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An innovative seismic-resistant steel frame with reinforced concrete infill walls

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Highlights

- An innovative steel frame with reinforced concrete infill walls is presented.
- A seismic design procedure for the presented structural system is proposed.
- Numerical and experimental studies validate its structural behaviour.

Abstract

Steel frames with reinforced concrete infill walls (SRCW) are an interesting seismic-resistant structural solution. However, an effective seismic design of SRCWs is not easy due to the current lack of specific capacity design rules that allow controlling the formation of a proper energy dissipating mechanism. In order to overcome such an issue, a ductile design procedure is presented in this paper. The proposed procedure leads to innovative SRCW systems where energy dissipation is expected to take place only in the vertical elements of the steel frame, which are subjected mainly to axial forces. The non-ductile components, i.e. reinforced concrete wall and steel-to-concrete connections, are expected to suffer negligible damage. Accordingly, the system is designed to control the formation of diagonal struts in the infill walls and behaves as a lattice brace instead of a shear wall. Experimental test results and nonlinear finite element analyses are illustrated to support the developed ductile design approach and highlight the advantages of SRCWs.

Introduction

During the two past decades increasing interest has been given to hybrid steel and concrete structures, obtained through the combination of structural elements made of reinforced concrete (RC), steel, and composite steel-concrete, arranged to create more efficient and economical seismic resistant solutions, e.g. [1], [2], [3], [4], [5], [6], [7], [8], [9]. Attention is here focused on hybrid steel and concrete systems made by steel frames with reinforced concrete infill walls (SRCWs) owing to their many advantages as seismic-resistant systems [1], [7], i.e. high initial stiffness beneficial in reducing building damage under low-intensity earthquakes, effective damping characteristics, and potentially easy repairs after moderate damage through the use of epoxy resins on the cracked wall. In this way, SRCWs provide a promising structural solution potentially able to reduce the seismic risk in all its aspects, i.e., economic loss and fatalities, as for example contemplated in recent studies [10], [11] following the 2012 Emilia earthquakes in Italy and highlighting the necessity of an adequate structural behaviour also for low-to-moderate seismic events.

In SRCWs three different lateral resisting mechanisms can be identified (Fig. 1): (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 frames and the RC infill walls through friction and shear connectors. The contribution of each resisting mechanism to the overall horizontal resistance depends on the mechanical properties and geometrical configuration of the SRCW. Accordingly, different typologies of SRCWs can be identified depending on the beam-to-column joint typology and to the distribution of shear studs along the interface between the frame and the infill wall. Systems in which the beam-to-column joint is able to transfer significant portion of the flexural moment without important relative rotations are usually referred to as Fully-restrained SRCWs (FSRCWs); otherwise they are referred to as Partially-restrained SRCWs (PSRCWs) [12], [13]. Integral infilled frames are characterized by connectors distributed along the interfaces between the frames and the infill walls, while non-integral infilled frames are not provided with connectors. Intermediate configurations can be classified as semi-integral infilled frames.

The seismic behaviour of SRCWs has been the object of many theoretical and experimental studies over more than four decades. Test results of Mallick and Severn [14] showed that the presence of shear connectors in the corner of the steel frame prevented the rotation of the infill walls, increased the overall stiffness, and did not affect the lateral strength. Furthermore, integral infilled frames exhibited shear failure of the infill walls, while non-integral infilled frames were characterized by diagonal compression failure of the infill walls. Liauw and Lee [15], Liauw [16], and Liauw and Kwan [17] studied the influence of the shear studs distribution along the steel frames through a series of static, dynamic, and cyclic tests on both integral and non-integral SRCWs. Test results showed that the presence of shear connectors along the entire interface between steel frame and infill walls caused an increment of global strength, stiffness, and energy dissipation capacity. In Japan, a series of cyclic tests was carried out by Makino et al. [18] and Makino [19] on one-third scale FSRCW specimens equipped with few studs having the primary purpose to prevent the out-of-plane collapse of the RC infills. These tests showed that infilled frames having columns bent about their strong axis had ductile behaviour comparable to that of typical bare steel frames. Tong et al. [20] experimental investigation on PSRCWs highlighted that infill walls tended to develop a pattern of closely-spaced diagonal cracks, prior to any significant yield in the steel frame. The presence of reinforcing cages around the headed studs helped to avoid the concrete brittle failure modes. However, low-cycle fatigue of the headed studs became the main failure mode. Similar results on the importance of the reinforcing cages and on the behaviour of shear studs were obtained by Saari et al. [21]. Their experimental tests showed that the presence of axial tension greatly reduced the strength and deformation capacity of the studs. However, by providing confinement to the studs in the form of a reinforcement cage, the full strength and deformation capacity of the studs could be achieved. A more recent study carried out by Sung et al. [22] investigated PSRCW with solid infill walls and PSRCW with concealed vertical slits. The former showed an excellent initial stiffness and strength, a moderate deformation ductility (in the range of 4.30–4.63) and a shear-dominated behaviour where the wall developed a resisting mechanism made up of a series of inclined struts in compression. The latter showed an excellent deformation capacity (ductility ratio was approximately in the range of 5.94–7.66), a good cyclic energy dissipation capacity, and good initial stiffness and strength, provided mainly by the flexure-dominated behaviour of the wall portion comprised by the concealed vertical slits. The main problem of this system dwells in the concrete crushing at the early loading stage, thus, limiting the performance associated to the damage limitation limit state, considered to be one of the most important factor affecting the seismic risk of a building from an economic point of view [23].

The review of the state of the art demonstrates how the intuitive idea of stiffening a steel frame with a RC infill is, in reality, rather difficult to be applied because the actual resisting mechanism is affected by many variables. Ambiguity in the definition of the resisting mechanism is accompanied by a lack of capacity design rules able to produce a tailored hierarchy among the structural components. This situation is reflected by design standards providing specific design rules for SRCWs, i.e. European Eurocode 8 EN1998-1 [24]. Specifically, Eurocode 8 [24] considers SRCW systems to behave essentially as RC walls able of dissipating energy in the vertical steel sections and in the vertical reinforcements of the walls. In addition, the same detailing provisions provided for RC walls are repeated for SRCWs except for indications on the edge shear connections.

Refined numerical analyses carried out on SRCWs [7] designed according to the Eurocodes pointed out an unsatisfactory brittle behaviour due to the severe damage occurring to concrete long before yielding of the ductile elements. The failure mechanism is generally characterised by yielding of the steel frame concentrated mainly in the elements near the bottom corners of the wall. The plastic deformation on the concrete infill walls concentrates in a diagonal path clearly highlighted by the distribution of cracking. In addition, localized plastic deformations are also present near the corners of the infill walls due to the forces transmitted by the diagonal strut (Fig.2). All these issues demonstrate how the idea, suggested by design standards, that SRCWs may behave as a RC shear walls is far from reality, especially for medium and high rise buildings. The presence of boundary steel profiles leads rather to the formation of a unique diagonal strut within the RC infill wall contributing to the formation of a truss-like resisting mechanism.

This paper presents the outcomes of a research project aimed at developing a novel SRCW. The system is realized in order to assure yielding of the side steel elements by controlling the formation of diagonal struts in the RC infill walls. It behaves as a lattice structure whose elements can be designed to produce energy dissipation at the various storeys along the building height and to achieve the needed global ductility. A specific capacity design procedure, able to assure the desiderated energy dissipation mechanism, is proposed consistently with the Eurocode 8 [24] framework and explained in detail. Numerical models are then adopted to better understand the global behaviour of the system and to check the validity of the proposed design procedure. Finally, the results of an experimental campaign on two different one-storey specimens are illustrated to testify the effectiveness of the design procedure and to provide insight into the influence of the shear studs distribution on the behaviour of the proposed SRCW system.

Section snippets

Structural concept

As previously discussed, the behaviour of SRCWs may be very different from that assumed in the design because the resisting mechanism within the RC infill can only be roughly controlled. The idea that the system behaves as a RC shear wall as a whole, in which vertical steel elements contribute to resist the overturning moments, acting as reinforcements, whereas the RC infill walls have to resist the storey shear, might be far from reality especially for medium and high rise buildings and when…

Details of the design procedure

As discussed in the previous section, the proposed SRCW should develop a resisting mechanism in which the steel elements of the frame are subjected mainly to axial forces and the concrete walls are characterised by the formation of diagonal struts (Fig.3b). A statically determinate truss model (Fig.4a) describes such a limit behaviour of the system. This scheme can be adopted in a force-based procedure because the stress resultants in the elements do not depend on the dimension of members and…

Validation of the design procedure

The innovative SRCW system is designed by considering an equivalent lattice-like lateral resisting structure. Nevertheless, the real system is characterised by the presence of the reinforced concrete infill walls that may behave differently from simple diagonal struts since biaxial stress fields are expected to develop. Furthermore, joints of the steel frame are not hinged but are rather characterised by the presence of the diagonal welded plates (placed to control the formation of the diagonal …

Conclusions

In this paper a novel SRCW is presented, conceived on the basis of 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. A tailored capacity design procedure developed consistently with the Eurocode framework for seismic design is illustrated including a discussion the various steps. Nonlinear finite element analyses are used to preliminary validate the outcomes of the…

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