

**PROGETTAZIONE SISMICA ED ANALISI PRELIMINARI DI
UNA PARETE PREFABBRICATA IBRIDA ACCIAIO-
CALCESTRUZZO**

**SEISMIC DESIGN AND PRELIMINARY ANALISES OF A
MODULAR HYBRID STEEL-CONCRETE WALL**

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ABSTRACT

Steel frames with reinforced concrete infill walls (SRCWs) are an interesting structural solution for applications in seismic areas if designed to exploit the stiffness of reinforced concrete (RC) and the ductility and dissipative capacity of steel. Three horizontal resisting mechanisms can be identified in SRCW: 1) contribution of the steel frame; 2) direct interactions between the steel frame and the compression strut in the RC infill walls; 3) interactions between steel frame and the RC infill wall through friction and shear connectors. While Eurocode 8 considers SRCWs to behave essentially as RC walls, numerical analyses demonstrated that this assumption may be far from reality. Innovative solutions for SRCW and relevant design approaches were eventually proposed in order to achieve a structural system able to fully exploit the advantages of the steel and RC components. In this context, the present study investigates a type of innovative modular SRCW through numerical simulations allowing a better understanding of its structural behaviour.

SOMMARIO

Telai in acciaio con pareti in calcestruzzo armato collocati all'interno di ciascun campo sono sistemi strutturali con potenziali vantaggi nei confronti dell'azione sismica quali l'elevata rigidità, legata alla presenza delle pareti in c.a. e la possibilità di sfruttare l'elevata duttilità delle componenti in acciaio. In tali sistemi è possibile individuare tre meccanismi resistenti alle forze orizzon-

tali: 1) il contributo del telaio in acciaio; 2) le interazioni dirette tra il telaio in acciaio e la diagonale compressa nella parete in c.a.; 3) le interazioni tra il telaio in acciaio e la parete in c.a. tramite le forze di attrito e i connettori a taglio tra le due componenti. L'Eurocodice 8 considera il comportamento di tali sistemi assimilabile a quello di pareti in solo c.a. Tuttavia, analisi numeriche hanno dimostrato che l'assunzione che il sistema ibrido si comporti come una parete in c.a. può essere lontana dalla realtà. Soluzioni innovative per questa tipologia strutturale e metodi di progetto sono stati proposti con l'obiettivo di ottimizzare i vantaggi delle componenti e dei due materiali coinvolti. In questo contesto, nel presente lavoro, modelli numerici sono utilizzati per studiare alcuni aspetti relativi alle prestazioni sismiche di tali pareti ibride con l'obiettivo di fornire indicazioni utili al progetto.

1 INTRODUCTION

Steel frames with reinforced concrete infill walls (SRCWs) have potential advantages as seismic-resistant systems, e.g., high initial stiffness of the concrete useful to minimize the damage of non-structural elements under 'frequent' (i.e., low and moderate-intensity) earthquakes and the ductility and dissipative capacity of the steel allowing a good performance under 'rare' (i.e., high-intensity) events. Besides, hybrid steel-concrete structures combine the versatility of metal structures in the provisional phase, with the resistance of the composite sections in the working phase. The completely self-supported elements, produced at the factory, are mounted at the site, eliminating the need for formwork and temporary shoring, thus, enabling a fast construction. Eurocode 8 [1] considers SRCW systems to behave essentially as reinforced concrete (RC) walls able to dissipate the seismic input energy in the vertical steel sections and in the vertical reinforcing bars of the concrete wall. The same detailing provisions provided for RC walls are proposed also for SRCWs except for a few recommendations concerning the distribution and resistance of the shear connections. It is noted that Eurocode 8 [1] provides only few executive details and suggestions in order to carry out analyses of SRCWs systems and detailed design rules are missing [2]. Furthermore, numerical analyses recently carried out on SRCWs, designed according to the Eurocodes, pointed out an unsatisfactory seismic behaviour and demonstrated how the assumption that SRCWs behave as a RC shear wall may be far from reality [3]. Three horizontal resisting mechanisms can be identified in SRCW: 1) contribution of the steel frame; 2) direct interactions between the steel frame and the compression strut in the RC infill walls; 3) interactions between the steel frame and the RC infill wall through friction and shear connectors. Different types of SRCWs can be identified depending on the type of beam-to-column connection of the steel frame, on the distribution of shear studs along the interface between the steel frame and the infill wall [3][4]. Test results showed that the presence of shear connectors along the interface between the steel frame and the infill walls increases the global strength, stiffness and energy dissipation capacity [5] [6] of the system. Numerical analyses of the system, investigating the influence of the shear studs distribution [4] on the structural behaviour of SRCWs, highlighted that the presence of the shear studs in the column of the frame does not influence in a sensitive way the initial stiffness and the global resistance. Differently, the presence of the shear studs at the corners of the steel frame significantly increases the initial stiffness, while the global resistance is not affected [4]. A review of the state-of-the-art of SRCWs reveals how the intuitive idea of stiffening a steel frame with a RC infill is, in reality, a rather complex mechanism to be controlled and affected by many variables. Ambiguity in the definition of the resisting mechanism is accompanied by a lack of capacity design rules [3]. In this study, some of the developments made for innovative SRCW in [2] and [3] are transferred to hybrid shear walls made of steel and concrete partially precast and cast in situ. Numerical models are analysed to provide a better understanding of the global behaviour of the considered SRCWs and to check the validity of the proposed structural solutions.

2 PROPOSED SRCW SYSTEMS

The proposed SRCWs are designed following these assumptions: 1) structures remain elastic under the design seismic events, i.e., no dissipative components are considered and, hence the behaviour factor is equal to 1.5 according to Eurocode 8 [1]; 2) shear studs are introduced at the corners and along the horizontal beam of the steel frame only, i.e., no shear studs are adopted between the columns and the RC wall; 3) the use of several different steel profiles is investigated, i.e., HEB sections and concrete-filled hollow sections. Moreover, while the SRCWs are always considered as the main resisting system for the horizontal actions, the influence of the horizontal resistance of the gravity frame working in parallel is investigated. This may be negligible when the gravity frame has 'pinned' beam-to-column connections, whereas, it may be important and significantly influence the seismic behaviour of the structure when the gravity frame is constituted by steel-concrete composite components. Several situations are investigated in this context. A first structural configuration, indicated as Type S, is considered representing SRCWs connected to a gravity frame constituted by 'pinned' steel components. A second configuration, named Type SCC, is considered to represent SRCWs connected to a gravity frame constituted by composite steel-concrete components. The composite gravity framed structure is made of concrete-filled hollow section columns and composite truss beams with steel bottom plate. Given that the experimental tests reported in [2] and [3] showed that infill walls tends to develop a pattern of diagonal cracks (Fig. 1), SRCWs are analysed as lattice structures whose elements can be dimensioned based on statically-determinate schemes (see Fig. 2), as detailed in [3]. The use of concrete-filled hollow section columns in SRCWs is evaluated in order to increase the compatibility with the Type SCC solution, allowing easy connection with the composite beams of the framed building. The corners of the frame are shaped to support the diagonal strut formation through the use of inclined stiffened plates, as already developed and tested in [2] and [3]. Design rules not explicitly illustrated here were defined in accordance with the Eurocodes [7-9].

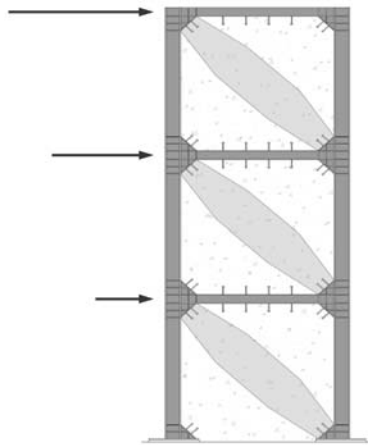


Fig. 1. SRCW system.

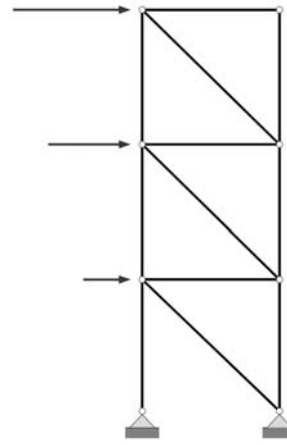


Fig. 2. Lattice structure representation of the SRCW.

3 CASE STUDIES

3.1 Steel frame (Type S)

A three-storey steel frame with SRCWs is considered as case study and analysed under several design conditions. The building has a $25.00\text{ m} \times 16.70\text{ m}$ floor footprint (Fig. 3) and constant inter-storey height (3.50 m). The same building was previously investigated and information regarding the gravity loads are reported in [2]. The building is assumed located in Camerino, Italy and the seismic action is defined based on a reference peak ground acceleration a_g equal to $0.193g$ and a soil type B, i.e., soil factor S equal to 1.2 [2]. In the present configuration, four SRCWs are considered for each direction.

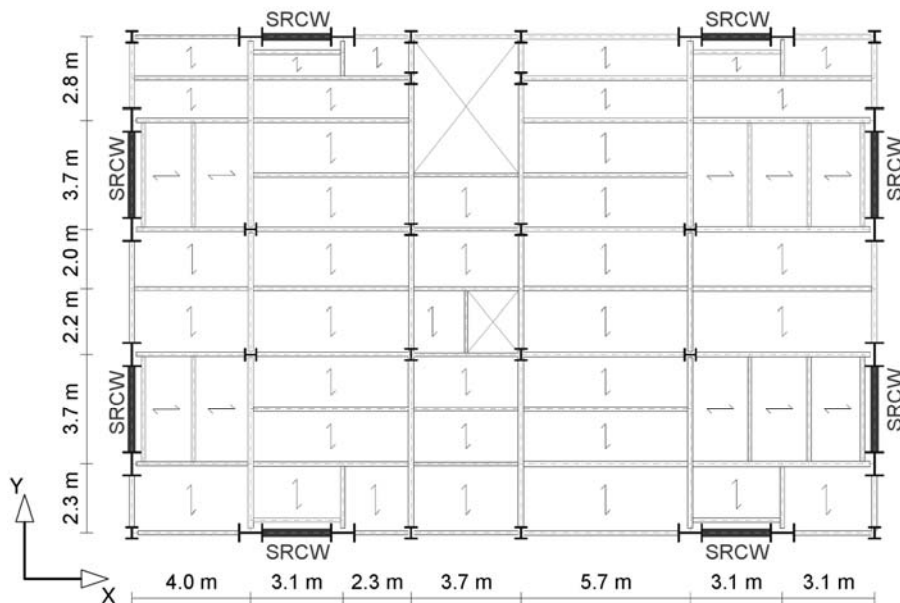


Fig. 3. Floor geometry of the benchmark structure with positions of the SRCWs.

The three considered models (see Table 1) are made of steel columns (HE200B) and beams (IPE) for each storey. Steel S275 is used for steel frames.

Table 1. SRCWs of the steel frames.

Model	Steel frame	SRCW system		
		Columns	Beams	Wall thickness
S1	Gravity-resisting frame	HE340B	HE220B	220 mm
S2	Gravity-resisting frame	$300\text{ mm} \times 400\text{ mm}; t = 10\text{ mm}$	HE220B	220 mm
S3	Moment-resisting frame	$300\text{ mm} \times 400\text{ mm}; t = 10\text{ mm}$	HE220B	220 mm

The SRCW systems are considered as lattice structures and designed according to statically-determinate schemes (Type S). The SRCWs have infill walls with thickness equal to 0.22 m and made with concrete C35/45 and steel bars B450C. The diagonal struts of the SRCWs were modelled as RC beams (0.22 m \times 0.51 m) that are pinned at their ends. Steel S355 is used for the steel frame of the hybrid systems. The models S1 and S2 have different SRCWs (see Table 1) connected to the same steel frames. These SRCWs have concrete-filled hollow section columns. Differently, the third case (model S3) is considered with the aim to investigate the influence of the conventional simplification of ‘pinned’ connections. In order to do so, by keeping the same dimensions of the structural elements, the opposite condition of fixed beam-column connections is evaluated. Geometry, material properties, loads, and the SRCWs are the same of the model S2.

3.2 Steel-concrete composite frame (Type SCC)

A four-storey steel-concrete composite frame is considered as case study. The building has total floor dimensions of 42.50 m \times 12.80 m as reported in Fig. 4 and constant inter-storey height (3.40 m). The building uses unidirectional floors, made of self-supporting slabs for lengths up to 5 m partially precast and cast in situ. The building is located in Domegge di Cadore, Italy and the seismic action is defined based on a reference peak ground acceleration a_g equal to 0.133g and a soil type C, i.e., soil factor S equal to 1.5, and a topographic factor equal to 1.2. The gravity loads are: permanent structural load $G = 2.30$ kN/m², non-structural members load $G = 2.00$ kN/m² and variable actions $Q = 2.00$ kN/m² or 4.00 kN/m² arising from residential occupancy or communal passages, respectively. The roof loads are: permanent load $G = 2.00$ kN/m², non-structural members load $G = 2.00$ kN/m² and variable actions $Q = 3.00$ kN/m². Two types of concrete-filled composite columns were used simultaneously: circular section with external diameter equal to 508 mm (steel thickness equal to 6.35 mm) and square section 400 mm \times 400 mm (steel thickness equal to 12.5 mm). The structural members used for the columns are concrete-filled hollow sections with circular section (i.e., external diameter of 508 mm and steel thickness of 6.35 mm) and square section (i.e., 400 m \times 400 mm with thickness of 12.5 mm). Steel S235 and steel S275 are used for circular and square columns, respectively. The concrete for the composite columns is C28/35. The composite truss beams are made of steel S355 and concrete C28/35. These beams have rectangular cross sections of dimensions equal to 0.40 m \times 0.26 m or to 0.50 m \times 0.26 m. The effects of creep were taken in account according to Eurocode 4 § 5.4.2.2 [11]. The flexural stiffness of the composite beams and columns were determined respectively according to Eqns. 7.13 and 7.14 Eurocode 8 § 7.7.2 [1].

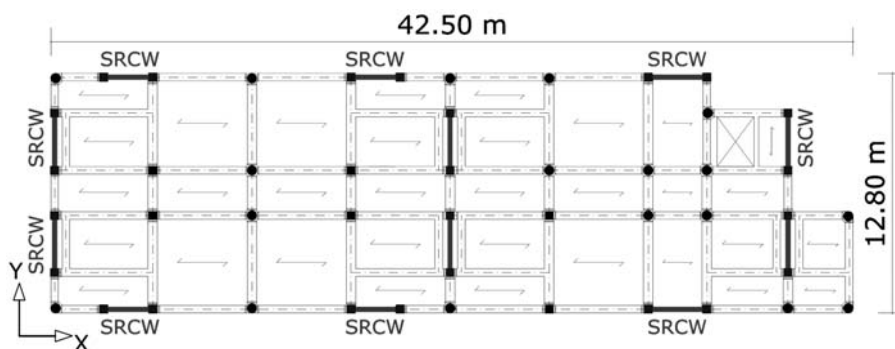


Fig. 4. Floor geometry of the steel-concrete composite structure with SRCWs (case study provided by Tecnostrutture s.r.l.).

The model SCC1 is the described moment-resisting composite frame where a behaviour factor q equal to 3.2 was used for the design. In the second case (model SCC2), the moment-resisting composite frame of the case SCC1 includes also the addition of six SRCWs for each direction (Fig. 4). The third case analysed (model SCC3) has the same structure of SCC2, but the concrete-filled hollow sections columns of the frames have different cross sections (see Table 2).

Table 2. SRCWs of the steel-concrete composite frames.

Model	Concrete-filled hollow section columns		SRCW system		
	External diameter	Steel thickness	Square Column		Steel beam
			Dimensions	Steel thickness	
SCC1	508 mm	6.35 mm	-	-	-
SCC2	508 mm	6.35 mm	400 mm × 400 mm	12.5 mm	HE220B
SCC3	406 mm	10.00 mm	400 mm × 400 mm	12.5 mm	HE220B

The hybrid shear walls connected to steel-concrete composite frames are not considered as lattice structures, due to the joint type between the composite truss beams and the SRCWs. Thus, the filled composite columns are affected by both axial force and bending moment. The SRCW systems are made of steel S275 and concrete C28/35. The diagonal struts of the SRCW systems have thickness equal to 0.22 m and they are modelled as RC frame elements, with dimensions 0.22 m × 0.51 m, pinned at their ends and connected with the beam-column intersections of the steel frame. Infill walls are made of concrete C28/35 and steel bars B450C.

4 PRELIMINARY RESULTS

4.1 Steel frame (Type S)

For the considered buildings the inter-storey drifts are smaller than 5%. The inter-storey drifts of the model S2 are slightly smaller than those of the model S1 due to the different stiffness of the SRCWs while it is about the same for the models S2 and S3. In order to investigate the influence of both the stiffness of the SRCWs and the connection types of the steel frames is useful to compare the internal forces of the hybrid shear walls (see Table 3).

Table 3. Compressive forces for the elements of a representative SRCW.

Representative SRCW system - X direction										
Storey	Model S1		Model S2				Model S3			
	Diagonal strut	Steel Columns	Diagonal strut		Filled composite columns		Diagonal strut		Filled composite columns	
	N (kN)	N (kN)	N (kN)	Δ_{S1} (%)	N (kN)	Δ_{S1} (%)	N (kN)	Δ_{S2} (%)	N (kN)	Δ_{S2} (%)
1	-1171.5	-1171.4	-1212.5	+3.5	-1238.8	+5.8	-1180.0	-2.7	-1178.4	-4.9
2	-899.3	-447.5	-935.6	+4.0	-480.3	+7.3	-904.5	-3.3	-448.5	-6.6
3	-486.7	-32.4	-510.8	+4.9	-39.8	+22.9	-480.7	-5.9	-36.7	-7.8

The compression forces of the diagonal struts and of the columns of SRCWs of the model S2 are slightly bigger than those of the model S1 due to an increment of the stiffness of the considered SRCWs in X-direction. Similar results are observed for the Y-direction. For gravity-resisting steel frames the increment of the stiffness of SRCWs is useful to control the inter-storey drifts.

The models S2 and S3 have the same hybrid shear walls. The internal forces of the SRCWs for the model S3 are slightly smaller than those of the model S2, due to the influence of the moment-resisting connections of the gravity frames of the model S3. On the other side, the gravity columns of the model S3 have normal stress larger than those of the model S2 (with increase at least equal to 30%). This highlights that the connection type influences significantly the normal stress of the gravity frames while both the inter-storey drifts and the components of the SRCWs are slightly influenced due to the stiffness of the hybrid walls.

4.2 Steel-concrete composite frame (Type SCC)

The use of SRCWs in the model SCC2 causes a significant decrement of the bending moments in the internal and perimeter columns of the frames. On the other side, the comparison between the models SCC1 and SCC2 highlighted that the variations of axial forces are negligible for the internal columns (see Table 4). The comparison between the models SCC1 and SCC2 highlighted remarkable decreases of inter-storey drifts. Furthermore, the internal columns are not affected by tensile axial forces. Thus, the increment of the seismic input for the model SCC2, due to the reduction of the behaviour factor q , is supported by SRCWs. These results allowed reducing the dimensions of the cross section for the circular columns (model SCC3, see Table 2). The inter-storey drifts of the model SCC3 are very close to those of the model SCC2. The comparison between the internal forces of the SRCWs for the models SCC2 and SCC3 highlighted that the differences are negligible. In the model SCC3, the columns highlighted an additional reduction of the bending moments compared to those of the model SCC1 (see Table 5).

Table 4. Envelope of the internal axial forces and bending moments of the internal circular columns for the models SCC1 and SCC2

Axial forces or bending moments	Model SCC1	Model SCC2	Δ_{SCC1} (%)
N_{\min} (kN)	-1056.22	-1060.82	0.44
N_{\max} (kN)	-398.49	-402.20	0.93
$M_{y,\max}$ (kNm)	137.12	116.13	-15.31
$M_{x,\max}$ (kNm)	167.66	122.10	-27.17

Table 5. Envelope of the internal axial forces and bending moments of the internal circular columns for the model SCC1 and SCC3.

Axial forces or bending moments	Model SCC1	Model SCC3	Δ_{SCC1} (%)
N_{\min} (kN)	-1056.22	-1030.85	-2.40
N_{\max} (kN)	-398.49	-397.48	-0.25
$M_{y,\max}$ (kNm)	137.12	77.62	-43.39
$M_{x,\max}$ (kNm)	167.66	83.34	-50.29

5 CONCLUSIONS

The present study investigates the seismic performance of steel frames with reinforced concrete infill walls (SRCWs) under several design conditions and when used in combination with gravity steel frames or steel-concrete composite frames. The preliminary results provide some insights demonstrating the effectiveness of the proposed solution in both limiting the damage of the non-structural elements and reducing the internal actions of the connected frames. Future research in this direction will focus on the experimental evaluation of the proposed system allowing the validation of accurate numerical models and the definition of thresholds for damage states. Non-linear dynamic analysis will be performed accounting also for the effect of the record-to-record variability allowing the definition of fragility curves.

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REFERENCES

- [1] UNI EN 1998-1, Eurocode 8, Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, 2005
- [2] Dall'Asta A., Leoni G., Zona A., Hoffmeister B., Bigelow H., Degée H., Braham C., Bogdan T., Salvatore W., Morelli F., Tsintzos P., Karamanos S. A., Varelis G. E., Galazzi A., Medici E., Boni P., Innovative hybrid and composite steel-concrete structural solutions for building in seismic area, Final Report, EUR 26932 EN, European Commission, 2015
- [3] Dall'Asta A., Leoni G., Morelli F., Salvatore W., Zona A., An innovative seismic-resistant steel frame with reinforced concrete infill walls, *Engineering Structures*, Vol. 141, pp 144-158, 2017
- [4] Morelli F., Mussini N., Salvatore W., Influence of shear studs distribution on the mechanical behaviour of dissipative hybrid steel frames with r.c. infill walls, *Bulletin of Earthquake Engineering*, Vol. 17, pp 957-983, 2019
- [5] Morelli F., Manfredi M., Salvatore W., An enhanced component based model of steel connection in a hybrid coupled shear wall structure: development, calibration and experimental validation, *Computers & Structures*, Vol. 176, pp 50-69, 2016
- [6] Tong X., Hajjar J. F., Schultz A. E., Shield C. K., Cyclic behavior of steel frame structures with composite reinforced concrete infill walls and partially restrained connections, *Journal of Constructional Steel Research*, Vol. 61, pp 531-52, 2005
- [7] EN 1992-1-1, Eurocode 2, Design of concrete structures - Part 1-1: General rules and rules for buildings, 2005
- [8] EN 1993-1-1, Eurocode 3, Design of steel structures - Part 1-1: General rules and rules for buildings, 2005
- [9] EN 1994-1, Eurocode 4, Design of composite steel and concrete structures - Part 2: General rules and rules for bridges, 2006

KEYWORDS

Hybrid structures, Seismic design, Shear walls, steel structures, steel-concrete composite structures.