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Spiral-based confinement in slabs for the seismic performance enhancement of steel-concrete composite frames

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Abstract

The seismic performance analysis of steel-concrete composite frames involves, as known, the interaction of several load-bearing components that should be properly designed, with multiple geometrical and mechanical parameters to account. Practical recommendations are given by the Eurocode 8 – Annex C for the optimal detailing of transversal rebars, so as to ensure the activation of conventional resisting mechanisms. In this paper, the attention is focused on the analysis of effects and benefits due to a novel confinement solution for the reinforced concrete (RC) slab. The intervention is based on the use of diagonal steel spirals, that are expected to enforce the improve the overall compressive response of the RC slab, thanks to the activation of an optimized strut-and-tie resisting mechanism. The final expectation is to first increase the resistance capacity of the slab, that can thus transfer higher compressive actions under seismic loads. Further, as shown, the same resisting mechanism can be beneficial for the yielding of steel rebars, depending on the final detailing of components, and thus possibly improve the ductility of the system To this aim, a refined Finite Element (FE) numerical analysis is carried out for several configurations of technical interest. The in-plane compressive behaviour and the activation of resisting mechanisms is explored for several spiral-confined slabs, based on various arrangements. Major advantage is take from literature experimental data on RC slabs, that are further investigated by introducing the examined confinement technique. As shown, once the spirals are optimally placed into the slab, the strength and ductility parameters of the concrete struts can be efficiently improved, with marked benefits for the overall resisting mechanisms of the slab, and thus for steelcomposite frames as a whole.

Keywords: composite frames; seismic design; spiral confinement; numerical analysis.

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1. Introduction

1.1. State-of-art

For civil engineering applications, it is known that the use of continuous spiral reinforcements can represent an efficient tool for improving load-bearing capacity of structural members. Major benefits can be expected, according to literature, especially for the seismic performance enhancement of reinforced concrete (RC) members, thanks to the intrinsic benefits of confinement. Several research studies have in fact demonstrated that spiral-based confinements are characterized by large potential especially for concrete columns, where both the ductility and energy dissipation capacity can be greatly improved. Beneficial applications of spirals for confinement can be found for example in (Marvel et al., 2014; Sankholkar et al., 2018), where the attention has been focused both on Glass Fiber–Reinforced Polymer (GFRP) spirals or steel spirals respectively. In (Simões et al., 2001; Simões and Simões da Silva, 2001), the attention has been paid on the identification of concrete confinement contribution on composite columns belonging to steel-concrete composite frames, as well as on the assessment of strength and stiffness degradation.

In this paper, major attention is focused on the use of steel spirals for the seismic reinforcement of slabs belonging to composite steel-concrete frames. The goal is to assess and optimize the spiral-based confinement effect and its benefits to improve the role of the slab on the overall joint response in seismic conditions. To this aim, the in-plane compressive response is first explored in detail, being responsible of a typical strut-and-tie mechanisms which has relevant contribution on structural capacity assessment. The analysis and design of steel-concrete composite frames is known to represent a challenging issue, requiring multiple attentions, due to a combination of several geometrical and mechanical parameters that should be satisfied to optimize the expected seismic performances. To this aim, a number of experimental, analytical and numerical investigations have been dedicated to the assessment of resisting mechanisms and to the definition of design proposals (Thermou et al., 2004; Salvatore et al., 2005; Aribert et al., 2006; Li et al., 2011; Pecce and Rossi, 2015; Tartaglia et al., 2018), in support or refinement of conventional approaches that can be found in the Eurocode 8 (EC8) for seismic resistant steel-concrete composite frames (CEN, 2004).

For the present study, a primary role is assigned to refined and computationally efficient Finite Element (FE) numerical models developed in ABAQUS/Explicit to explore the elastic and post-damage response of selected systems. A focus is given to both local and global structural effects due to different design and / or arrangement of spirals specifically introduced into the slab to improve the strength and ductility of concrete struts for the composite joint. As shown, the detailing of spirals is crucial to ensure the activation of optimized resisting mechanisms. Besides, once the spirals are properly arranged in the slab, the overall compressive resistance of the slab can be largely increased, with enhanced benefits for the steel-concrete composite frames. Further, the introduction of steel spirals can also improve the whole post-cracked stage of the steel-concrete composite system, given that (depending on the desired yielding of transverse reinforcement in the slab) even major ductility in the slab can be achieved.

1.2. Preliminary considerations for spiral-based confinement technique

According to EC8 – Annex C provisions for seismic design of steel-concrete composite frames, a multitude of aspects and details should be taken into account for structural optimization purposes (Fasan et al. 2022). In this context, the implementation of the proposed spiral-based confinement technique finds optimal place in internal joints under seismic combinations of loads like in Figure 1(a). The confinement technique based on the use of steel spirals for the seismic improvement of RC slabs in steel-concrete composite frames is elaborated as in Figure 1(b), where the typical layout of circular spirals can be schematized as in Figure 1(c). In doing so, the proposed spiral-based technique is expected to enhance the overall compressive capacity of the slab, and especially to positively improve the resisting “mechanism 2” according to Eurocode provisions. Such a goal is achieved based on a simple strut-and-tie configuration which is qualitatively reproduced in Figure 1(d), see also (Fasan et al. 2022), and can be properly optimized in design details. For the present analysis, selected configurations of technical interest are quantitatively and qualitatively addressed. A major advantage for the analysis of load-bearing capacities and failure mechanisms is taken from the FE numerical analysis of RC slabs under in-plane compression.

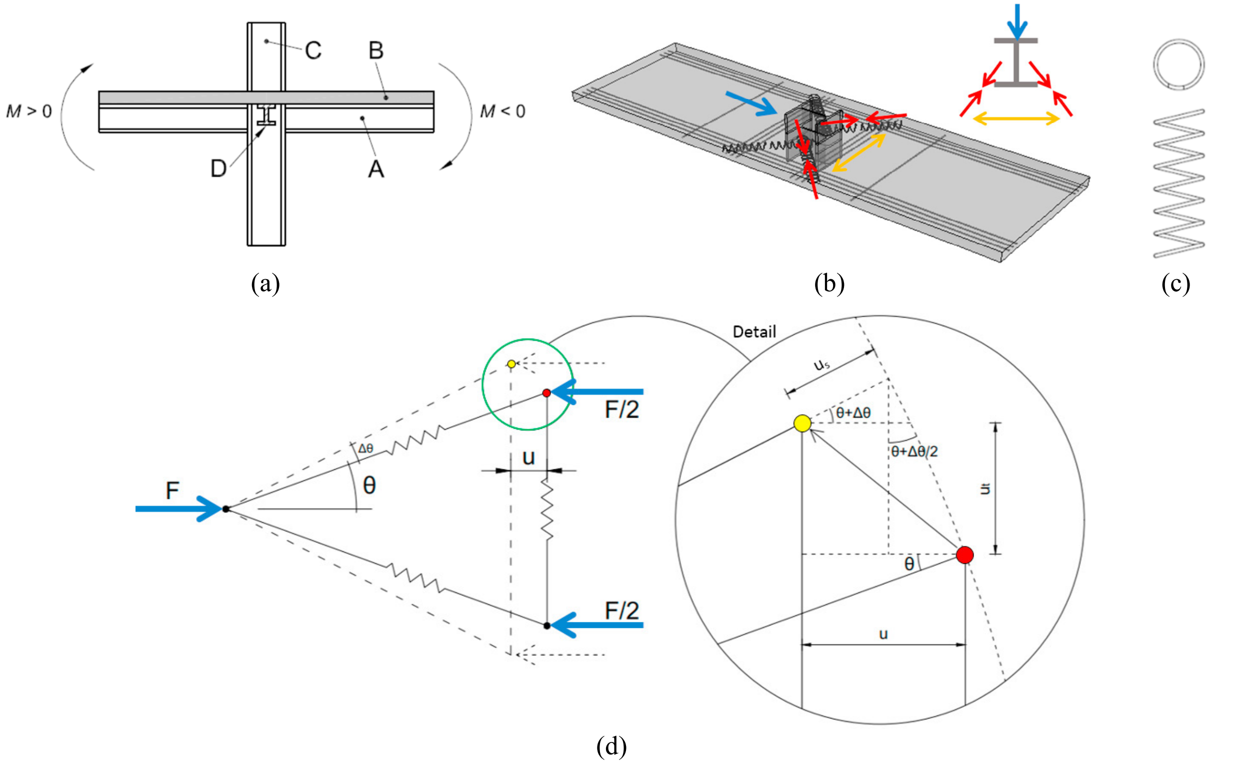


Fig. 1. Example of load-bearing mechanism for a concrete slab with spiral-based confinement: (a) steel-concrete composite frame in seismic conditions (Eurocode 8); (b) proposed strut-and-tie mechanism and (c) spiral detail, with (d) corresponding mechanical model for the definition of stiffness contributions of the strut-and-tie resisting mechanism in the RC slab in compression.

2. Analysis on full-scale steel-concrete composite frame

2.1. Geometrical layout and materials

The investigated steel-concrete composite frame for the present analysis takes inspiration from the full-scale experimental specimen that was numerically explored in (Amadio et al., 2017b). The original structural system is schematized in Figure 2 and consists of two IPE300 type steel beams (2.1 m their nominal length), an HEB260 column (2.77 m the total height) and a solid RC slab (120 mm in thickness and 1.2 m in width). The connection of steel beams and concrete slab is offered by a set of steel shear studs (with 19 mm in diameter and 75 mm in total height), that were used to ensure a fully rigid mechanical connection. Those shear connectors were 75 mm and 150 mm spaced along the transverse and longitudinal beams axis, respectively.

Regarding its composition, material properties are considered as for f_{ck}= 35 MPa in the case of concrete and f_y= 450 MPa for steel rebars. The longitudinal rebars are given by 8 ϕ 14 and 8 ϕ 6 bars, lying on the top and bottom layers of the slab respectively. The primary transverse rebar consists of 5 ϕ 16 bars, 50 mm spaced, with a minimum distance of 220 mm from the column axis.

2.2. Finite Element numerical modelling

The RC slab and a short segment of the HEB260 column were extracted from the full FE assembly in Figure 2, and the primary attention of present analyses was focused on the compressive strength and collapse mechanisms of in-plane loaded concrete slabs only. The ongoing investigation also includes bending response assessment of full-size steel-concrete composite frames as in Figure 2 and subjected to seismic loading conditions. In this sense, knowledge and quantification of basic mechanical terms and expected contributions is the primary step for design optimization of the proposed confinement technique. In doing so, careful consideration was paid for FE numerical modelling of slab components, and this was carried out in ABAQUS/Explicit in accordance with earlier modelling assumptions and validations for steel-concrete composite frames (see also (Fasan et al. 2022; Amadio et al. 2017a; Amadio et al. 2017b) for further details and calibration of constitutive laws for materials).

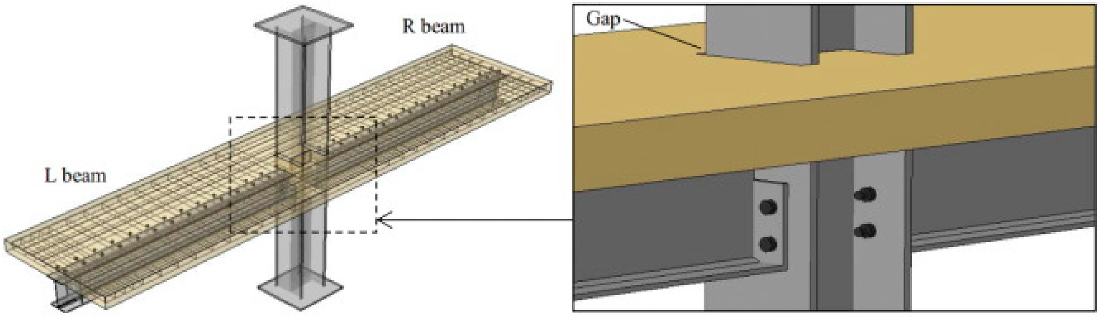


Fig. 2. Axonometry and detail view of the steel-concrete composite frame object of study for the assessment of spiral-based confinement technique (ABAQUS/Explicit).

2.3. In-plane compression load-bearing capacity assessment

The in-plane load-bearing capacity of the RC slab with or without steel spirals was explored according to Figure 3. To this aim, basic slab components and spiral-based confinement constituents were extracted from the overall FE assembly as in Figure 2 and adapted for stan-alone in-plane compression load-bearing capacity assessment. More precisely, the loading setup as in Figure 3 was numerically reproduced in ABAQUS. The HEB260 column was rigidly restrained towards possible displacements. The top face of the RC slab was subjected to a uniform imposed displacement u_y. This was monotonically increased in the step time of analysis. At the same time, the longitudinal rebars were subjected to an equivalent imposed displacement u_y.

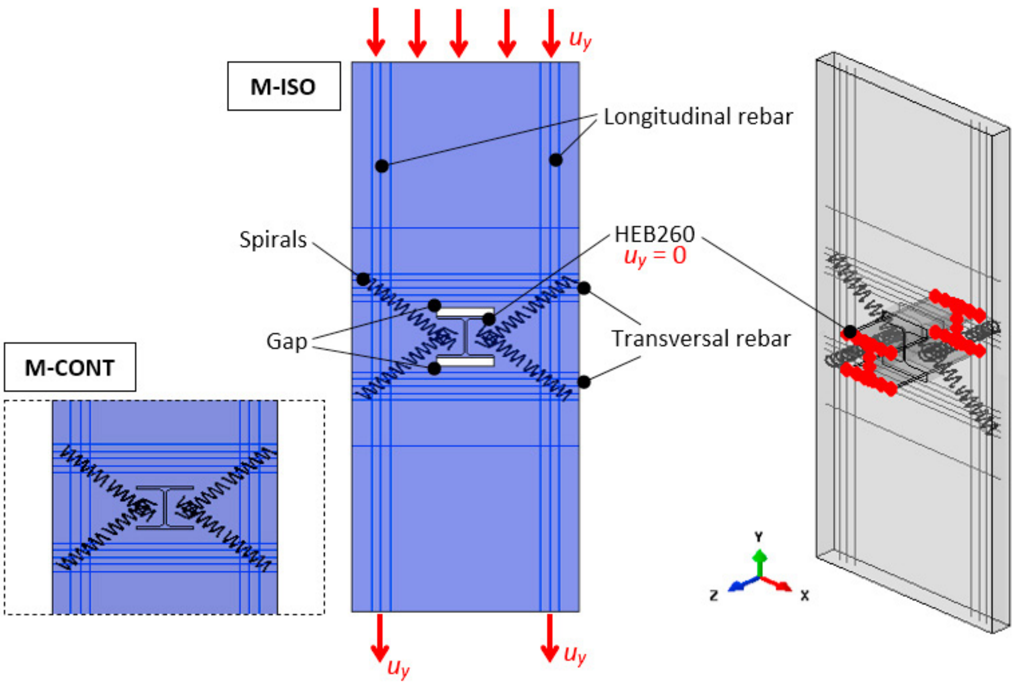


Fig. 3. Numerical setup for the analysis of confining steel spirals in full-scale slabs (ABAQUS/Explicit).

A similar setup and loading approach was considered for two limit conditions (both with or without steel spirals), herein detected as “M-ISO” model (with isolated RC slab from the column and “mechanism 2” only) and “M-CONT” model, being representative of full ideal contact for the RC slab and the adjacent HEB260 column (with the effect of the activation of both mechanisms “1” and “2”). For sake of clarity, numerical results discussed in this paper refer to spiral-based confinement technique with an inclination angle of 45° only, as also schematized in Figure 3.

3. Analysis of numerical results

Through the post-processing analysis of numerical results, the attention was first focused on the total reaction force sustained by each slab configuration (with or without spiral confinement). Given that the reference simulation consisted of a displacement-controlled analysis, this reaction force was calculated as the resultant vertical reaction transferred to the lateral (restrained) faces of the column.

The major outcome of parametric simulations can be quantified as in Figure 4, where major benefits from the activation of the strut-and-tie resisting mechanism due to spirals can be better quantified. The typical load-displacement response for the selected configurations given in fact evidence of marked benefits from the adopted technique. Also, the substantially different behavior for the slabs with or without gap / column contact can be emphasized. In Figure 4(a), analytical resistance values are also proposed for the examined configurations, as obtained from nominal material and geometrical properties in use.

More in detail, it can be noted that the “M-ISO” and “M-CONT” assemblies are thus characterized by significant variations in the total compressive resistance of the slab, as a direct effect of the corresponding mechanisms “1” and “2”. The M-CONT assembly presents relatively higher stiffness than M-ISO, and much higher maximum resistance in compression. Besides, the same M-CONT system shows a slope variation in the load-displacement response, at an approximate total displacement of ≈ 1.5 mm, which can be rationally justified by the propagation of cracks in the slab, with the consequent reduction of global stiffness and activation of the steel members. Once the RC slab is no more efficient due to severe damage, the residual resistance capacity of the M-CONT model decreases and is assigned to the transverse rebars only.

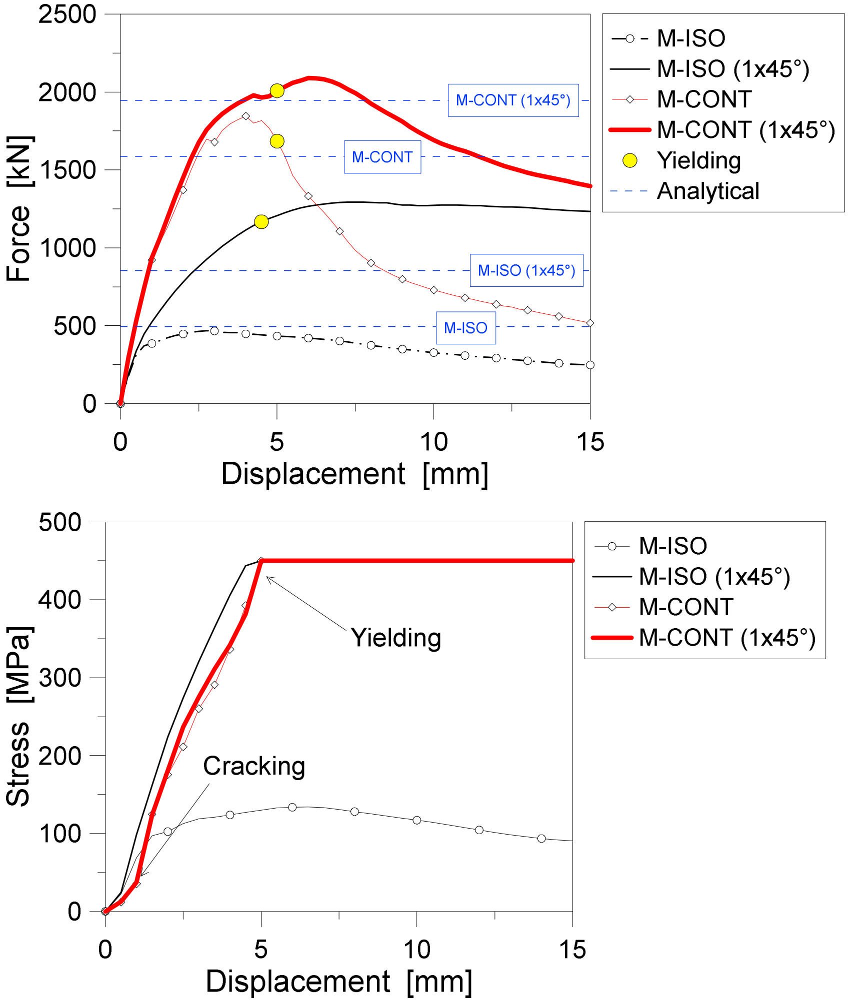
Worth of interest in Figure 4(a) is thus the beneficial contribution that can be perceived especially for the proposed spirals in the M-ISO configuration. Besides, as expected, the M-CONT system takes minor benefit from the spirals introduction, in the initial stage of the collected load-displacement responses.

As shown for the M-ISO solution, the presence of spirals can be noticed in a certain increase of stiffness and resistance for the RC slab. This effect derives from the composite mechanism that the spirals can activate with the transverse rebars (once they are properly placed and designed).

In the case of the M-CONT assembly, the spirals are able to offer a limited post-cracked resistance and stiffness increase in the first 5mm of imposed displacement, compared to the un-confined slab. Yielding of transverse rebars can be observed around ≈ 4-5 mm of deformation. Due to crushing of concrete, part of the spirals contribution vanishes for large imposed displacements but can be still noticed in comparison to the un-confined solution. On the other side, an optimal performance can be observed in Figure 4(a) for the M-ISO system with the confining spirals. The maximum resistance is calculated in the order of ≈ 500 kN for the un-confined system, and up to ≈ 2.5-3 times higher for the confined configuration. Most importantly, the confined M-ISO system suffers slightly for the concrete fracture. This effect can be appreciated in Figure 4(a) in the form of a rather stable overall trend for the load-displacement curve, with relevant post-cracked residual capacities.

Finally, it is worth to emphasize in Figure 4(a) that the residual resistance of both the un-confined M-ISO and M-CONT models tends to a comparable minimum value. Once the eventual contribution of concrete vanishes due to crushing, the final resistance and ductility of the system depends on the steel members only.

A more detailed analysis of the collected FE responses, in this regard, can be extended to the stress peaks in the transverse rebars, that are expected to take benefit and maximize their role from the strut-and-tie mechanism with the presence of spirals. Figure 4(b), in this regard, shows the maximum stresses in the transverse rebars for all the examined configurations, as a function of the imposed displacement. It can be seen that steel members behave elastically up to ≈ 4-5 mm of deformation. Yielding appears more or less in the same order of displacement. This is not the case of the un-confined M-ISO system, where stress peaks are up to 150 MPa and the slab is not able to resist more. Relevant structural benefits can be achieved also in terms of stress distribution and evolution in the involved structural members, as well as in damage propagation in the concrete slab (Fasan et al. 2022).



(a)

(b)

Fig. 4. Load-displacement response of the full-scale RC slab in compression, with or without spirals and gap (ABAQUS/Explicit): (a) load-displacement response and (b) stress evolution in the transverse rebar.

4. Conclusions

According to Eurocode 8 provisions, the structurally efficient design of steel-concrete composite frames and joints, represents a challenging issue, which involves several parameters to optimize. Especially for seismic design considerations, careful attention is needed on single resisting mechanisms and components.

In this paper, a spiral-based confinement technique was proposed for improving the compressive response and bending performance of concrete slabs for composite frames. In this sense, the in-plane compressive response of a set of geometrical and mechanical configurations of technical interest was explored with the use of computationally efficient, full three-dimensional numerical models. A shown, the proposed confinement technique is able to improve the resisting "mechanism 2" from Eurocode provisions. The presence of optimally designed and arranged steel spirals was proved to strongly enhance the basic strut-and-tie mechanism of slab, both in terms of strength and ductility at collapse.

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