Preliminary studies on a prefabricated hybrid steel-concrete seismic-resistant wall

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Keywords: Hybrid structures, Seismic design, Shear walls, Steel-concrete composite structures.

ABSTRACT
Steel frames with reinforced concrete infill walls (SRCWs) have potential advantages as seismic-resistant systems. However, the review of the state of the art highlighted how the behaviour of hybrid shear walls is rather difficult to be controlled due to ambiguities in the definition of the resisting mechanism and lack of capacity design rules. While Eurocode 8 considers SRCWs to behave essentially as reinforced concrete walls, numerical analyses carried out on SRCWs demonstrated that this assumption may be far from reality. In this study an innovative structural concept of hybrid shear walls made of steel and partially precast concrete is presented. Numerical models are used to investigate the seismic performances of the proposed SRCW system and its components when connected to steel and steel-concrete composite frames.

1 INTRODUCTION

Recent earthquakes highlighted the need to develop structural solutions able to ensure both life safety and reduce economic losses (Braga et al. 2014). Significant repair and reconstruction costs (Demartino et al. 2017), as consequence of earthquake events, fostered the need to define innovative structural systems able to minimize both non-structural damages and content losses after 'frequent' low-to-moderate seismic events.

The use of innovative hybrid steel and reinforced concrete structures has proved to be a possible interesting solution for the design of seismic-resistant structures with the potential of limiting both structural and non-structural damages. Several steel-concrete hybrid systems have been investigated (Dall'Asta et al. 2015). Amongst others, several studies focus on the seismic behaviour of steel-concrete hybrid coupled shear walls (HCSW) and steel frames with reinforced concrete infill walls (SRCW).

HCSW are considered in some international structural codes and also mentioned in Eurocode 8 (EN 1998-1, 2004) where, however, very few detailing rules are provided.

An innovative solution for HCSW systems was developed by the connection of a reinforced concrete (RC) wall to two steel side columns through steel dissipative links (Zona et al. 2018). This structural solution is conceived to limit building damage under low-intensity earthquakes, thanks to the stiffness of the RC wall, and to dissipate the seismic energy of high-intensity earthquakes, exploiting the ductility of the steel links. Also, the possibility to develop a ductile mechanism in which plastic deformations are mainly attained in the steel links has been analysed (Zona et al. 2016, Das at al. 2018).

Eurocode 8 (EN 1998-1, 2004) also considers SRCW systems, intended to behave as RC walls able to dissipate the seismic input energy through yielding of the vertical steel components of the frames. For this structural typology, however, Eurocode 8 (EN 1998-1, 2004) does not provide detailed design rules.

Three horizontal resisting mechanisms can be identified for SRCWs (Dall'Asta et al. 2017):

1. contribution of the frame od SRCW;
2. interactions between the steel frame and the compression struts in the RC infill walls;

3. interactions between steel frame and the RC infill wall through friction and shear connectors.

Different SRCWs can be identified based on the beam-to-column connection type and the distribution of shear studs along the interface between the frame and the RC infill wall (Dall'Asta et al. 2017). Other types of SRCWs incorporate also steel plates (Wang et al. 2017), concrete-filled columns and sandwich RC slabs (Suizi et al. 2019). The influence of shear connectors position between the steel frame and the RC infill wall was investigated by experimental test (Morelli et al. 2016; Tong et al. 2005) and numerical analyses (Morelli et al. 2019). Moreover, a tailored capacity design procedure, consistent with the Eurocode framework for seismic design, was developed for a SRCW system (Dall'Asta et al. 2017), i.e., the hybrid shear wall is conceived as a simple statically determinate structural scheme where the RC walls work as diagonal struts and energy dissipation occurs in the vertical steel elements yielding in tension.

Based on such a proposal, the innovative design concepts are here transferred to the new SRCWs. Numerical models are analysed to investigate the seismic performances of the proposed SRCWs when used in steel frames as well as in steel-concrete composite structures. The SRCW systems are designed to remain in the elastic range when design earthquakes occur; in this way the design criteria and the detailing rules for dissipative structural behaviour, i.e. capacity design rules, are avoid. Furthermore, this assumption allows to avoid the replacement of dissipative elements and to reduce the repair costs.

In order to make easier the design procedure for the steel-concrete composite structures, i.e. the design of the beam-to-column connection according to Eurocodes, the hybrid walls are conceived to support principally the horizontal forces; thus, attentions id made to investigate if the steel-concrete composite structure connected to SRCWs can be basically designed as a gravity-frame. This outcome has applications for steel-concrete composite moment-resisting frames.

2 PROPOSED SRCW SYSTEMS

2.1 Construction issues

The considered SRCW systems (Figure 1) have two main differences compared to hybrid walls analysed in other researches (Dall'Asta et al. 2015):

(1) The use of different column types, i.e., wide-flange cross section (Figure 2) and concrete-filled composite columns (Figure 3). The concrete-filled hollow section columns are investigated since they facilitate the connection between the SRCWs and the steel-concrete composite frames.

(2) No shear studs are adopted between the columns and the RC wall. Thus, the shear studs are introduced at the corners and along the horizontal steel beam of the frame only.

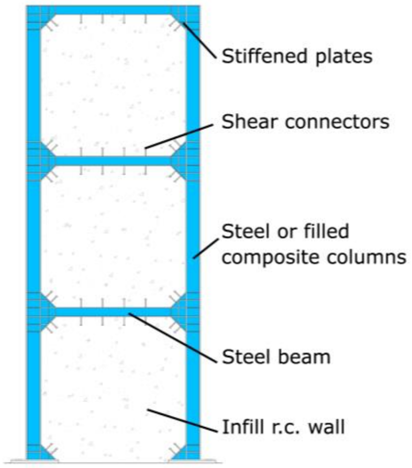

Figure 1. SRCW system.

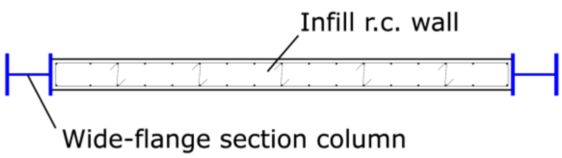

Figure 2. SRCW with wide-flange section columns.

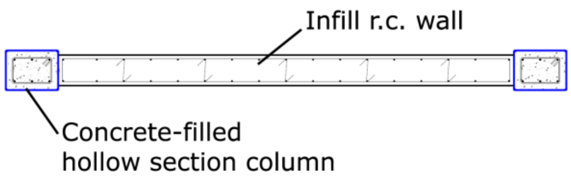

Figure 3. SRCW with concrete-filled hollow section columns.

2.2 Structural concept

Shear studs are placed at the corners and along the horizontal beams (Figure 1) of the steel frame in order to support the shear forces between the RC walls and the frame. This allows the development of appropriate stiffness and to prevent the out-of-plan overturning of the infill walls. Corners of the frame of the SRCWs are shaped in such a way to support the diagonal strut formation through the use of inclined stiffened steel plates. These permit the force exchanges between the RC infill walls and the frame of SRCW (Figure 4).

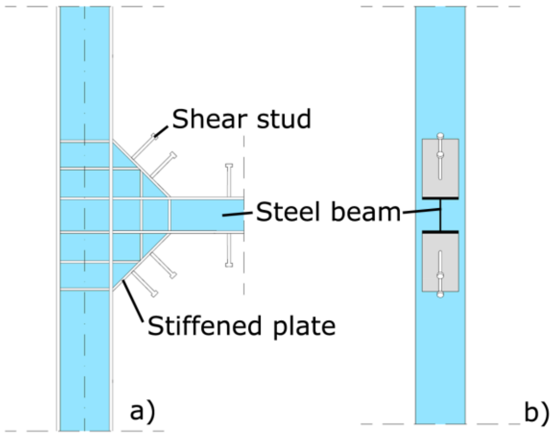

Figure 4. Corner of the SRCW system: (a) frontal and (b) transversal view.

When earthquakes strike, the SRCWs should be able to develop a resisting mechanism made up of a series of inclined struts affected by compression axial force (Figure 5). The considered structural concept is based on two assumptions:

(1) The described SRCW systems remain in the elastic range when the design seismic events occur and thus, the behaviour factor is assumed equal to 1.5 according to Eurocode 8 (EN 1998-1, 2004).

(2) If the SRCW system is connected to steel beams then it is intended to behave as a truss structure, whose elements can be dimensioned based on statically-determinate schemes, provided that there are not dual resisting systems generated by the interactions between SRCWs and the gravity frames. On the other side, when SRCW systems are connected to the considered composite truss beams the hybrid shear walls are not conceived as a truss-like structure.

Accordingly, two structural configurations are considered and investigated for the SRCWs. A first structural configuration, indicated as Type S, is considered to represent SRCWs connected to a steel frame. Experimental tests reported in literature (Dall'Asta et al. 2017), showed that infill walls tends to develop a pattern of diagonal cracks (Figure 5), therefore SRCWs are analysed as truss structures whose elements can be dimensioned based on statically-determinate truss model (Figure 6). All the components of the SRCWs are designed to remain in elastic range (or should to undergo very limited damages) when seismic events occurred.

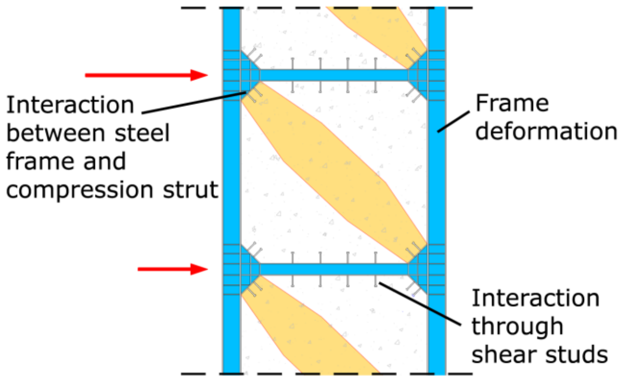

Figure 5. SRCW resisting mechanisms to horizontal actions.

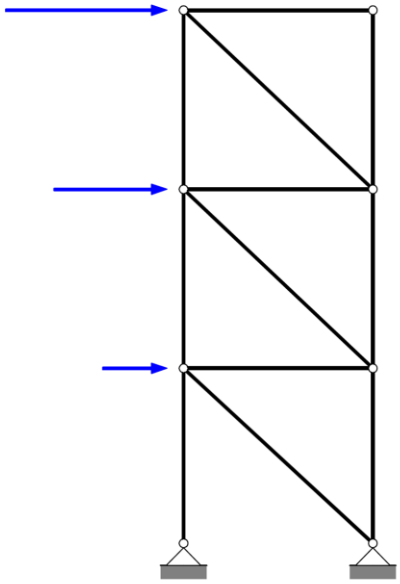

Figure 6. Truss structure representation of the SRCW for Type S.

A second structural configuration, indicated as Type SCC, is considered to represent SRCWs connected to steel-concrete composite frames. In particular, the considered system include concrete-filled hollow section columns and composite truss beams with steel bottom plate (Figure 7). The use of concrete-filled composite columns in the SRCW systems allows an easy connections with the composite truss beams of the frames. The composite truss beams for Type SCC are partially precast and completed in situ by concrete casting. The typology of connection between the SRCW system and the composite truss beams does not permit to consider the shear wall as a truss-like structure. Thus for Type SCC, the concrete-filled composite columns of the SRCW are affected by both axial force and bending moments.

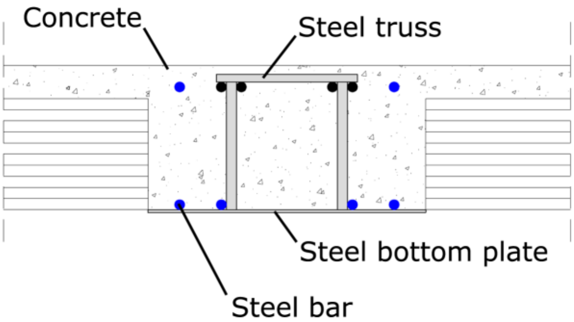

Figure 7. Transversal section of a steel-concrete composite truss beam.

Hence, the concrete-filled composite columns are affected by both axial force and bending moment and a different structure representation of SRCW must be considered for Type SCC (Figure 8).

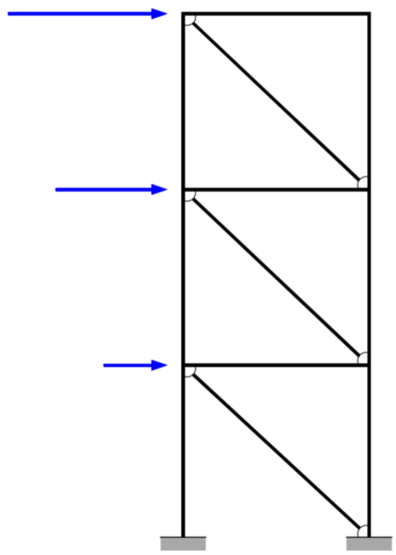

Figure 8. Structure representation of SRCW for Type SCC.

Also for the Type SCC, the corners of the SRCWs are shaped to support the diagonal strut formation through the use of inclined stiffened steel plates. Design rules of Eurocodes, i.e. EN 1992-1-1, EN 1993-1, EN 1994-1 and EN 1998-1, are considered for the SRCW components.

3 CASE STUDIES

3.1 Steel frame with SRCWs

A three-storey steel frame with SRCWs is considered as case study and analysed under several design conditions. The structure has a 25.00 m × 16.70 m floor footprint (Figure 9) and constant inter-storey height (3.50 m). The same building was previously investigated and information regarding the gravity loads are reported in (Dall'Asta et al. 2015). The building is assumed located in Camerino, Italy. 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 (Dall'Asta et al. 2015).

In the present configuration, four SRCWs are considered for each direction (Figure 9). The three considered models (Table 1) are made of steel columns and beams for each storey. Steel S275 is used for steel frames. The SRCW systems are considered as truss structures and designed according to statically-determinate schemes (Type S). The SRCWs (Table 2) have RC infill walls with thickness equal to 0.22 m and they are made of concrete C35/45 and steel bars B450C. The diagonal struts of the SRCWs were modelled as RC beams (0.22 m × 0.51 m) that are pinned at their ends. Steel S355 is used for the steel frame of the hybrid systems.

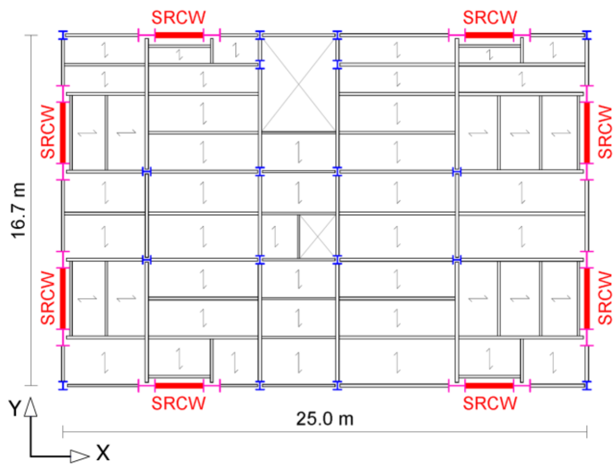

Figure 9. Floor geometry of the considered steel structure with SRCWs.

Table 1. Steel frame analysed (Type S).

Model	Steel frame		
	Type	Columns	Beams
S1	Gravity-resisting frame	HE200B	IPE
S2	Gravity-resisting frame	HE200B	IPE
S3	Moment-resisting frame	HE200B	IPE

Table 2. SRCWs connected to steel frame (Type S).

Model	SRCW system connected to steel frame	
	Columns	Beams
S1	HE340B	HE220B
S2	300 mm × 400 mm; t = 10 mm	HE220B
S3	300 mm × 400 mm; t = 10 mm	HE220B

The models S1 and S2 have different SRCWs (Table 2) connected to the same steel gravity-resisting frame with beams pinned at their ends.

These SRCWs have concrete-filled hollow section columns. Model S3 is considered to investigate the condition of moment-resisting steel frame connected to SRCWs. Models S2 and S3 have the same geometry, materials, loads and SRCW systems.

3.2 *Steel-concrete composite frame with SRCWs*

A four-storey steel-concrete composite frame is considered as case study. The building has total floor dimensions of 42.50 m × 12.80 m (Figure 10) 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 ag 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.

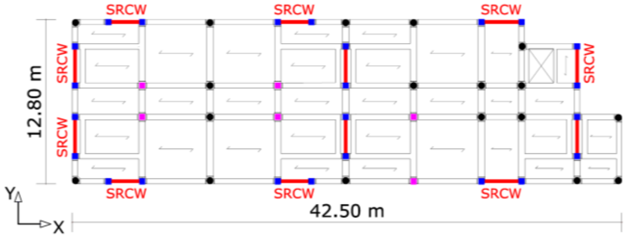

Figure 10. Floor geometry of the considered steel-concrete composite structure with SRCWs.

For each floor the permanent structural load G is equal to 2.30 kN/m^2, non-structural members load G is equal to 2.00 kN/m^2 and variable actions Q is equal to 2.00 kN/m^2 or 4.00 kN/m^2 arising from residential occupancy or communal passages, respectively. The roof has permanent load G equal to 2.00 kN/m^2, non-structural members load G equal to 2.00 kN/m^2 and variable actions Q equal to 3.00 kN/m^2. 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 m × 400 mm (steel thickness equal to 12.5 mm). Steel S235 and steel S275 are used for circular and square columns, respectively.

Concrete C28/35 is used for the composite columns. 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 × 0.26 m or to 0.50 m × 0.26 m. The effects of creep were taken in account according to Eurocode 4 § 5.4.2.2 (EN 1994-1, 2006). 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 (EN 1998-1, 2004).

The first case analysed (model SCC1) is the described composite moment-resisting frame without SRCWs. The behaviour factor q used for the design of this structure is equal to 3.2. The second case analysed (model SCC2) is made of the same steel-concrete composite frames of the case SCC1 with the addition of six SRCWs for each direction (Figure 10). The third case analysed (model SCC3) has the same structure of the case SCC2, but the columns of the frames have different cross sections (Table 3).

Table 3. Circular columns of the steel-composite frame (Type SCC).

Model	Concrete-filled hollow section columns	
	External diameter (mm)	Thickness of steel section (mm)
SCC1	508	6.35
SCC2	508	6.35
SCC3	406	10.00

The hybrid shear walls (Table 4) of the models SCC2 and SCC3 are not considered as a truss-like structure (Figure 8), due to the joint type between the composite truss beams and the SRCWs.

The SRCW systems are made of steel S275 and concrete C28/35. Infill walls are made of concrete C28/35 and steel bars B450C.The diagonal struts of the SRCWs have thickness equal to 0.22 m and they are modelled as RC elements, with section dimensions 0.22 m × 0.51 m, pinned at their ends.

Table 4. SRCWs connected to steel-concrete composite frame (Type SCC).

Model	SRCW system		
	Square Column		Steel beam
	Dimensions (mm)	Thickness of steel section (mm)	
SCC1	-	-	-
SCC2	400 × 400	12.5	HE220B
SCC3	400 × 400	12.5	HE220B

4 SEISMIC PERFORMANCES

4.1 *Steel structures with hybrid shear walls*

The model S2 has vibration periods (Table 5) and inter-storey drifts (Table 6) that are smaller than those of the model S1 due to the different stiffness of the SRCWs (Table 2). In fact, the hybrid shear walls of the model S2 have concrete-filled composite columns with stiffness bigger than that of the wide-flange columns of the hybrid walls of model S1. The models S2 and S3 have the same SRCWs but different structural concepts of the steel frame: the model S2 has a gravity-resisting frame while model S3 has a moment-resisting frame. The inter-storey drifts of the model S3 are very close to those of model S2.

Table 5. Vibration periods of the models (Type S).

Vibration periods T (s)			
Mode	Model S1	Model S2	Model S3
1	0.338	0.301	0.292
2	0.295	0.266	0.258

Table 6. Inter-storey drifts of the models S1 and S2.

	Model S1	Model S2
Level (m)	Inter-storey drift in X direction (m)	Inter-storey drift in X direction (m)
3.5	0.0021	0.0020
7.0	0.0030	0.0024
10.5	0.0030	0.0023
Level [m]	Inter-storey drift in Y direction (m)	Inter-storey drift in Y direction (m)
3.5	0.0018	0.0018
7.0	0.0025	0.0023
10.5	0.0027	0.0021

The analysis of the internal forces of SRCWs for the analysed models allowed to understand the influence of both the stiffness of the hybrid walls and the type of beam-to-column connection. In X-direction, the columns (Table 7) and the diagonal struts (Table 8) of SRCWs of model S2 have axial forces slightly bigger than those of the model S1 due to an increment of the stiffness of SRCWs (Table 2). Similar results are obtained for the Y-direction.

Table 7. Axial forces for the columns of a representative SRCW system - X direction.

Storey	Model S1	Model S2		Model S3	
	N (kN)	N (kN)	Δ_{S1} (%)	N (kN)	Δ_{S2} (%)
1	-1171.4	-1238.8	5.8	-1178.4	-4.9
2	-447.5	-480.3	7.3	-448.5	-6.6
3	-32.4	-39.8	22.9	-36.7	-7.8

Table 8. Axial forces for the diagonal struts of a representative SRCW system - X direction.

Storey	Model S1	Model S2		Model S3	
	N (kN)	N (kN)	Δ_{S1} (%)	N (kN)	Δ_{S2} (%)
1	-1171.5	-1212.5	3.5	-1180.0	-2.7
2	-899.3	-935.6	4.0	-904.5	-3.3
3	-486.7	-510.8	4.9	-480.7	-5.9

The axial forces of the SRCWs for the model S3 are slightly smaller than those of the model S2, due to the different beam-to-column joints of the frames (Table 7 and Table 8). The columns of the frames of model S3 have normal stress significantly bigger than those of the gravity-resisting frames of model S2 (with increase at least equal to 30%). Therefore, the type of beam-to-column connection influence significantly the normal stress of the columns of the steel frame.

On the other side, the inter-storey drifts and the internal forces of SRCWs are slightly influenced by the joint type at the beam ends. These results can be obtained in the case of suitable stiffness of the SRCWs.

4.2 Steel-concrete composite structures with hybrid shear walls

The use of SRCWs in the model SCC2 caused both an increase of the stiffness of the structure and a significant decrement of the vibration periods (Table 9) respect to model SCC1. The SRCWs of model SCC2 causes an important decrement of the bending moments in the internal circular columns (Table 10).

Table 9. Vibration periods of the model SCC1 and SCC2.

Vibration periods T (s)		
Mode	Model SCC1	Model SCC2
1	0.692	0.358
2	0.678	0.323
3	0.588	0.262

Table 10. Envelope of the axial forces and bending moments of the internal circular columns for 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	-402.2	0.93
$M_{y,max}$ (kNm)	137.12	116.13	-15.31
$M_{x,max}$ (kNm)	167.66	122.10	-27.17

The SRCWs causes a decrease of the bending moments also for the perimeter circular columns.

The differences between the axial forces of the internal columns of models SCC1 and SCC2 are negligible (Table 10). The square columns of models SCC1 and SCC2 highlighted similar results (Table 11). The internal columns of the model SCC2 are not affected by tensile axial force (Table 10 and Table 11) in spite of the increment of the seismic input. The model SCC2 has a behaviour factor q equal to 1.5 while the model SCC1 has a behaviour factor equal to 3.2.

It is important to remark that the increment of the seismic input for the model SCC2, due to the reduction of the behaviour factor q, is supported by the hybrid shear walls connected to the composite moment-resisting frames.

Table 11. Envelope of the axial forces and bending moments of the internal square columns for models SCC1 and SCC2.

Axial forces or bending moments	Model SCC1	Model SCC2	Δ_{SCC1} (%)
N_{min} (kN)	-1072.61	-1085.77	1.23
N_{max} (kN)	-498.87	-541.63	8.57
$M_{y,max}$ (kNm)	144.89	123.76	-14.58
$M_{x,max}$ (kNm)	196.21	110.16	-43.86

The comparison between the models SCC1 and SCC2 highlighted the decrease of the bending moments of the truss composite beams (Table 12 and Table 13) due to seismic load in Y direction. Similar results are obtained for X direction. The square composite columns of the SRCWs are affected by both bending moments and axial forces (Table 14).

Table 12. Envelope of bending moments due to seismic actions of representative truss composite beams for models SCC1 and SCC2 – Y direction.

Model	Beam 3-13	Beam 13-23	Beam 23-34
	$M_{r\text{-}e}^{(-)}$ (kNm)	$M_{r\text{-}e}^{(-)}$ (kNm)	$M_{r\text{-}e}^{(-)}$ (kNm)
SCC1	-143.4	-127.5	-146.2
SCC2	-117.0	-92.9	-118.1
Δ_1 (%)	-18.4	-27.1	-19.2

Table 13. Envelope of bending moments due to gravitational loads ($M_{r\text{-}g}$) and seismic actions ($M_{r\text{-}e}$) of representative truss composite beams for models SCC1 and SCC2 – Y direction.

Model	Beam 3-13			Beam 23-34		
	$M_{r\text{-}g}^{(-)}$ (kNm)	$M_{r\text{-}e}^{(-)}$ (kNm)	Δ_g (%)	$M_{r\text{-}g}^{(-)}$ (kNm)	$M_{r\text{-}e}^{(-)}$ (kNm)	Δ_g (%)
SCC1	-107.4	-143.4	33.5	-103.8	-146.2	40.86
SCC2	-107.4	-117.0	8.9	-103.8	-118.1	13.76

Table 14. Envelope of the axial forces and bending moments for the columns of SRCWs (model SCC2).

Axial forces or bending moments	Model SCC2
N_{min} (kN)	-1865.93
N_{max} (kN)	2076.79
$M_{y,max}$ (kNm)	129.81
$M_{x,max}$ (kNm)	139.69

The SRCWs causes a decrease of the inter-storey drifts in the model SCC2 (Table 15) in X-direction. A similar result is obtained for the Y-direction. These results demonstrate the effectiveness of the SRCWs to limit the damage of the non-structural elements and to reduce the internal forces also for moment-resisting frames made of steel-concrete composite components. The decrease of the bending moments in the concrete-filled composed columns, due to SRCWs, allowed the reduction of the cross section for the circular columns (see Table 3) of the model SCC3.

Table 15. Inter-storey drifts of the models SCC1 and SCC2.

	Model SCC1	Model SCC2
Level [m]	Inter-storey drift in X direction (m)	Inter-storey drift in X direction (m)
3.4	0.0044	0.0020
6.8	0.0069	0.0030
10.2	0.0057	0.0032
13.6	0.0036	0.0027

The vibration periods of the model SCC3 are smaller than those of the model SCC1 (Table 16). The comparison between the models SCC2 and SCC3 highlighted that the differences of the vibration periods are negligible.

Table 16. Vibration periods of the model SCC1 and SCC3.

Vibration periods T (s)		
Mode	Model SCC1	Model SCC3
1	0.692	0.360
2	0.678	0.325
3	0.588	0.263

In the third case (model SCC3) the circular columns highlighted an additional reduction of the bending moments compared to those of the model SCC1 (Table 17). The square columns highlighted a reduction of the bending moments (Table 18).

Table 17. Envelope of axial forces and bending moments of the internal circular columns for models 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

Table 18. Envelope of axial forces and bending moments of the internal square columns for models SCC1 and SCC3.

Axial forces or bending moments	Model SCC1	Model SCC3	Δ_{SCC1} (%)
N_{min} (kN)	-1072.61	-1086.79	1.32
N_{max} (kN)	-498.87	-541.07	8.46
$M_{y,max}$ (kNm)	144.89	125.23	-13.57
$M_{x,max}$ (kNm)	196.21	111.67	-43.09

The decrease of the cross section for the circular columns does not influence both the axial forces and bending moments of the SRCWs (Table 19 and Table 20). Furthermore, the inter-storey drifts of the model SCC3 are very close to those of the model SCC2 (Table 15).

Table 19. Envelope of the axial forces and bending moments for the square columns of SRCWs.

Axial forces or bending moments	Model SCC2	Model SCC3	Δ_{SCC2} (%)
N_{min} (kN)	-1865.93	-1873.67	0.41
N_{max} (kN)	2076.79	2088.4	0.56
$M_{y,max}$ (kNm)	129.81	131.19	1.06
$M_{x,max}$ (kNm)	139.69	140.06	0.26

Table 20. Envelope of the axial forces for the diagonal struts of SRCWs in X-direction. Similar results are obtained in Y-direction.

	Model SCC2	Model SCC3	
Diagonal struts in X direction	N (kN)	N (kN)	Δ_{SCC2} (%)
C40-C2	-1120.26	-1133.48	1.18
C4-C41	-1093.07	-1108.95	1.45
C7-C8	-1210.00	-1227.66	1.46
C47-C33	-1135.52	-1148.21	1.12
C35-C48	-1110.17	-1125.50	1.38
C38-C39	-1213.00	-1228.82	1.30

The SRCW systems of models SCC2 and SCC3 support about 80% of the base shear forces of the structure when design earthquakes occur. The comparison between the previous models highlighted a low increment (equal to 3%) of the base shear force for the SRCWs of model SCC3 due to the decrease of the dimension of the cross sections of the circular columns.

The comparison between the model SCC1 and the model SCC2 highlighted the reduction of the base shear forces for the internal columns of the structure. These results demonstrate that the increment of the seismic input for the model SCC2, due to the reduction of the behaviour factor q, is supported by the hybrid shear walls connected to the composite moment-resisting frames. In the third case (model SCC3) the circular columns highlighted an additional reduction of the base shear forces compared to those of the model SCC1 (Table 21).

Table 21. Total base shear force for the internal circular columns of the structure in X-direction. Similar results are obtained in Y-direction.

Total base shear force (kN) of internal circular columns				
Model SCC1	Model SCC2	Δ_{SCC1} (%)	Model SCC3	Δ_{SCC1} (%)
597.13	560.21	-6.18	479.16	-19.76

5 CONCLUSIONS

In order to develop a feasible and competitive structural solution able of effective bracing functions in seismic areas at the ultimate limit state while reducing as much as possible non-structural damage at damage limit state, an innovative steel frame with reinforced concrete infill wall (SRCW) system is presented, designed, and analysed in this paper. The components of the SRCWs are conceived to remain in their elastic range under the design seismic condition. Several case studies are analysed to understand the structural behaviour and the seismic performance of proposed SRCWs used in combination with steel frames or steel-concrete composite frames.

In the case of hybrid shear walls connected to steel frames, the SRCWs are analysed as truss structures whose elements can be dimensioned based on statically-determinate scheme. The stiffness of SRCWs allow to control the inter-storey drifts of gravity-resisting steel frames with steel beams that are pinned at their ends. The type of beam-to-column joint influences significantly the normal stress of the steel frames while the SRCWs are slightly influenced due to their stiffness.

A different structure scheme is adopted when SRCWs are used in combination with steel-concrete composite frames due to the different connection type between the composite truss beams and the hybrid shear walls. In this case the columns of the SRCW are affected by both axial forces and bending moments. Despite of the increment of seismic input, the SRCWs causes both a decrement of the bending moments of the frames and the absence of tensile axial forces in the internal columns. The hybrid shear walls allow to limit the inter-storey drifts.

These results demonstrate the effectiveness of the SRCWs to limit the damage of the non-structural elements and to reduce the internal forces also for moment-resisting frames made of steel-concrete composite components under design seismic excitations. The SRCWs are designed to remain in the elastic range when seismic actions occur; this assumption allowed both to avoid the replacement of dissipative elements and to make easier the design procedure based on the Eurocodes rules.

Further studies are needed to validate numerical models throw experimental tests. Future investigations will concern the definition both of thresholds for damage states and fragility functions.

ACKNOWLEDGEMENTS

This research is supported by Tecnostrutture in a joint research programme at the University of Camerino and the University College of London. The support is gratefully acknowledged by the Authors.

REFERENCES

Braga, F., Gigliotti, R., Monti, G., Morelli, F., Nuti, C., Vanzi, I., Salvatore, W., 2014. Speedup of post earthquake community recovery. The case of precast industrial buildings after the Emilia 2012 earthquake, *Bulletin of Earthquake Engineering*, **12**(5), 2405-18.

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., 2015. Innovative hybrid and composite steel-concrete structural solutions for building in seismic area. Final Report, EUR 26932 EN, European Commission.

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

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

Demartino, C., Vanzi, I., Monti, G., 2017. Probabilistic estimation of seismic economic losses of portal-like precast industrial buildings, *Earthquakes and Structures*, **13**(3), 323-335.

EN 1992-1-1, 2005. Eurocode 2, Design of concrete structures - Part 1-1: General rules and rules for buildings.

EN 1993-1-1, 2005. Eurocode 3, Design of steel structures - Part 1-1: General rules and rules for buildings.

EN 1994–1, 2006. Eurocode 4, Design of composite steel and concrete structures - Part 2: General rules and rules for bridges.

EN 1998-1, 2004. Eurocode 8, Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings.

Morelli, F., Manfredi, M., Salvatore, W., 2016. An enhanced component based model of steel connection in a hybrid coupled shear wall structure: development, calibration and experimental validation, *Computers & Structures*, **176**, 50-69.

Morelli, F., Mussini, N., Salvatore, W., 2019. Influence of shear studs distribution on the mechanical behaviour of dissipative hybrid steel frames with r.c. infill walls, *Bulletin of Earthquake Engineering*, **17**(2), 957-983.

Suizi, J., Wanlin, C., Zibin, L., Wei, D., Yingnan, S., 2019. Experimental Study on a Prefabricated Lightweight Concrete-Filled Steel Tubular Framework Composite Slab Structure Subjected to Reversed Cyclic Loading, *Applied Sciences*, **9**(6), 1264.

Tong, X., Hajjar, J.F., Schultz, A.E., Shield, C.K., 2005. Cyclic behavior of steel frame structures with composite reinforced concrete infill walls and partially restrained connections, *Journal of Constructional Steel Research*, **61**, 531-52.

Wang, B., Jiang, H., Lu, X., 2017. Seismic performance of steel plate reinforced concrete shear wall and its application in China Mainland, *Journal of Constructional Steel Research*, **131**, 132-143.

Zona, A., Degeé, H., Leoni, G., Dall'Asta, A., 2016. Ductile design of innovative steel and concrete hybrid coupled walls, *Journal of Constructional Steel Research*, **117**, 204-213.

Zona, A., Tassotti, L., Leoni, G., 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.