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STEEL AND CONCRETE HYBRID STRUCTURES: RECENT ADVANCEMENTS AND THEIR IMPLICATIONS FOR SEISMIC DESIGN

Alessandro ZONA[1], Fabio FREDDI[2], Graziano LEONI[3] & Andrea DALL'ASTA[4]

Abstract: *The optimum combination of steel and concrete elements to constitute hybrid steel-concrete seismic-resistant structural systems should exploit the stiffness of concrete and the ductility and dissipative capacity of steel. If the seismic damage is limited to some, easy to replace, steel components only and the residual deformations are limited, the structural system can be quickly repaired and go back to the full functionality even in the aftermath of major earthquakes. This design strategy allows obtaining structural resilient systems. In this context, the present work aims at reviewing the recent outcomes of a European research project where two hybrid structural systems were numerically and experimentally investigated. A proposal for design recommendations consistent with the framework of the Eurocodes is also presented. The first hybrid system considered is a steel frame with reinforced concrete infill walls designed as a truss structure where seismic damage is concentrated in the vertical steel components with reduced sections undergoing yielding in tension. All other steel elements as well as the reinforced concrete infill walls are designed to work within their elastic range. The second hybrid system considered is a reinforced concrete wall coupled to two steel columns by means of steel links. Both columns and the wall are designed to work in their elastic range while the yielding of the coupling links allows dissipating the seismic energy. Design criteria aiming at activating all links along the building height and the effect of the coupling ratio are discussed.*

Introduction

Steel and concrete hybrid structures

The development and investigation of innovative steel-concrete seismic-resistant hybrid structures gained the attention of many researchers in the last two decades, *e.g.,* Morino (1998), Hajjar (2002), El-Tawil et al. (2010), Dall'Asta et al. (2015). The aim is to take advantage of the structural performances and specific characteristics of the two materials through their combination. The present paper reviews the results obtained during the European research project INNO-HYCO, founded within the Research Funds for Coal and Steel (RFCS) scheme, and focusing on the development of innovative steel-concrete seismic-resistant hybrid structures (Dall'Asta et al. 2015). Two structural configurations were investigated, *i.e.,* steel frames with reinforced concrete infill walls and reinforced concrete walls coupled to steel columns by means of dissipative steel links. These two systems are briefly described hereafter.

Steel frames with reinforced concrete infill walls

Steel frames with reinforced concrete infill walls (SRCWs) are seismic-resistant hybrid systems classified as 'Type 1' in the Eurocode 8. Accordingly, these structures are expected to behave as reinforced concrete walls and dissipate the seismic energy through the yielding of the vertical steel sections and of the vertical reinforcements of the walls. Detailing provisions are the same provided for reinforced concrete walls with the only exception for the indications on the edge shear connections. However, the actual behaviour of these two structural systems might be very different. In fact, in SRCWs, the presence of the steel frame induces the formation of diagonal compression struts in the concrete, resulting in cracks in the tension diagonal and crushing in the compression diagonal (Dall'Asta et al 2015, 2017). Such issues are strictly related to the lack of a specific capacity design procedure that allows to control the formation of the

[1] Associate Professor, University of Camerino, Ascoli Piceno, Italy, alessandro.zona@unicam.it
[2] Lecturer, University College of London, London, UK
[3] Professor, University of Camerino, Ascoli Piceno, Italy
[4] Professor, University of Camerino, Ascoli Piceno, Italy

dissipating mechanism. Refined analyses carried out on SRCWs designed according to Eurocodes demonstrated an unsatisfactory fragile behaviour due to the severe damage occurring to the concrete long before yielding of the ductile elements (Dall'Asta et al. 2015, 2017). The failure mechanism was generally characterised by yielding of the steel frame concentrated in the elements near the bottom of the wall, at the connections between the horizontal and the vertical parts. The plastic deformation on the concrete infill walls develops along a diagonal path. In addition, localized plastic deformations are also present near the corners of the infill walls due to the local action of the first studs of the horizontal and vertical elements (Dall'Asta et al. 2015, 2017).

The innovative SRCWs system depicted in Figure 1 was proposed in the INNO-HYCO project to overcome such critical aspects. The reinforced concrete infill walls are not connected to the vertical columns where the energy dissipation is expected. The system is conceived to control the formation of diagonal struts in the infill walls and behaves as a truss brace instead of a shear wall. The energy dissipation takes place only in the vertical elements of the steel frame subjected mainly to axial forces without involving the reinforcements of the infill walls. Detailing of the connection of the dissipative elements should allow their replacement and the possible use of buckling-restrained elements. The formation of the diagonal strut is ensured by joint stiffeners and bearing plates. The joint may be welded in shops allowing speeding up the erection phases.

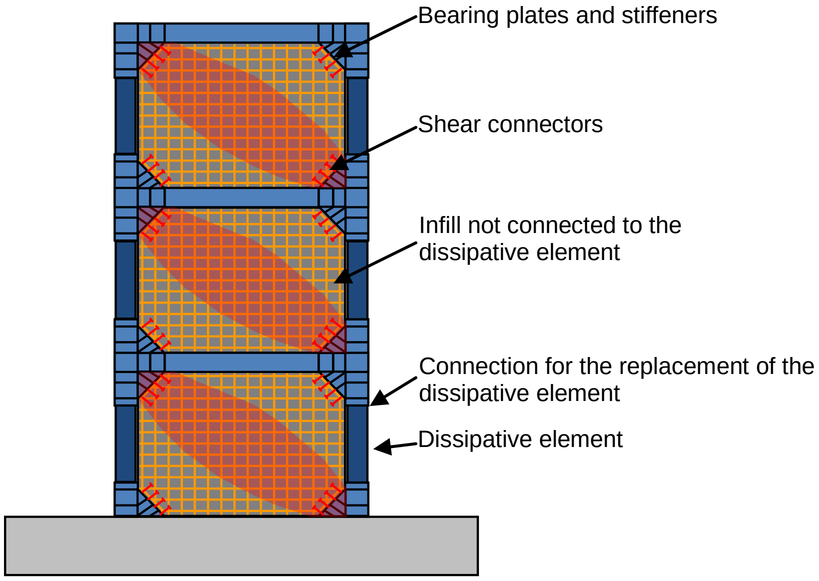

Figure 1. Innovative SRCW developed and tested.

Reinforced concrete walls coupled with steel links

The term hybrid coupled walls (HCWs) commonly refers to a structural scheme made by two reinforced concrete walls connected through steel or composite steel-concrete coupling beams, *e.g.* El-Tawil et al. 2010. Such conventional HCWs derive from coupled reinforced concrete walls where the reinforced concrete coupling beams are substituted by the more efficient and easier to repair steel or steel-concrete counterparts. Innovative HCWs, as developed within the INNO-HYCO project, are made by a single RC wall coupled to two steel side columns by means of steel links, as depicted in Figure 2. The coupling steel links transmit to the side columns their shear force and no bending moment while both shear and bending moment are exchanged between the links and the reinforced concrete wall. Accordingly, the side columns are subject to an alternation of compression and tension with small bending moments due to the eccentricity of the link connections and to the geometric nonlinear effects determined by the lateral displacements. For the same reasons, the reinforced concrete wall is subjected to bending with a small and constant amount of axial force deriving from permanent loads.

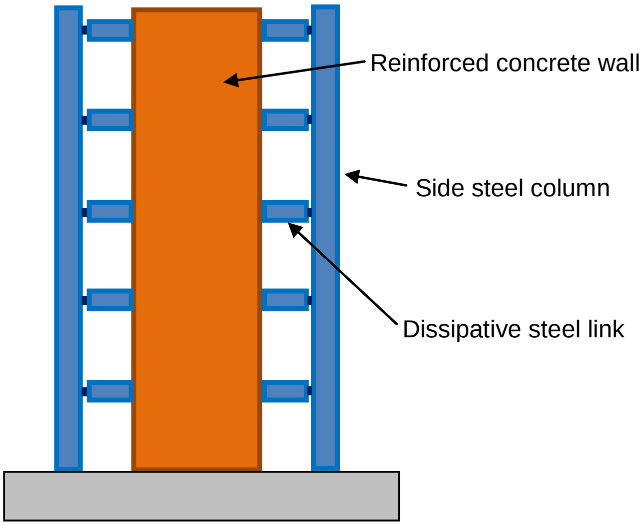

Figure 2. Innovative HCW proposed and tested.

Seismic design of steel frames with reinforced concrete infill walls

The proposed innovative SRCW is composed by elements with specific tasks according to a proper capacity design. The design procedure is force-based and considers the simple statically determined scheme representing the limit behaviour of the SRCW as depicted in Figure 3.

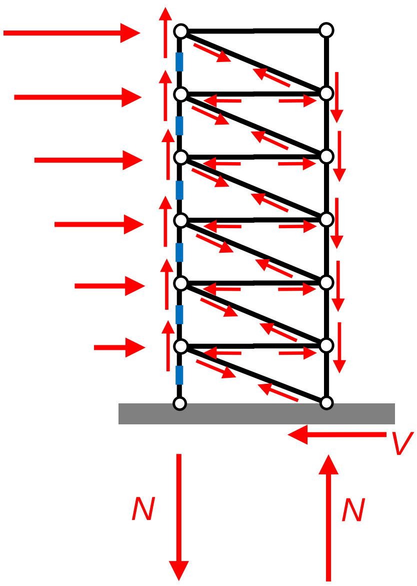

Figure 3. Static scheme of the considered SRCW system.

The following nine steps are required for the seismic design of the proposed innovative SRCW: 1) definition of the static equivalent lateral loads and calculation of the truss actions with a design spectrum reduced by a suitable behaviour factor; 2) design of the cross sections of the ductile boundary elements in tension (these elements are subjected also to compression under the reversed loadings but they are not expected to undergo plasticization under these forces); 3) capacity design of the connection of the ductile elements and of the adjacent elements; 4) calculation of geometric over-strength factors (as the ratio of the real plastic resistance of the ductile element and the relevant design force) to guarantee yielding of the edge steel elements at the different levels and avoid soft storeys (differences between the maximum over-strength and the minimum value must be less than 25%); 5) calculation of axial forces in non-ductile elements by combining the effects of gravity loads with those of the seismic action suitably magnified; 6) capacity design of the reinforced concrete infill against concrete crushing to assure the good performance of the system that should not be affected by the wall failure (concrete crushing); 7) design of the beams in tension for magnified axial forces; 8) check and possible re-design of the compressed edge elements, design the shear connection between the wall and the frame, check of the vertical strut developing in the wall; 9) calculation of the length of the dissipative element, in order to ensure the compliance between local and global ductility. Details for the nine design steps can be found in Dall'Asta et al. (2017).

A number of case studies designed according to the outlined procedure were analysed (Dall'Asta et al. 2015, 2017). In order to provide a sample of the obtained results, comparisons are made between a refined nonlinear finite element model developed in ABAQUS using shell elements and the simplified model upon which the design procedure is developed (Figure 4). In the finite element model, the geometry of the system was closely reproduced and concrete infills were supposed to be connected only at the inclined bearing plates where stud connectors are placed. Wall reinforcements were considered by introducing two layers of rebars. A coarse mesh (mean size of 0.5 m) was adopted for the concrete walls whereas a more refined mesh (mean size of 0.1 m), was adopted for the steel members. A smeared cracking model with full shear retention was adopted for concrete by assuming the Mander's law in compression and a linear elastic law in tension; a linear softening branch was adopted to simulate the tension-stiffening of bars after cracking. Elastoplastic-hardening models were considered for the steel rebars and the steel frame calibrating stiffness coefficients, yielding points and ultimate strengths with the mechanical characteristics of materials adopted in the design. Figure 4 shows a comparison between the pushover curve obtained by using the proposed design method for SCRW systems and the pushover curve given by the finite element analysis. The yielding pattern, characterised by plastic strain only at the ductile elements, fully agrees with the dissipating mechanism to which the design procedure is aimed. Even the sequence of yielding of ductile elements is well predicted in the design phase. The good agreement between results demonstrates that the design procedure proposed is suitable for the dimensioning of the system elements.

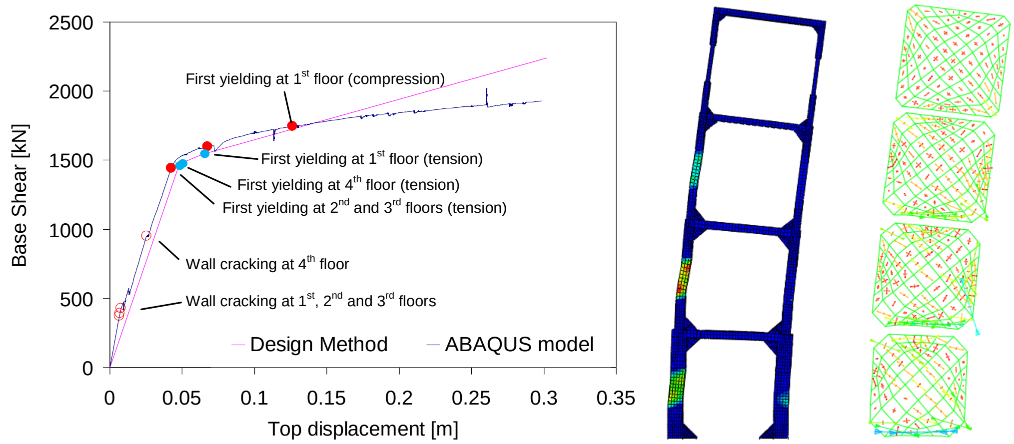

Figure 4. Comparison of pushover curves for SRCW and stress field in the steel frames and in the reinforced concrete wall.

Seismic design of reinforced concrete walls coupled with steel links

A ductile design procedure was proposed in Zona et al. (2016) in order to accomplish a seismic resistant behaviour where yielding of a large number of the replaceable steel links occurs while the RC wall is still undamaged. The main design parameter is the coupling ratio (CR), *i.e.* the ratio of the overturning moment resisted by the two side columns and the total resisted overturning moment:

$$CR = \frac{M_c}{M_c + M_w} \tag{1}$$

where M_w is the moment at the base of the reinforced concrete wall and $M_c = N_c{\cdot}L_{tot}$ is the moment resulting from the coupling of vertical forces resisted by the two side columns (*i.e.*, N_c is the axial force in the columns as shown in Figure 5), being $M_c + M_w$ the total overturning moment at the base of the HCW.

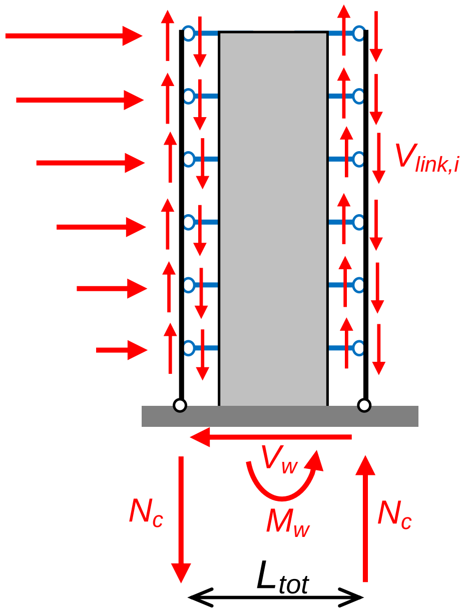

Figure 5. Static scheme of the considered HCW system.

The main design steps used for dimensioning the seismic-resistant mechanism are: 1) the reinforced concrete wall is proportioned in bending to have sufficient lateral deformation capacity to allow yielding of the steel links and its cross section designed and detailed to remain undamaged until all links are yielded; 2) the dissipative steel links are designed based on the chosen CR assuming a distribution along the HCW height of shear forces (uniform or non-uniform); 3) the side steel columns are designed to remain in the elastic range (strength and stability requirements) enforcing over-strength with respect to the condition of all links yielded in shear; 4) the base shear force corresponding to the fully developed plastic mechanism is estimated and assigned entirely to the reinforced concrete wall enforcing its over-strength to avoid any collapse mechanisms in shear. The dissipative shear links are designed using the prescriptions of Eurocode 8 for dissipative links in eccentric braces, given the similarities of their seismic behaviour, either with no specific enforcement on the link damage mechanism or requiring a shear dissipative mechanism, *i.e.* short link classification (Das et al. 2018).

Nonlinear finite element analyses on various case studies designed according to the proposed innovative design procedure highlighted the expected good seismic performance of the innovative HCW (Zona et la. 2016, 2018, Das et al. 2018). For example, Figure 6 shows the results of nonlinear dynamic analyses performed using as seismic input a set of 30 natural ground motion records from the European Strong Motion Database scaled to match on average the Eurocode 8 type I soil A pseudo-acceleration response spectrum with PGA = 0.20g. The scalded accelerograms are multiplied by a factor varying from 0.1 (PGA 0.02g) to 3.5 (PGA 0.70g). The incremental analyses are terminated whenever one of the following events is attained first: a) the maximum concrete strain (values averaged over the 30 accelerograms) reaches the ultimate concrete strain; b) PGA 0.70g is reached. Overall, the following general conclusions can be made: a) for CRs equal to 0.40 and 0.60 all the steel links are yielded when the reinforced concrete wall is still in its elastic range; b) if the design is made with CR 0.80 the obtained HCWs are stiffer and unable to yield all steel links before yielding the reinforced concrete wall, thus, the design objectives are not completely met; c) regardless the value of CR adopted, failure of the reinforced concrete wall either in bending or in shear is reached for seismic intensities significantly higher than those considered in the design, thus, the design objectives aiming at a dissipative behaviour that excludes collapse in the reinforced concrete wall are met; d) the side steel columns remain in their elastic range regardless of the adopted CR, thus, the design objective of side columns undamaged is satisfied.

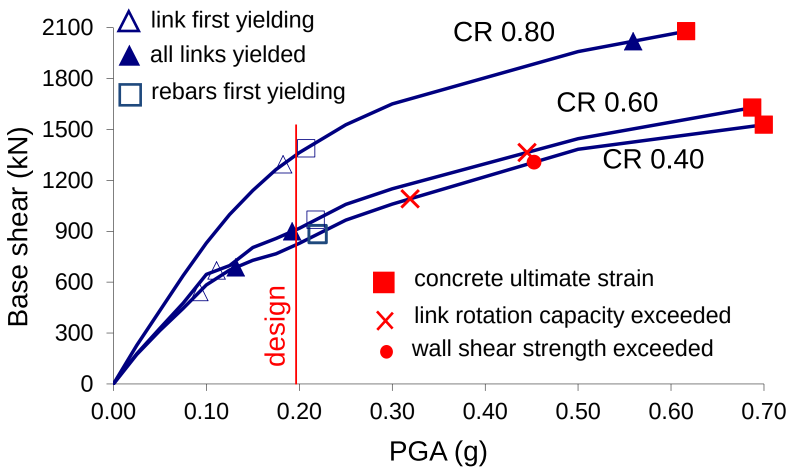

Figure 6. Results of multi-record nonlinear incremental dynamic analysis for a 6-storey HCW case study (results averaged over 30 accelerograms).

Conclusions

The combination of steel and concrete for the development of innovative hybrid structural systems appears to be a promising way to design against earthquakes in an effective and efficient manner. In this context, two innovative structural systems developed within a recent European research project were reviewed in order to highlight that simple design concepts and procedures allow achieving superior seismic performances with the seismic dissipation concentrated in selected steel components, acting as fuses that can be easily substituted if damaged after major seismic events.

References

Dall'Asta A, Leoni G, Morelli F, Salvatore W and Zona A (2017), An innovative seismic-resistant steel frame with reinforced concrete infill walls, *Engineering Structures*, 141(1): 144-158

Dall'Asta A, Leoni G, Zona A, Hoffmeister B, Bigelow H, Degée H, Braham C, Bogdan T, Salvatore W, Morelli F, Tsintzos P, Karamanos SA, Varelis GE, Galazzi A, Medici E, Boni P (2015), Innovative hybrid and composite steel-concrete structural solutions for building in seismic area, Final Report, EUR 26932 EN, European Commission

Das R, Zona A, Vandoren B and Degeé H (2018), Optimizing the coupling ratio in the seismic design of HCW systems with shear dissipative links, *Journal of Constructional Steel Research*, 147(1): 393-407

El-Tawil S, Harries K, Fortney P, Shahrooz B, and Kurama Y (2010), Seismic design of hybrid coupled wall systems: state of the art, *Journal of Structural Engineering*, 136(6): 755-769

Hajjar JF (2002), Composite steel and concrete structural systems for seismic engineering, *Journal of Constructional Steel Research*, 58(1): 703-723

Morino S (1998), Recent developments in hybrid structures in Japan: research, design and construction, *Engineering Structures*, 20(1): 336-346

Zona A, Degeé H, Leoni G and Dall'Asta A (2018), Ductile design of innovative steel and concrete hybrid coupled walls, *Journal of Constructional Steel Research*, 117(1): 204-213

Zona A, Tassotti L, Leoni G and Dall'Asta A (2018), Nonlinear seismic response analysis of an innovative steel and concrete hybrid coupled wall system, *Journal of Structural Engineering*, 144(7): 04018082