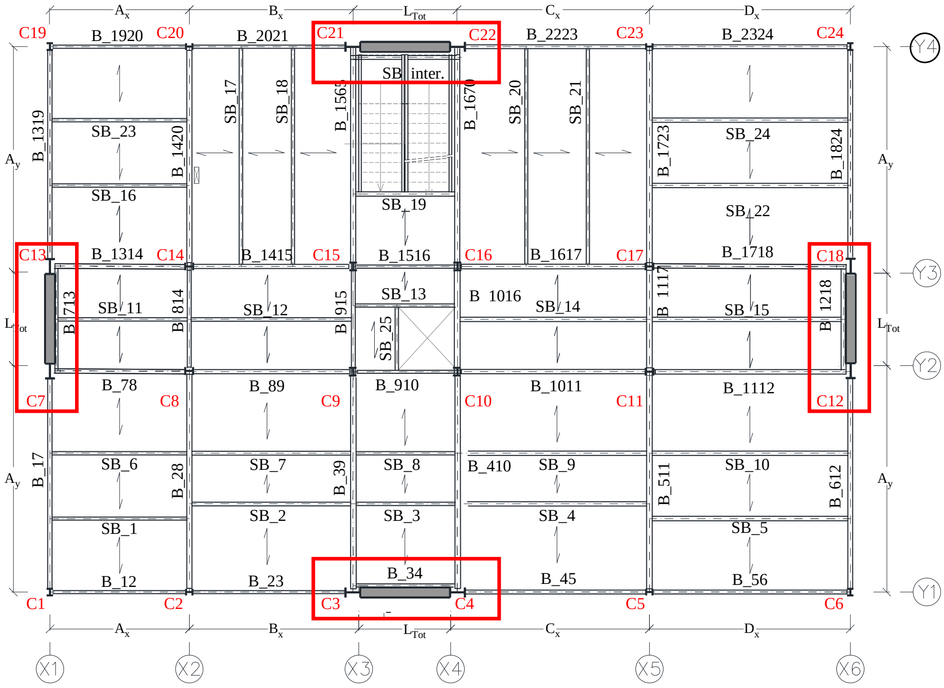

Figure 2: Plant configuration of the case study and positions of the HCSW systems.

3 MODELLING OF HCSW SYSTEMS

The finite element models of the investigated earthquake-resistant system were developed into the platform OpenSees [7]. These models derive from the assembly of different types of finite elements employed to describe each system component. The dissipative link was modelled on the basis of the model proposed for steel links used in eccentrically braced frames in [8] based on the constitutive model presented in [9], modified according to the static scheme of the considered steel links and to improve the computational efficiency. In particular, the finite element model of the steel link is composed by four elements connected in series (EL0, EL1, EL2 and ES1). The central element (EL0) is a displacement-based formulation element with length equal to link length l_{link}, measured from the steel plate of the link-to-wall connection to the centre of the double-angle link-to-column connection. The Gauss-Lobatto formulation was adopted and five integration points were inserted in the element. The flexural and shear stiffness of this element were posed equal to infinity since the behaviours of the link were concentrated in the zero-length elements EL1 and EL2 while the axial stiffness is computed from the link section. The elastic and inelastic flexural behaviour of the link were assigned to the EL2 zero length element, while the shear behaviour was modelled in the EL1 element. The "Steel01" material models were defined to describe the flexural and shear behaviour. ES1 is a zero-length element added to the elements series in order to model the link-to-column connection. From trial analyses conducted by accounting for the connection flexural behaviour it was observed that its contribution on the local and global response of the system is negligible. In the EL1 element the initial elastic shear stiffness corresponds to $k_v = GA_v/l_{link}$, where A_v is the shear area of the link cross-section and G is the tangential modulus of elasticity. Yield shear force of the same material corresponds to the plastic shear computed according to Eurocode 8 Part 1 [6] by using the average value of the resistance. The same reference was adopted for computing the yield moment. Initial flexural stiffness is defined as $k_m = 3EI_z/l_{link}$, where E is the steel Young's modulus and I_z the moment of inertia of the cross-section. Strain hardening ratio (ratio between post-yield tangent and initial elastic tangent, "$b") and isotropic hardening parameters of both the materials were calibrated to obtain the best fit of the simulated results to the experimental results obtained from the experimental campaign carried out in [1].

The RC wall was modelled using fibre-based frame elements by employing the force based formulation element ("nonlinearBeamColumn" element). Five integration points were inserted in each element and the Gauss-Lobatto element integration method was used to integrate the curvatures. The "Steel01" material was defined to describe stress – strain behaviour of the steel bars and two "Concrete04" material models, based on the Popovics work [10], were created to describe both the unconfined and confined concrete, respectively. The validation of the proposed model was performed through the comparison between the simulated and experimental results in [11] where down-scaled wall specimens were constructed and tested.

The global model was obtained by assembling the single components models above de-scribed. Figure 3 shows the numerical description of the system and the single components employed. Since the influence of the beam-to-column connections can be neglected, a material with null flexural stiffness was as-signed at the ES1 element. Elements were placed in their actual positions and connected each other by means of rigid elastic displacement-based formulation elements. Beam elements with null flexural stiffness connect the HCSW system with an equivalent column that simulates the presence of the gravity-resistant frame.

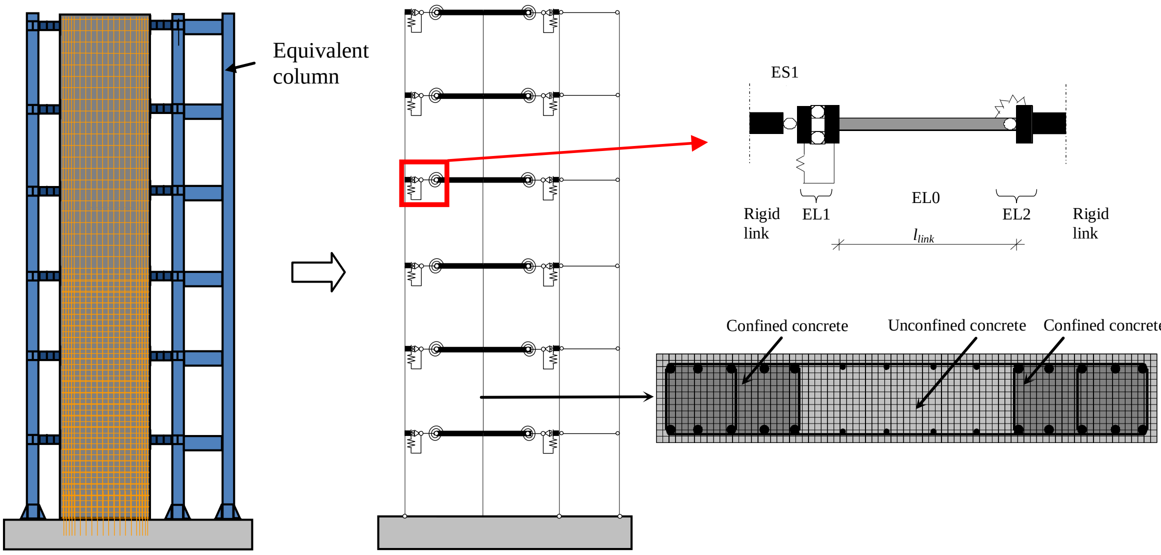

Figure 3: FE model of the innovative hybrid coupled wall system.

The inertia properties are modelled via translational horizontal masses lumped at the DOFs of the frame elements' external nodes. In particular, the tributary deck mass of the coupled wall is concentrated in each floor node, at the wall elements ends. The gravity–vertical loads, deriving by floor loads and self-weight elements, are applied at the top of each wall and column element.

The Rayleigh damping model [12] was used to model structural damping other than the one produced by the hysteretic behaviour of materials. The Rayleigh damping matrix is proportional to the mass matrix and initial stiffness matrix. The mass and stiffness related coefficients calibrated such that the values of the damping factor of 5% are obtained for the first two vibration modes.

4 ANALYSIS RESULTS

The seismic performance of the innovative HCSW systems was investigated on the basis of multi-record nonlinear incremental dynamic analysis. For this purpose, a set of 7 natural ground motion records compatible to the Eurocode 8 type I soil type A (soil factor S = 1.0) pseudo-acceleration response spectrum [6] were selected**.** Figure 4 reports the acceleration response spectrum of the records, the mean spectrum, and the code spectrum relative to the building site.

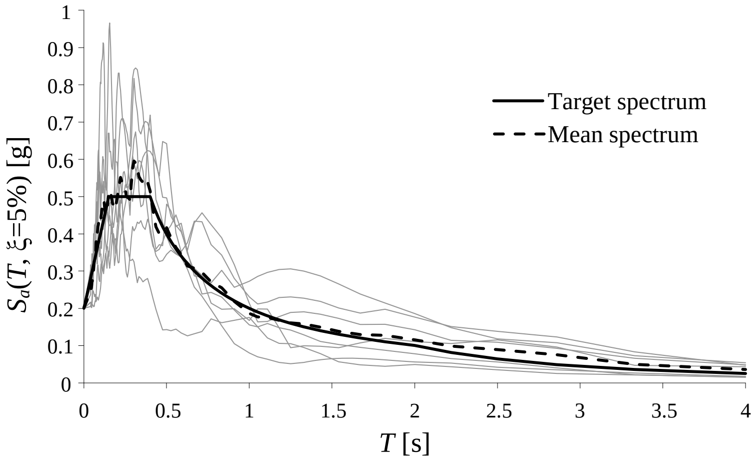

Figure 4: Acceleration response spectra of code spectrum-compatible natural records

Figure 5 shows the IDA curves up to PGA 0.30g for the case studies with 6 (Figure 5a) and 12 floors (Figure 5b), having CR 0.80. In the same figure, it possible to observe the evolution of yielding when increasing the seismic intensity. White triangles indicate shear yielding in the link while the white rhombus represent the bars yielding. Almost all links yield in shear when the wall was still undamaged. On the other hand, the reinforcements yield only at the wall base. This can be explained by noting that the seismic performance is dominated by the cantilever behaviour of the RC wall. Moreover, it is observed that increasing the coupling ratio causes an decreasing of the lateral displacements and, thus, of the interstorey drifts.

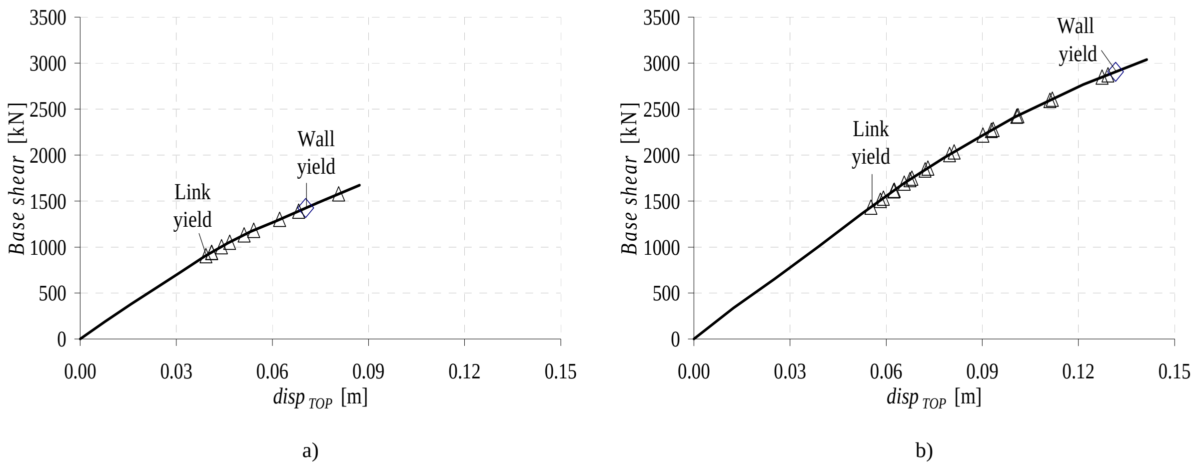

Figure 5: Comparison between IDA and pushover curves for the case study: a) with 6 floors; b) with 12 floors.

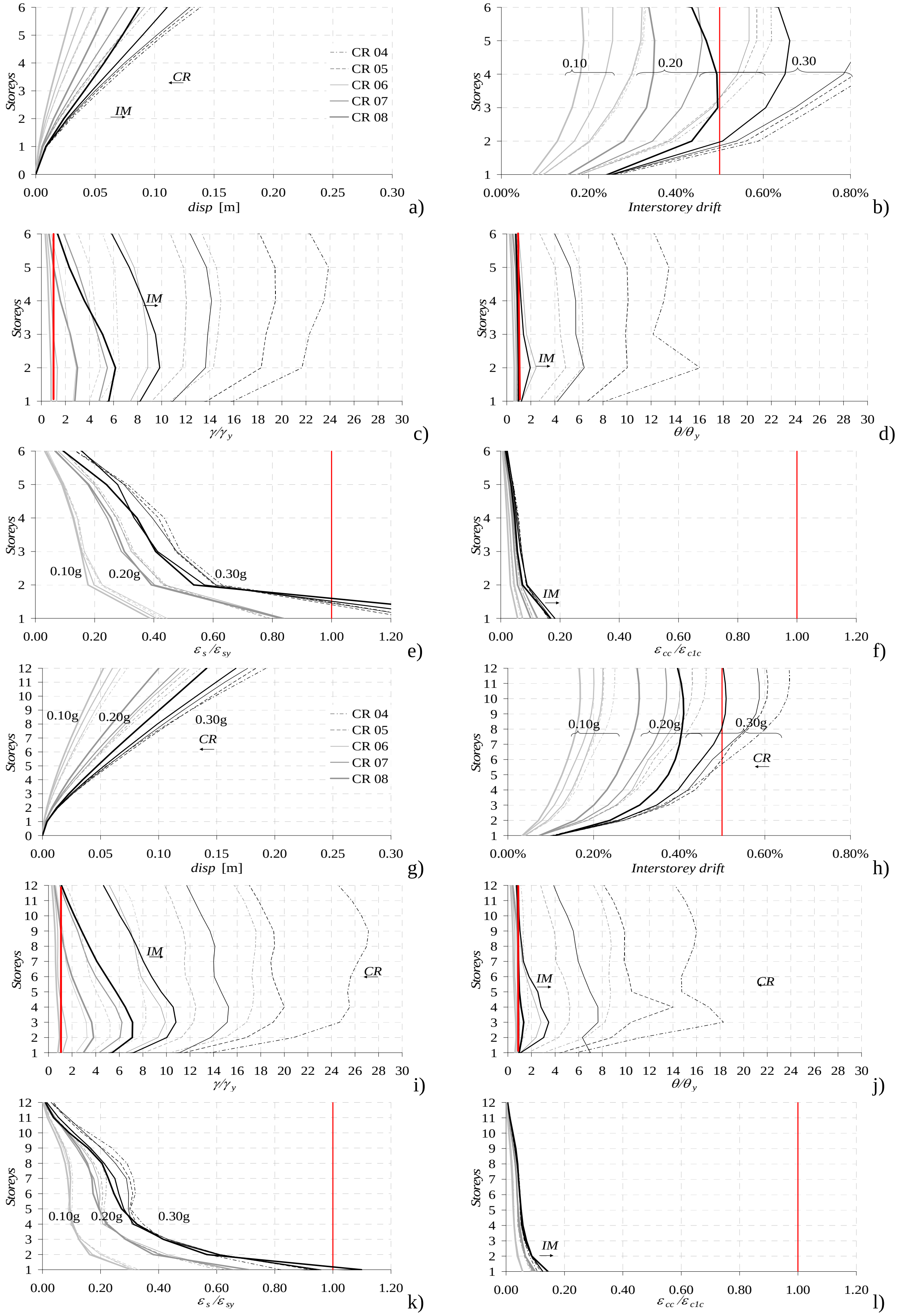

Figure 6: Mean values of the global and local response parameters for selected intensity measures.

The trend of a selection of engineering demand parameters EDPs averaged over the considered accelerograms for the case studies with 6 and 12 floors is reported in Figure 6 for peak ground acceleration (PGA) values 0.10g, 0.20g, and 0.30g and for each considered CR. Figure 6a-b and Figure 6g-h show the floor displacements and the interstorey drifts for the cases with 6 and 12 floors, respectively. From these figures it is noted that the displacement and the interstorey drifts decrease with the increasing of the coupling ratio. Figure 6c-d and Figure 6i-j plot the normalized average values of the shear rotation angle γ and of the chord rotation angle θ for the cases with 6 and 12 floors, respectively. The shear rotation angle γ was evaluated a posteriori by dividing the local transverse relative displacement, recorded in the zero length element EL1 of the link, by the link length l_{link}. Shear and flexural plastic deformations in the steel links are very notable although do not exceed the ultimate deformations assumed equal to those for the steel links in bracing steel frames [6]. Figure 6e-f and Figure 6k-l report the normalized steel bars strains ε_s and the confined concrete strains ε_{cc} in the wall for the case studies with 6 and 12 floors, respectively. The normalized concrete strains are small while the normalized steel strains are larger than one even if the ultimate condition is not attained. These deformations appear not sensitive to the value of CR.

5 CONCLUSIONS

This work analyzed the seismic performance of an innovative hybrid coupled shear wall system (HCSW) made by a single reinforced concrete (RC) wall coupled to two side steel columns by means of dissipative and replaceable steel links. A refined finite element model capable of simulating the nonlinear seismic response for increasing level of the seismic intensity and of monitoring specific global and local EDPs, was developed in OpenSees. A wide set of case studies was adopted in order to evaluate the influence of various geometric and design parameters. With reference to the seismic behaviour, the following conclusions are drawn based on the seismic response averaged over the considered accelerograms for the case studies with 6 and 12 floors: (1) the proposed structural system is able to dissipate the seismic energy through the activation of the inelastic behaviour of the steel links before yielding in the reinforced concrete wall; (2) the coupling ratio notably influence the structural behaviour.

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