Structures 70 (2024) 107689

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Optimised rotational-spring component-based modelling strategy for seismic resistant steel-concrete composite joints and frames with continuous or isolated slab

Marco Fasan [a], Chiara Bedon [b,*], Maria Rosaria Pecce [c]

[a] University of Trieste, Department of Engineering and Architecture, Trieste, Italy
[b] University of Trieste, Department of Engineering and Architecture, Trieste, Italy
[c] University of Napoli Federico II, Department of Structures for Engineering and Architecture, Italy

ARTICLE INFO

Keywords:
Steel-concrete composite frames
Beam-to-column joints
Component-based model
X-Concentric bracings
Pushover analysis

ABSTRACT

Joints and frames in steel-concrete composite systems represent complex mechanical assemblies that require specific calculation procedures to optimise their detailing and structural capacity, particularly under seismic loads. To this aim, component-based modelling approaches should be able to account for the most relevant mechanisms and resistance/stiffness behaviours of individual members, and their mutual interaction. In this paper, two different simplified non-linear approaches are considered for steel-concrete composite beam-to-column joints, and are specifically applied to a seismic resistant case-study frame with X-concentric bracings. Both beam-to-column joints with or continuous ("JA" joint) or fully isolated ("JB" joint) slab are examined. First, non-linear axial springs are assembled and calibrated on the base of a previous study ("Type 1″ model ("T1″)), according to force-displacement relationships proposed in the DPC-ReLUIS Italian guidelines. Successively, a novel modelling approach based on non-linear rotational springs is presented ("Type 2″ model ("T2″)), to further simplify the computational cost of T1 strategy, and allow to efficiently account for the moment-rotation behaviour of the examined joints. The preliminary numerical validation is carried out based on past literature experiments. Moreover, the optimized T2 approach is used to explore the in-plane lateral, seismic performance of a 2D steel-concrete composite frame, which is specifically designed with X-concentric bracings. The seismic capacity of the frame (and the associated interaction of components, especially the joint zone with the bracing system) is addressed on the base of pushover analyses.

1. Introduction

It is generally recognised that joints in steel-concrete composite frames represent complex mechanical assemblies, that require specific calculation procedures to optimise their detailing and structural capacity, particularly under seismic loads. To this aim, component-based modelling approaches can represent a major support for design [1–5]. However, these modelling strategies should be able to account for the most relevant mechanisms and resistance/stiffness behaviours of individual members, and the mutual interaction of components, under a multitude of geometrical configurations and loading conditions. In this sense, there may be several strategies to streamline a component-based model concept and optimize its computational efficiency.

In particular, a critical aspect is represented by the appropriate description of stiffness and resistance contributions of individual steel and concrete components [5], and by the implementation of key mechanisms. As a major difference compared to the numerical modelling of simple steel or simple concrete structures [6,7], the "active" components of a steel-concrete composite joint are in fact characterised by possible reciprocal interactions, which may be further exploited by geometrical details (such as a fully isolated or continuous concrete slab [8–10]) or even particular loading conditions (especially seismic loads, see Fig. 1).

The present study poses the attention on component-based modelling strategies for steel-concrete composite systems and for the seismic analysis of composite frames. As a reference, the technical recommendations proposed for seismic design by the DPC-ReLUIS guideline are taken into account [11]. In particular, the use of non-linear axial springs

* Corresponding author.
E-mail address: chiara.bedon@dia.units.it (C. Bedon).

https://doi.org/10.1016/j.istruc.2024.107689
Received 4 June 2024; Received in revised form 23 October 2024; Accepted 28 October 2024
Available online 31 October 2024

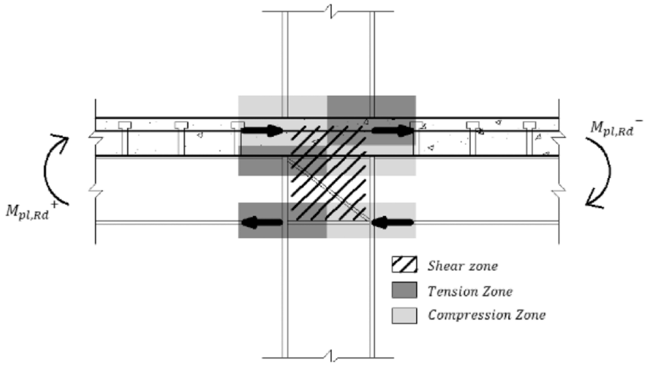


Fig. 1. Identification of active components in a steel-concrete composite joint under antisymmetric (seismic) loads.

(Type 1 model ("T1″)) or rotational springs ("T2″) is addressed in terms of computational efficiency and accuracy. In the first case (T1), the model calibration is carried out according to [5]. In the second case (T2), an original and optimised approach is proposed, to further maximize the model efficiency.

In doing so, the attention is given to both joint configurations with continuous / fully interacting concrete slab ("JA"), or fully isolated slab ("JB", see for example Fig. 2), given that they are characterised by major variations in mechanical response and possible activation of mechanisms [5]. The validation of joint modelling is carried out by taking into account some literature experimental results for steel-concrete composite joints under different loading conditions [8]. Successively, the optimised T2 component-based strategy is extended from the joint level to the analysis of a steel-concrete composite frame equipped by X-concentric bracings. Comparative results from the parametric numerical analysis are critically discussed, as obtained from pushover analyses, with careful consideration for the interaction in the joint zone with the bracing system, and possible effects on the global seismic performance of the frame.

2. Component-based modelling strategies

The implicit advantage of component-based modelling strategies is to reproduce and analyse even complex systems with efficiently implementable and cost-minimised numerical models that necessitate of a general commercial software (like Sap2000 [12], in the present study). This is not the case of full 3D numerical assemblies, where local and global mechanisms can be reproduced in detail, but major efforts are expected in terms of model assembly, calibration of components and simulation.

2.1. Key parameters for the constitutive law

As extensively shown in [5,8,11], the component-based model calibration assumes that non-linear springs are able to reproduce the steel detailing and slab arrangement, and their different interaction phenomena (and thus resisting mechanisms) under gravitational or seismic loads. To this aim, the steel components are described in terms of components in tension (i.e., bolts, webs, flanges), compression (i.e., webs and flanges), or shear (i.e., column web panel), depending on a multitude of geometrical and mechanical assumptions (Tables 1–2).

When the slab is continuous and fully interacting (JA), it is assumed that the possible slab response is typically associated to two major contributions, namely represented by:

a) longitudinal rebars in tension, for the steel-concrete composite joint under hogging bending moment (i.e., downward deflection), or
b) Concrete crushing, when the joint is subjected to sagging bending moment (i.e., upward deflection).

Besides, specific behaviours and interactions could take place when the concrete slab is fully isolated (JB), like the mechanism 4 which involves shear studs for the slab under positive / sagging bending moment.

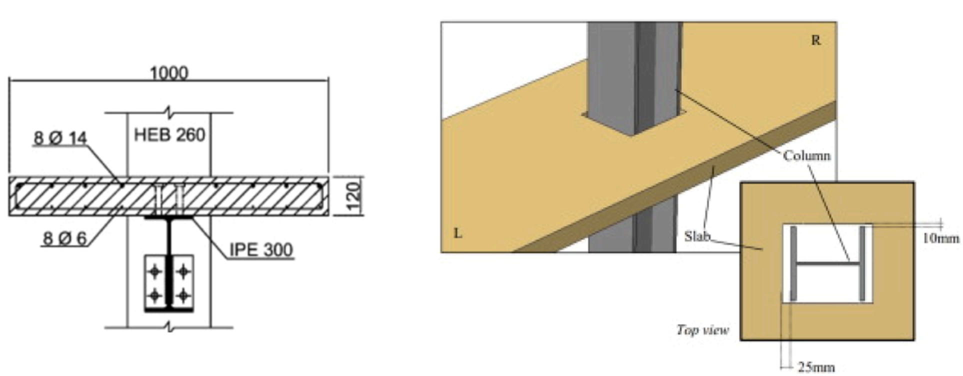
To verify the mechanical response and capacity, two different composite joint configurations and two different simplified modelling approaches are addressed in this paper, to support the seismic analysis of a full-scale composite frame. In doing so, the effect of slab continuity (JA) or discontinuity (JB) is taken into account. Regarding the modelling aspects, both the herein defined Type 1 (T1) approach based on axial springs (like in [5]) and a rotational-spring based strategy (Type 2 (T2)) are considered respectively in the analysis of both JA and JB arrangements. Successively, the optimised T2 approach is also exploited for the analysis of steel-concrete composite frames.

2.2. Resistance and stiffness

As a common strategy, the performance of the examined steel-concrete composite joints is referred as to the constitutive law of

Table 1
Component characterization for a welded steel-concrete composite joint.

Joint zone	Component
Tension	Column flange in bending [§EC3 1 −8 6.2.6.4.3]
	Column web in tension [§EC3 1 −8 6.2.6.3]
	Longitudinal rebars for the slab in tension [§DPC-ReLUIS]
Compression	Column flange in bending [§EC3 1 −8 6.2.6.4.3]
	Column web in compression [§EC3 1 −8 6.2.6.2]
	Slab in compression [§DPC-ReLUIS]
Shear	Column web panel in shear [§EC3 6.2.6.1]



(a) (b)

Fig. 2. Example of bolted steel-concrete composite joint with fully isolated slab (JB type): (a) cross section (dimensions in mm) and (b) axonometric view.

Table 2
Component characterization for a bolted steel-concrete composite joint.

Joint zone	Component
Tension	Longitudinal rebars for the slab in tension [§DPC-ReLUIS]
	Bolt in tension [§EC3 1 –8, 3.4]
	Punching [§EC3 1 –8, 3.4]
	Column web in tension [§EC3 1 –8 6.2.6.3]
	Column flange in bending [§EC3 1 –8 6.2.6.4.1 –2]
	Flange in bending [§EC3 1 –8 6.2.6.5]
	Beam web in tension [§EC3 1 –8 6.2.6.8]
Compression	Column flange in bending [§EC3 1 –8 6.2.6.4.3]
	Column web in compression [§EC3 1 –8 6.2.6.2]
	Slab in compression [§DPC-ReLUIS]
Shear	Column web panel in shear [§EC3 6.2.6.1]

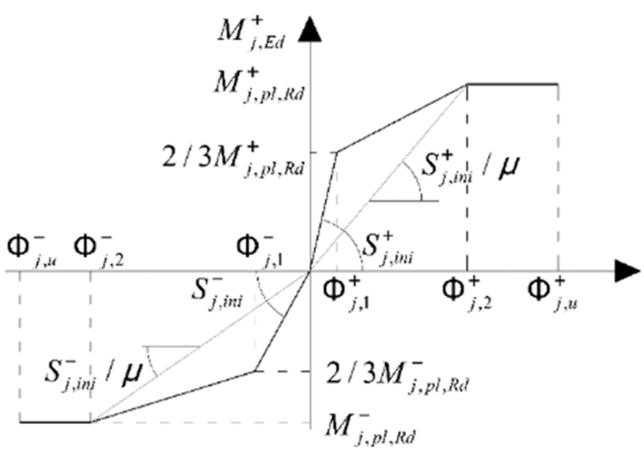


Fig. 3. Non-linear moment-rotation constitutive law of a steel-concrete composite joint.

Fig. 3, with particular attention to include the interaction/contribution of the superimposed concrete slab, with its typical mechanisms.

To describe the typical moment-rotation constitutive law as in Fig. 3, the resisting bending moment should be first determined based on the effective resistance of each active component ($F_{r,Rd}$), multiplied by the distance of each component (h_r) from a reference control point of the joint:

$$M_{j,pl,Rd} = \sum_{i=1}^{r} F_{r,Rd} h_r \tag{1}$$

Depending on the composite joint features (both for steel and slab components), however, the number of active components to include in Eq. (1), as well as their effective contribution, may largely change. The steel components of the joint object of study should be first distinguished as "welded" or "bolted", see Tables 1–2.

A special attention is required to implement the resistance contributions of the concrete slab, which further vary as a function of the slab interaction (JA or JB) and the loading condition (slab in compression or in tension). Basically, the JA configuration of continuous slab in contact with the column can generate the well-known mechanisms 1, 2 and 3 (Tables 1–2 and Fig. 4). When the concrete slab is fully isolated (JB), the effect of mechanism 4 should be properly quantified and taken into account [11].

In analogy to resistance considerations, stiffness coefficients necessitate a specific mechanical analysis and characterization, which strictly depends on the geometrical and mechanical features of a given joint (Fig. 5). Concerning steel components, the stiffness contributions recalled in Tables 1–2, based on EC3 provisions, while specific contributions for the concrete slab (as in Fig. 4) could be quantified in accordance with the DPC-ReLUIS guideline [5,11].

Following Fig. 3, the global initial stiffness of the steel-concrete composite joint is in fact quantified as (up to $2/3M_{j,pl,Rd}$):

$$S_{j,ini} = -d_{CR}\sum_{r=1}^{n} k_{eff,r} h_r + \sum_{r=1}^{n} k_{eff,r} h_r^2 \tag{2}$$

where:

$$k_{eff,r} = \frac{1}{\sum 1/k_{i,r}} \tag{3}$$

and:

$$d_{CR} = \frac{\sum_{r=1}^{n} k_{eff,r} h_r}{\sum_{r=1}^{n} k_{eff,r}} \tag{4}$$

In Eq. (3), $k_{i,r}$ represents the contribution (in series) of the i-th spring at a generic row r (i.e., with the same lever arm).

The secant stiffness term as in Fig. 3 is then given by $S_{j,ini}/\mu$, where:

$$\mu = \left(1.5\frac{M_{j,Ed}}{M_{j,pl,Rd}}\right)^{\psi} \tag{5}$$

with:

$$\varphi_{j,1} = 2/3M_{j,pl,Rd}/S_{j,ini} \tag{6}$$

$$\varphi_{j,2} = (M_{j,pl,Rd})/(S_{j,ini}/\mu) \tag{7}$$

A multitude of component features and arrangements should be consequently considered, and properly reproduced in mechanical and geometrical features by the component-based modelling approach [5].

3. Modelling assumptions

3.1. T1 model based on axial springs

Basic assumptions of the T1 modelling approach, which are extensively discussed in [5], typically include the use of axial springs able to account for resistance and stiffness parameters as in Section 2 [5,8,11]. For a given steel-concrete composite joint, it is required to account for:

- Non-linear axial links, to describe each component, like for example the "NL-link type" (with "multilinear" performance);
- Weightless "Rigid Link" elements to connect the NL-Links;
- Non-linear stress-strain relationships to describe steel and concrete materials. To note that concrete is considered to react in compression only;
- Frame elements to describe column and beams (equivalent inertial properties in the "section designer" tool), and steel rebars;
- Hysteretic models to describe the behaviour of materials and components (Takeda for concrete, kinematic for steel, Pivot for T-stub components);
- Mean mechanical properties for steel and concrete materials, in place of characteristic values, to reproduce experimental-like conditions.

Typical examples are shown in Fig. 6 for the fully isolated (JA) or continuous (JB) slab configurations respectively.

More in detail, key components of the JA model with continuous slab as in Fig. 6(a) are the steel components and the concrete slab, that can be efficiently schematized as:

- #1: column web panel in shear;
- #2: column web panel under transversal compression;
- #3a and #3b: T-stub components;
- #4: column web panel under transversal tension-compression;
- #5: mechanism 1;
- #6: longitudinal rebars for the concrete slab in tension.

Few but critical modifications are required in the JB model with fully

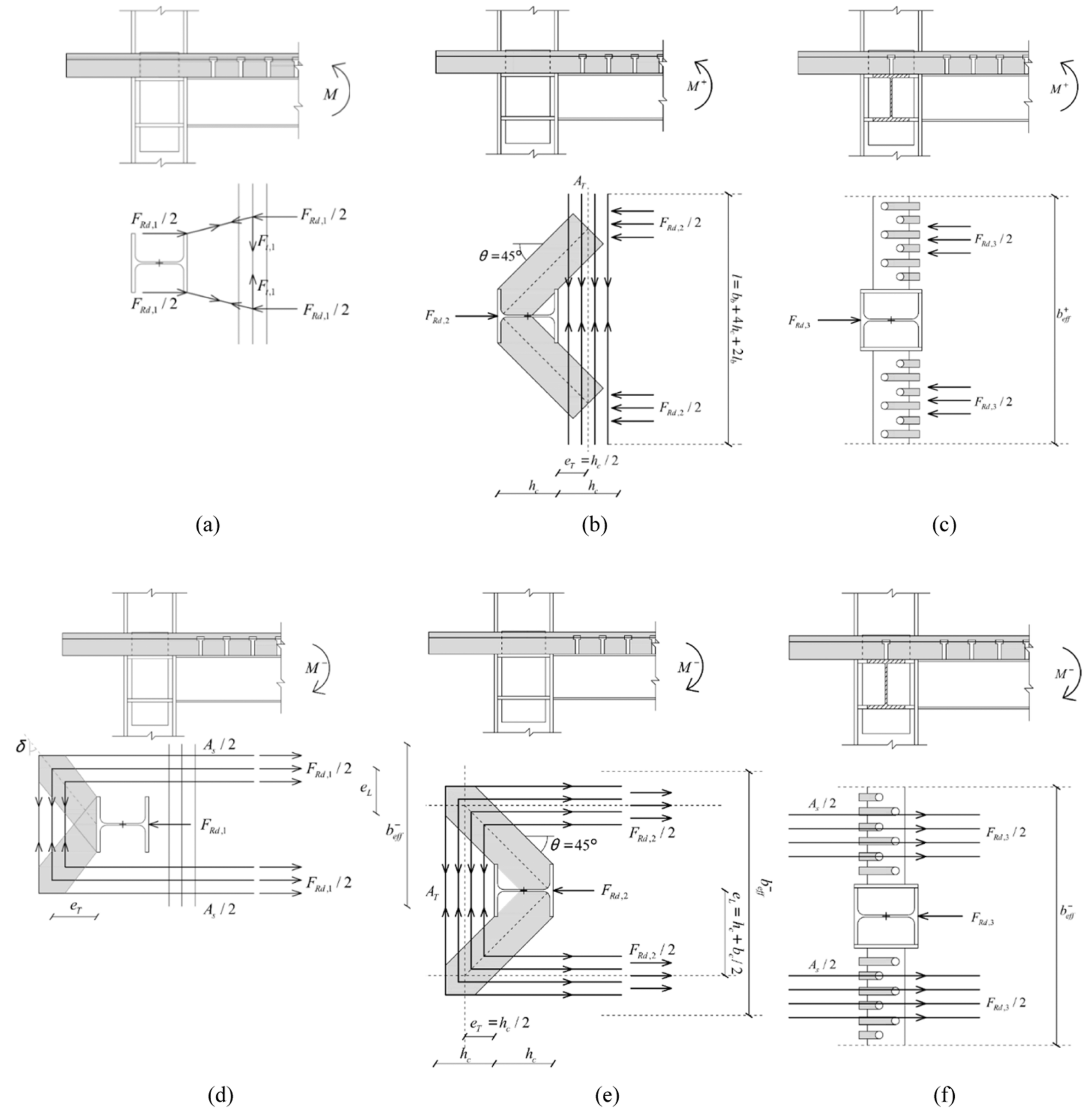


Fig. 4. Reference mechanisms for the concrete slab in compression or in tension: (a) mechanism 1; (b) mechanism 2; (c) mechanism 3 in compression; (d) mechanism 1; (e) mechanism 2; (f) mechanism 3 in tension.

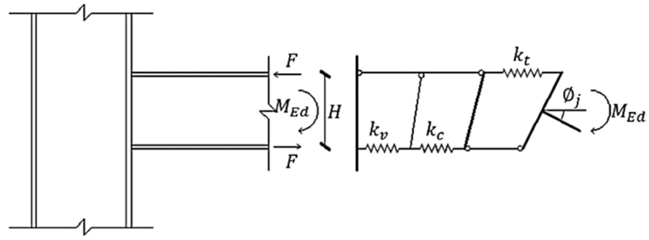


Fig. 5. Component-based mechanical model for a steel joint under negative / hogging bending moment.

isolated slab (Fig. 6(b)), to reproduce the additional contribution of mechanism 4. The attention goes specifically to components:

- #1: column web panel in shear;
- #5: mechanism 4 for the concrete slab in compression

3.2. T2 model based on rotational springs

The novel T2 approach assumes that the T1 model is further simplified in number of equivalent springs that are required to reproduce the contribution of active components, and can be thus maximized in computational efficiency.

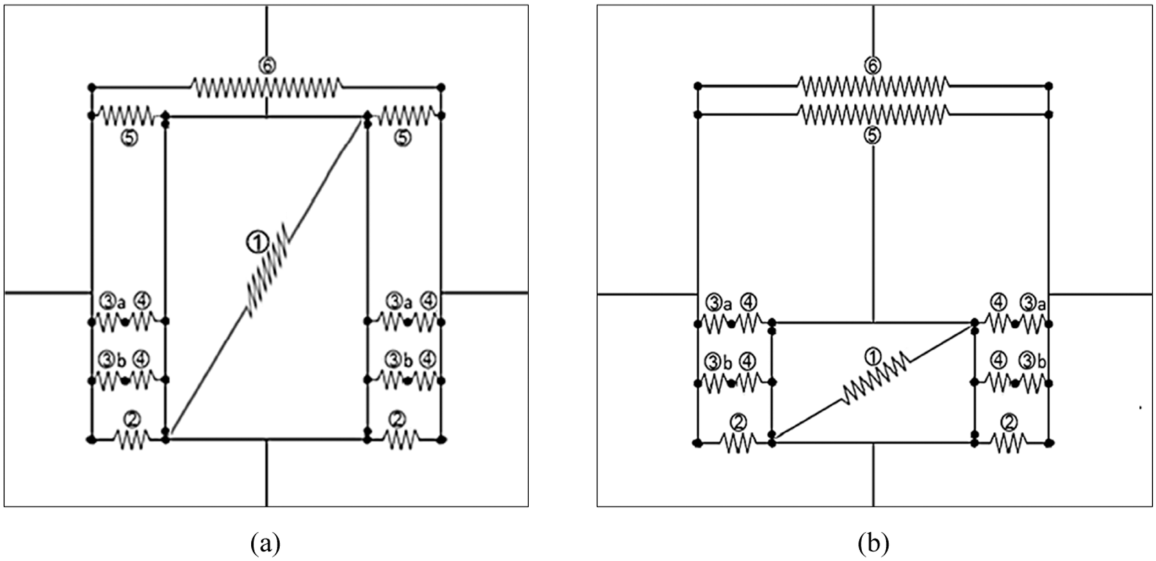


Fig. 6. Schematic representation of composite joint according to T1 strategy (non-linear axial springs): (a) continuous (JA) or (b) fully isolated slab (JB).

In doing so, the axial springs of T1 approach (see also [5]) are first defined, and grouped by active components like in Section 3.1. These components are successively replaced by rotational springs, with non-linear moment-rotation behaviour according to Eqs. (1)–(7). The final goal is to obtain the typical results as in Fig. 7.

To note that spring #1 (column web panel in shear) is still defined as for T1 (axial spring), while the other active components are mechanically simplified.

More in detail, for the JA joint with slab continuity (Fig. 6(a) and 7 (a)), the T2 strategy involves the following rotational springs:

- #2: rotational spring for all the steel components;
- #3: continuity spring, to account for the longitudinal rebars in tension (under negative / hogging bending moment);
- #4: contact spring to describe the contribution of the concrete slab in compression (mechanism 1).

In analogy, the composite joint JB, with isolated slab, can be optimized from Fig. 6(b) as schematized in Fig. 7(b), and includes:

- #2: steel components, defined as for joint JA;
- #3: rotational spring for the isolated slab, to account for mechanism 4 when the slab is in compression (under positive / sagging bending moment) or for the contribution of longitudinal rebars in tension (under negative / hogging bending moment) respectively.

The qualitative comparison of Figs. 6 and 7, as well as Table 3, further emphasises the minimisation of springs that are required to reproduce the active components according to the T2 strategy.

4. Preliminary numerical validation

4.1. Modelling and setup

Following the basic approach summarized in Section 3, a preliminary numerical validation was carried out on the joint specimen earlier investigated in [8] and schematically reproduced in Fig. 2. The present numerical study, based on T1 and T2 strategies, was performed in Sap2000 and verified with the support of past findings presented in [8].

According to Fig. 2(a), the reference geometrical configuration

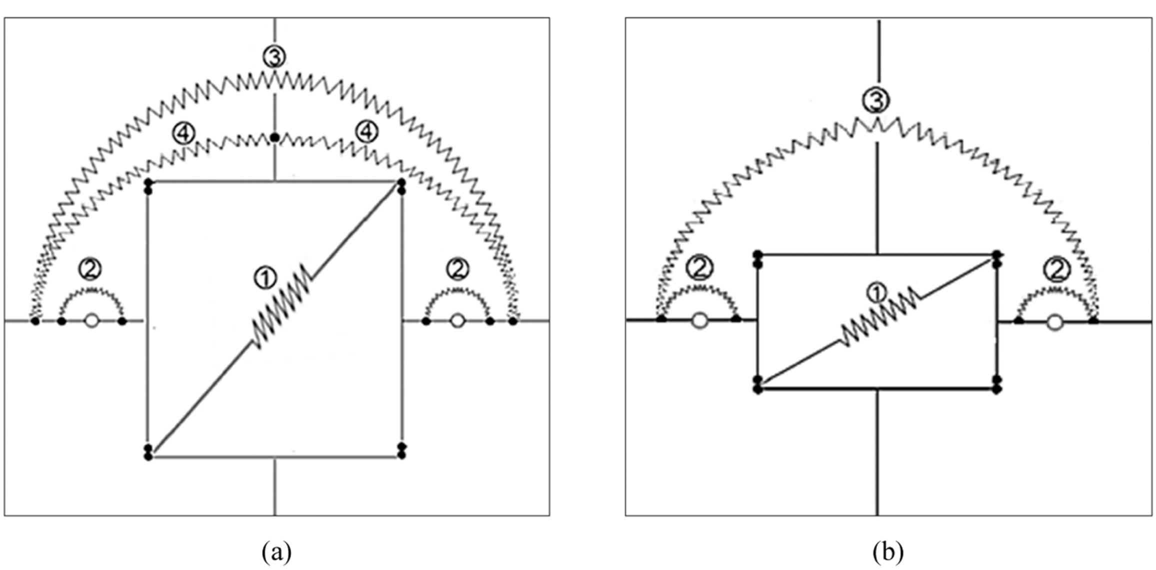


Fig. 7. Schematic representation of composite joint according to T2 strategy (non-linear rotational springs): (a) continuous (JA) or (b) fully isolated slab (JB).

Table 3
Example of typical constituent springs for the JA joint with continuous slab, according to T1 and T2 modelling strategies.

Component	
T1 (axial springs)	T2 (rotational springs)
#1: column web panel in shear	#1: column web panel in shear (axial spring)
#2: column web panel under transversal compression	#2: rotational spring for all the steel components
#3a and #3b: T-stub components	
#4: column web panel under transversal tension-compression	
#5: contact axial spring for the concrete slab in compression (mechanism 1)	#4: contact rotational spring for the concrete slab in compression (mechanism 1)
#6: continuity axial spring (longitudinal rebars in tension)	#3: continuity rotational spring (longitudinal rebars in tension)

consisted in fact in the steel-concrete composite joint extensively numerically analysed in [8], with the support of a refined full 3D numerical model described in Abaqus/Explicit [13] and past full-scale experiments. The specimen, more in detail, consisted of IPE300 type steel beams (2.1 m in nominal length), and an HEB260 column (2.77 m its total height). The steel beams were used to support a concrete slab, 120 mm in thickness and 1 m in width, as it can be seen in the schematic drawing of Fig. 2(a). A set of 8ϕ14 (on top) and 8ϕ6 (on bottom) bars was used for the longitudinal rebars. Steel shear studs with 19 mm in diameter (75 mm the height) ensured the rigid mechanical connection of the concrete slab with the supporting IPE300 beams, with a spacing of 75 mm and 150 mm along the transversal and longitudinal axis. The bolted beam-to-column joint consisted of four M20 bolts (8.8 the resistant class). The concrete slab was finally isolated from the steel column, by means of a 25 mm gap able to avoid contact (Fig. 2(b)).

Fig. 8(a)-(b) show the examined loading conditions according to [8], namely symmetric (gravitational) and antisymmetric (seismic) configurations. The monotonic loads were applied, according to the experimental setup presented in [8], at a distance of 1950 mm from the column flanges. In Fig. 8(c), the full 3D numerical model presented in [8] for validation and refined analysis of mechanisms is also proposed.

From Table 4, the summary of most important features for the comparative models further emphasised the marked difference in composition and computational cost. Most importantly, the presently elaborated models in Sap2000 are characterised by a very limited number of elements, compared to the full 3D assembly. Furthermore, it can be seen that the T2 strategy is able to mostly reduce to −50 % the number of elements to describe the examined steel-concrete composite joint, compared to the T1 approach.

Table 4
Summary of model features for the selected bolted steel-concrete composite joint.

Slab	Model	Element type	Number of elements	DOFs
Continuous (JA)	Full 3D (Abaqus)[8]	Solid + beam (for rebars only)	≈ 24,300	≈ 120,000
	T1 (Sap2000)	Frame + NL-Link	44	198
	T2 (Sap2000)	Frame + NL-Link	22	30
Fully isolated (JB)	Full 3D (Abaqus)[8]	Solid + beam (for rebars only)	≈ 23,000	≈ 110,000
	T1 (Sap2000)	Frame + NL-Link	39	154
	T2 (Sap2000)	Frame + NL-Link	20	28

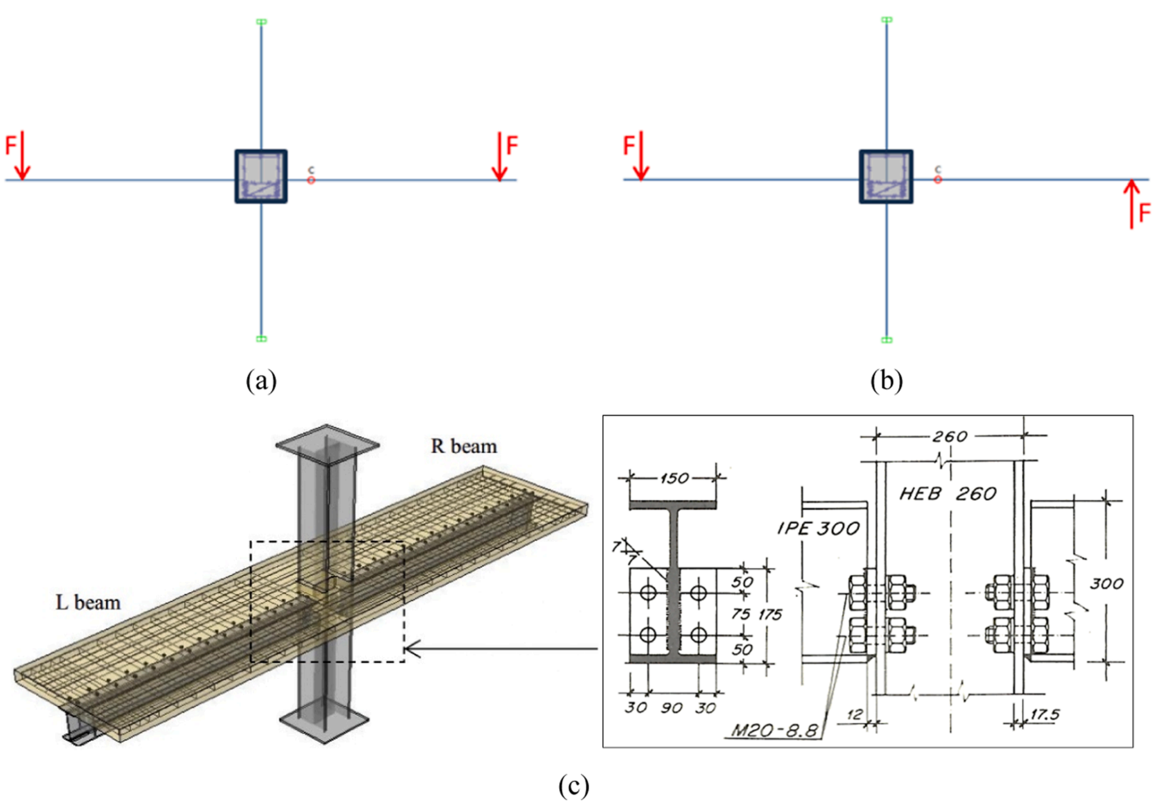


Fig. 8. Examined configurations for the joint model validation: (a) symmetric (gravitational) and (b) antisymmetric (seismic) loads, with (c) full 3D model. (reproduced from [8]).

4.2. T1 model calibration

The model calibration of axial springs for the active components as in Fig. 6 was carried out according to EC3 and DPC-ReLUIS (Tables 1–2). For the joint with continuous slab (JA), the typical constitutive laws are reported in Fig. 9.

Component #1 is elastic-plastic and symmetric in tension and compression, and can reach a maximum resistance of $\approx$ 115 kN at a displacement of $\approx$ 0.46 mm. The maximum resistance corresponds to the design shear strength of the column web panel. The component #2 corresponds to the column web panel under transversal compression and has a maximum capacity of $\approx$ 621 kN at a displacement of $\approx$ 0.16 mm. Disregarding the tensile effects, the obtained constitutive law contributes in compression only.

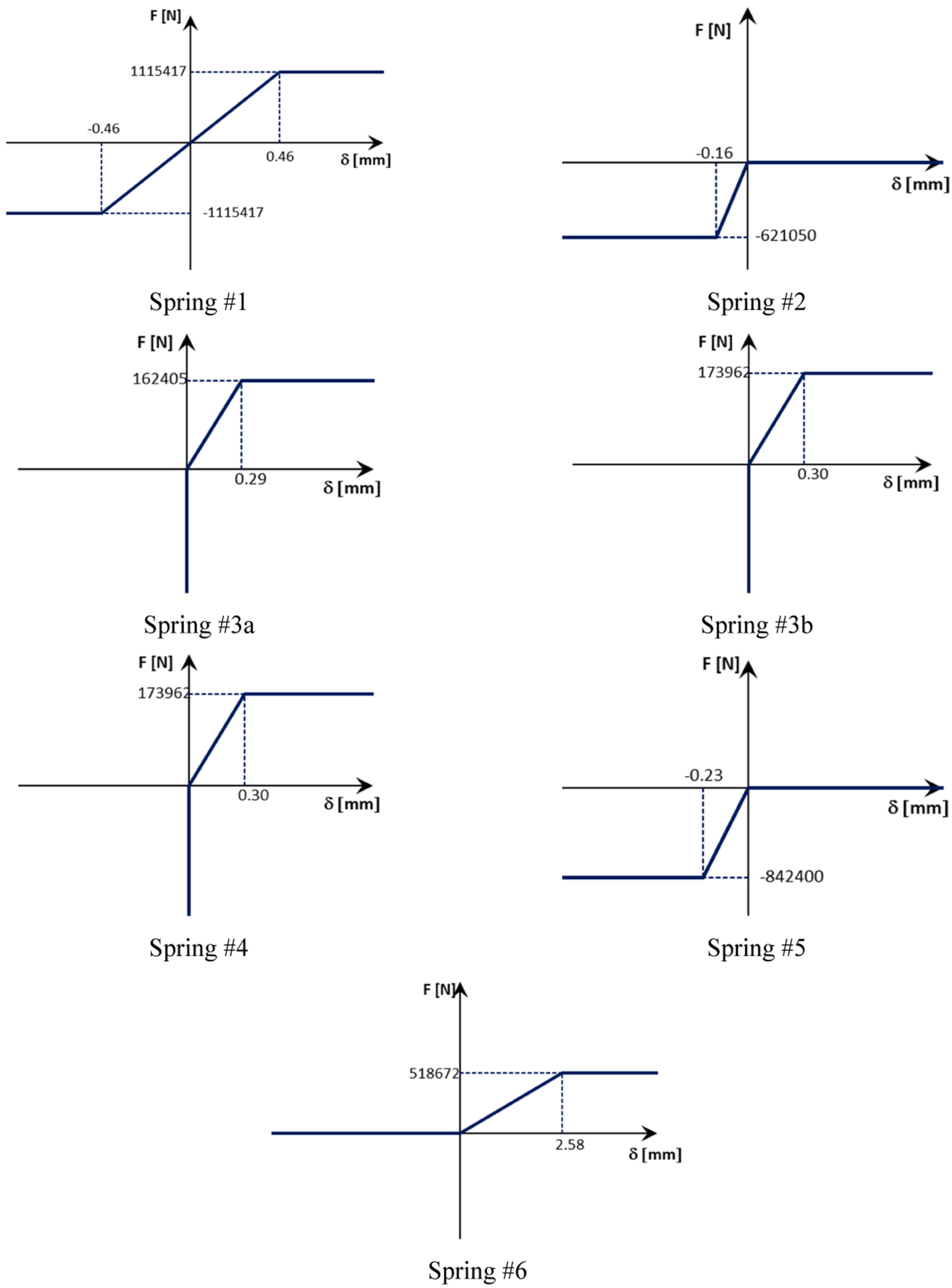


Fig. 9. Spring calibration for the joint with continuous slab (JA), based on T1 approach.

Components #3a and#3b are used to reproduce the T-stub mechanism of bolts, in terms of tensile resistance and stiffness. For the presently explored joint specimen, the estimated resistance (≈170 kN) depends on the weakest failure mechanism of the T-stub itself. For the present calculation example, the weakest failure mechanism is a ductile response of the flange. The corresponding yielding displacement is quantified in the order of ≈ 0.30 mm. The mechanical response in compression is defined as indefinitely rigid, both for springs #3a and #3b.

The calibration of component #4 (column web under transversal compression and tension) is similar to spring #2, assuming that the effective length corresponds to the width of the column flange. The final constitutive law is characterised by an elastic-plastic behaviour that is symmetric in tension and compression, with total resistance in the order of ≈ 410 kN and yielding displacement of ≈ 0.19 mm.

Component #5 is used to describe the active contribution of the concrete slab. Given that the JA joint is associated to a fully interacting and continuous slab, the resistance and stiffness parameters depend on the weakest mechanisms (1) for the slab in contact for compression. The final constitutive law does not react in tension and can reach a compressive resistance of ≈ 842 kN, at a displacement of ≈ 0.23 mm.

Finally, component #6 represents the contribution of the longitudinal rebars in tension. The corresponding unsymmetric constitutive law can reach a maximum tensile resistance of ≈ 518 kN at a displacement of ≈ 2.58 mm.

Regarding the calibration of active components for the steel-concrete composite joint with fully isolated slab (JB), compared to Fig. 9, there are several analogies and rather few but important modification that take place in components #1 and #5 (see Fig. 10). For component #1, there is a basic modification of the reference height of the column web panel (due to slab continuity or not), which is still associated to a symmetrical response in tension and compression. For component #5, the latter is required to reproduce the mechanism 4 that is typical of the fully isolated slab. The obtained resistance in compression is in the order of ≈ 751 kN, at a displacement of ≈ 1.34 mm.

4.3. T2 model calibration

The model calibration of rotational springs for the active components of JA and JB joint configurations involves a major minimisation in their number. The most important consideration refers to the calibration of active components (and thus resistance and stiffness parameters in tension or compression) considering separately the concrete slab subjected to hogging or sagging bending moments.

Concerning JA joint with continuous slab, the component #1 (column web panel) is identical to Fig. 9.

The rotational spring for component #2 is required to reproduce the active contribution of all the steel components. To this aim, it is first important to detect the possible active mechanisms for the joint under negative / hogging or positive / sagging bending moment respectively (Fig. 11). Overall, the calibration strategy follows in fact the T1 method earlier discussed, by grouping multiple axial springs that are then expressed in moment-rotational terms based on Eqs. (2)–(7). Component #2 based on T2 strategy is thus inclusive of the contributions deriving from springs #2, #3a, #3b and #4 (Fig. 11).

Component #3 is the continuity spring for the concrete slab subjected to negative / hogging bending moment (Fig. 12). As such, spring #3 reproduces the tensile resistance and stiffness of the longitudinal rebars only. Once the resistance is predicted, the derivation of the corresponding moment-rotation constitutive law is carried out according to Eqs. (2)–(7). Component #4 in Fig. 12, finally, is considered to contribute for JA joint when the concrete slab is subjected to positive / sagging bending moment, and basically derives from the T1 calibration (concrete slab in contact with the column, with the implicit limit represented by the tensile resistance of the T-stub mechanism).

The T2 model strategy for JB joint with fully isolated slab is even further reduced to a minimum, given that component #1 is still axial (column web panel) as for the T1 approach, while the rotational component #2 reproduces the contribution of steel members only (Fig. 13). Finally, component #3 accounts for the concrete slab mechanism (mechanism 4 of shear studs) under positive / sagging bending moment, or for the tensile contribution of rebars when the slab is subjected to negative / hogging bending moment (Fig. 13).

4.4. Results

The preliminary validation of the JA and JB joint configurations accounted for the numerical strategies earlier described and for the joint performance under symmetric (gravitational) or antisymmetric (seismic) loading conditions.

Typical force-displacement responses are collected in Figs. 14–15, where the Abaqus model from [8] is used as a reference from earlier experimental validation. It can be seen that the component-based strategy can in general properly capture the mechanical response of the examined joints, both in JA and JB configurations, and well reproduce the global performance of the system under both the selected loading configurations. To this aim, it is important to remind that the T1 component-based strategy was extensively addressed in [5], for exterior or interior composite joints, and for welded or bolted joint arrangements. As such, the T1 strategy is also further considered in the present analysis, whilst referred to a different configuration of interior joint, for comparative purposes.

Reminding the high computational efficiency of both T1 and T2 modelling strategies, it can be seen from Figs. 14–15 that the global response (especially the maximum resistance) is rather well captured. There are indeed some approximations that are implicit of the component-based strategy, compared to refined full 3D approaches. Typical examples can be noted in a partial overestimation of the elastic stiffness of the examined joint configurations, as well as an overestimation of the joint resistance in the first ≈ 5–8 mm of imposed vertical displacement. Also in this case, the effect derives from the spring calibration as in Section 3, which is basically carried out with elastic-

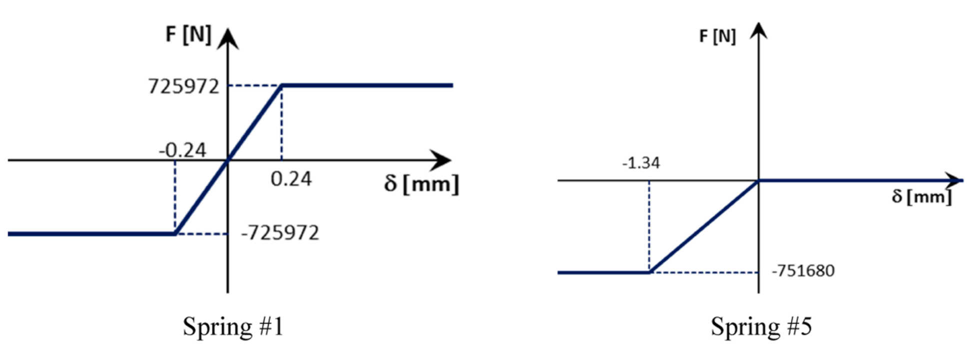
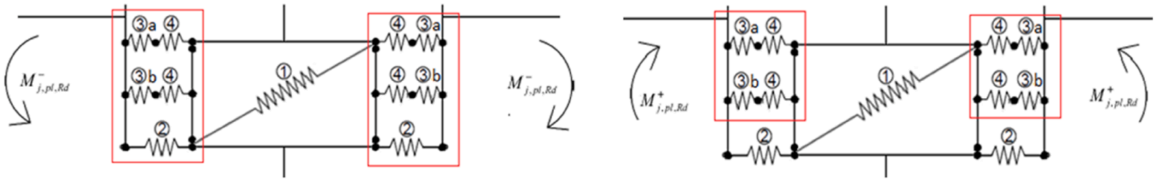
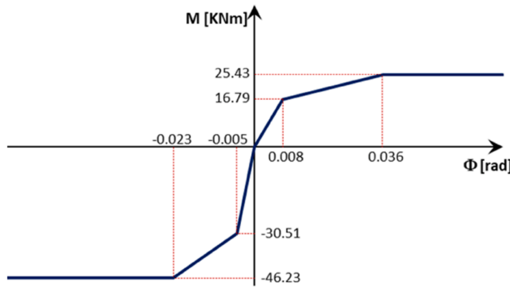


Fig. 10. Spring calibration for the joint with fully isolated slab (JB), based on T1 approach.



Negative / hogging bending moment Positive / sagging bending moment

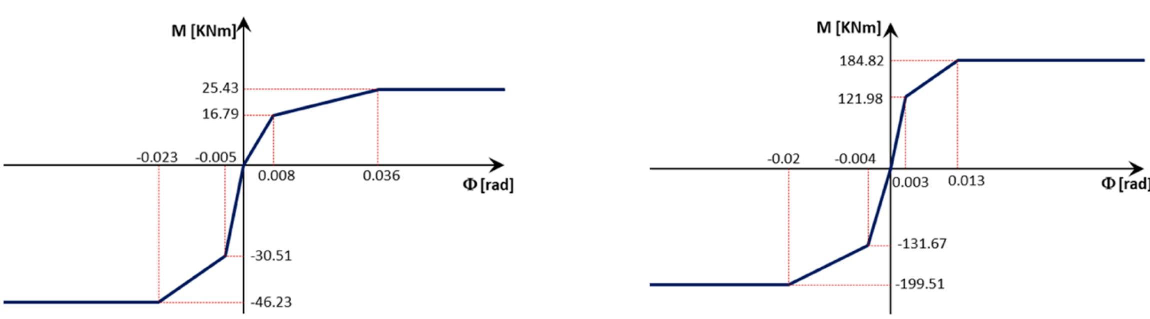


Spring #2

Fig. 11. Spring calibration of component #2 for the joint with continuous slab (JA), based on T2 approach.

Spring #3 Spring #4

Fig. 12. Spring calibration for the joint with continuous slab (JA), based on T2 approach.



Spring #2 Spring #3

Fig. 13. Spring calibration for the joint with fully isolated slab (JB), based on T2 approach.

plastic or rigid-plastic assumptions, and approximates the progressive damage propagation which is indeed taken into account by the refined 3D model in Abaqus, in terms of accurate geometrical description of components, and highly advanced constitutive laws and damage models for concrete and steel materials. Major discrepancies for the comparative plots in Figs. 14–15 are in fact observed when the prevailing damage mechanisms start to propagate in the steel or concrete members.

From Fig. 14 (c), it can be noted for the JA joint with continuous slab, that at a vertical displacement of 6.5 mm (antisymmetric loading) there are major plastic deformations in most of steel components, as well as a large crack distribution in the concrete slab, which both T1 and T2 approaches can only roughly simplify. In Fig. 15 (c), the evolution of plastic deformations in the steel components for the JB joint under symmetric (gravitational) loads is rather pronounced, and corresponds

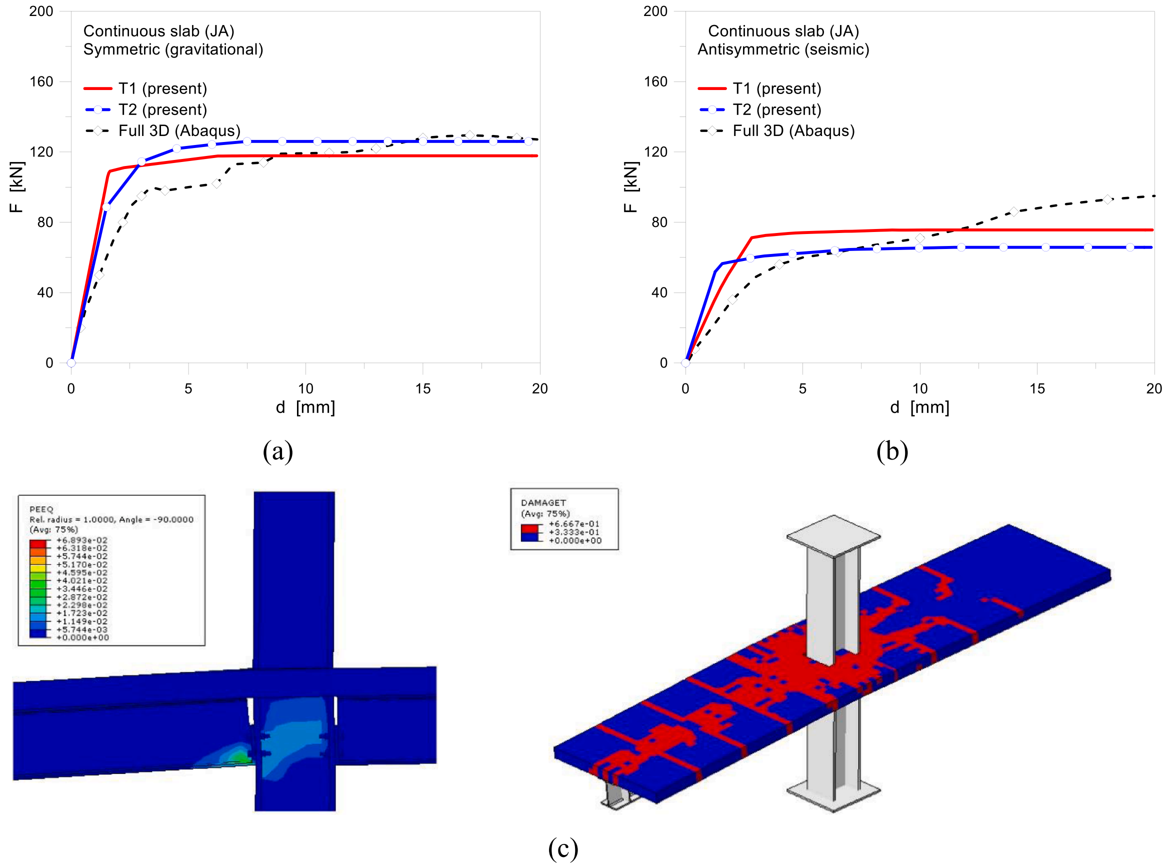


Fig. 14. Preliminary numerical validation of T1 and T2 component-based modelling approaches for the composite joint with continuous slab (JA type): load-displacement comparisons under (a) symmetric (gravitational) or (b) antisymmetric (seismic) loading; (c) plastic deformation in steel members and tensile cracks in the concrete slab (antisymmetric loading) at a vertical displacement of 6.5 mm.
(reproduced from [8]).

to the force drop of the "Abaqus" plot in Fig. 15 (a).

Besides, the joint performance is still well captured by both T1 and T2 approaches, thus suggesting some important implementations in even complex structural systems that require efficient numerical strategies.

Most importantly, Figs. 14–15 further emphasise the mostly different performance and load-bearing capacity of JA and JB joint arrangements, as a direct effect of the slab continuity and possible interaction with the resisting mechanisms of the active components. Regarding the T2 approach, it is also possible to observe that – although roughly simplified in number of equivalent springs – the model is still able to capture the resisting mechanisms of the examined joints, and to preserve a robust numerical efficiency. The scatter of T2 and T1 results is typically associated to the basic simplification of the model in its constituent active components. Besides, there is a still realistic prediction of the global performance, in the examined configurations.

5. Seismic analysis of a steel-concrete composite frame

5.1. Building layout

A seismic resistant, multi-storey steel-concrete composite frame (category B1/B2, offices and work areas) located in Benevento (seismic Zone 1 in Italy) was taken into account and designed in all its components, according to standards [14,15]. The construction was assumed regular in plan and in elevation, and to consist of X-concentric braced frames in both the principal *x*, *y* directions (Fig. 16 (a)).

As shown in Fig. 16 (b), the building height was set in 21.5 m, as obtained by 6 elevation levels with 3.5 m height (4 m for the ground floor only). In the *y* direction, the frames were arranged by 4 bays with 6 m span, and designed to carry on the gravitational and accidental vertical loads. In the latter case, a characteristic value of accidental load $q_k = 3.00$ kN/m^2 was taken into account for the inter-story floors. For materials, C20/25 concrete class was used for the slab, with B450C steel type for rebars, steel S235 type for beams and unbraced columns, and steel S355 for the braced columns.

Each frame was designed as composed of steel columns and steel-concrete composite beams with collaborating slab. The external frames were equipped by X-concentric bracings, that were verified as dissipative systems with active diagonal in tension (Table 5), with ductility class "B" and *q*-factor= 4 according to the Italian code NTC18 [15]. The bracing system was designed and assembled with members characterised by hollow cross-section according to EN 10210 [16].

The composite floor (120 mm in thickness) included a profiled sheeting (0.8 mm in thickness, type Hi-Bond A55/P600) and the concrete slab (65 mm thick). Steel shear studs (Nelson type) were used to connect slab and beams. Fig. 17 shows a schematic drawing of the typical section, with beam-to-column joint details.

The interior joints of the frame, see Fig. 16, were specifically designed to satisfy the standard requirements and account for the geometrical layout of primary members, including:

- Node type A: HE320B (S235) column & IPE270 beam (S235);
- Node type B: HE280B (S235) column & IPE270 beam (S235);
- Node type C: HE240B (S235) column & IPE270 beam (S235);
- Node type D: HE280M (S235) column & IPE270 beam (S235);
- Node type E: HE280B (S355) column & IPE270 beam (S235);
- Node type F: HE240B (S355) column & IPE270 beam (S235).

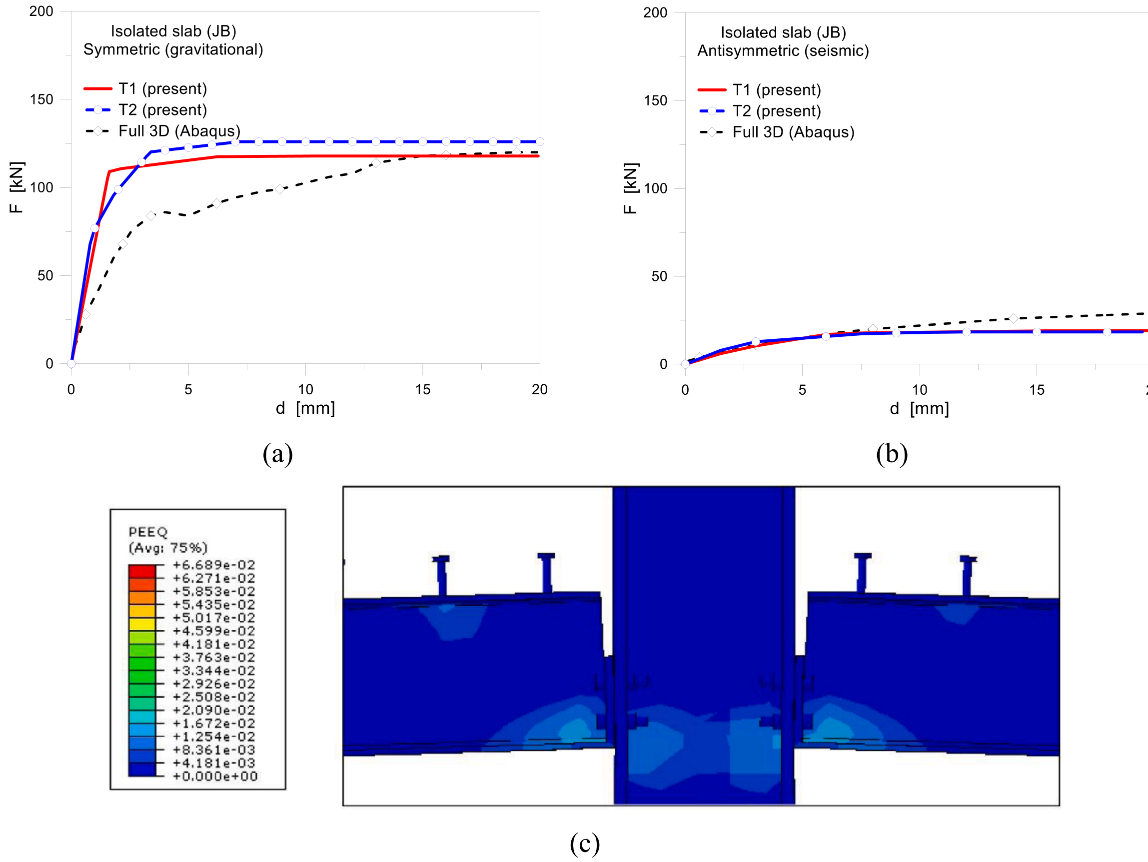


Fig. 15. Preliminary numerical validation of T1 and T2 component-based modelling approaches for the composite joint with isolated slab (JB type): load-displacement comparisons under (a) symmetric (gravitational) or (b) antisymmetric (seismic) loading; (c) plastic deformation in steel members (symmetric loading) at a vertical displacement of 6.5 mm.
(reproduced from [8]).

To note that the choice of composite joints with fully isolated slab (JB type), in combination with the X-bracing system, was adopted to possibly maximize the capacity optimization of the structure. According to the adopted layout (braced frame), the steel beams and columns were in fact designed to sustain the vertical loads only (JB type joints are expected to behave similarly to ideal hinges when subjected to horizontal loading).

5.2. Numerical modelling

The examined frame was modelled according to the T2 strategy with rotational springs. To note that the T1 calibration was also carried out, for preliminary comparative purposes. Compared to Section 3, additional NL-links were used to account for the diagonal members of X-concentric bracings (Table 5). In any case, the full building model described in Sap2000 (see Fig. 18) was still characterised by high computational efficiency, including a total of ≈ 1200 link elements and 160 frame elements (890 DOFs). For the purpose of present structural analyses, the set of 2D frames was arranged in series and connected by rigid links.

Material and geometrical non-linearity was taken into account for the components of joints and bracing members (NL-Links).

Pushover analyses were carried out in Sap2000 to assess the seismic performance of the examined structural system. Modal analyses were first carried out to verify the dynamic performance of the system.

The structural performance assessment for the examined steel-concrete composite frame with isolated slab (JB type joints) was in fact developed towards the response of the same structure equipped by composite joints with continuous slab (JA type). A third comparative configuration for the analysis of possible effects due to the arrangement of composite joints was finally detected in the frame system with X-bracings and ideal hinges to connect beam and columns. In this latter case, the non-linearity was lumped in the members of the bracing system only.

5.3. Analysis of numerical results

The case-study building was subjected to vertical / gravitational loads (seismic combination) and a typical pushover distribution of lateral loads, according to reference standards (with both 1st mode and mass proportional distributions).

Following the preliminary modal analyses, in particular, the period of vibration of the 2D braced frame was quantified in:

- $T_1 = 0.78$ s (73 % participating mass) for the frame with isolated slab (JB joints);
- $T_1 = 0.85$ s (with 72 % participating mass) for the frame with ideally hinges, and
- $T_1 = 0.73$ s (with 75 % participating mass) for the frame with continuous / fully interacting slab (JA joints).

As a result, such an outcome confirms that the arrangement and calibration of beam-to-column joints has direct effects also in terms of dynamic parameters and response of the structure. Most importantly, the braced frame with fully isolated slab (JB joints) still differs in terms of fundamental vibration period and participating mass from the structural model with ideal hinges.

The typical base shear (F_b) vs. top lateral displacement (d_c) response

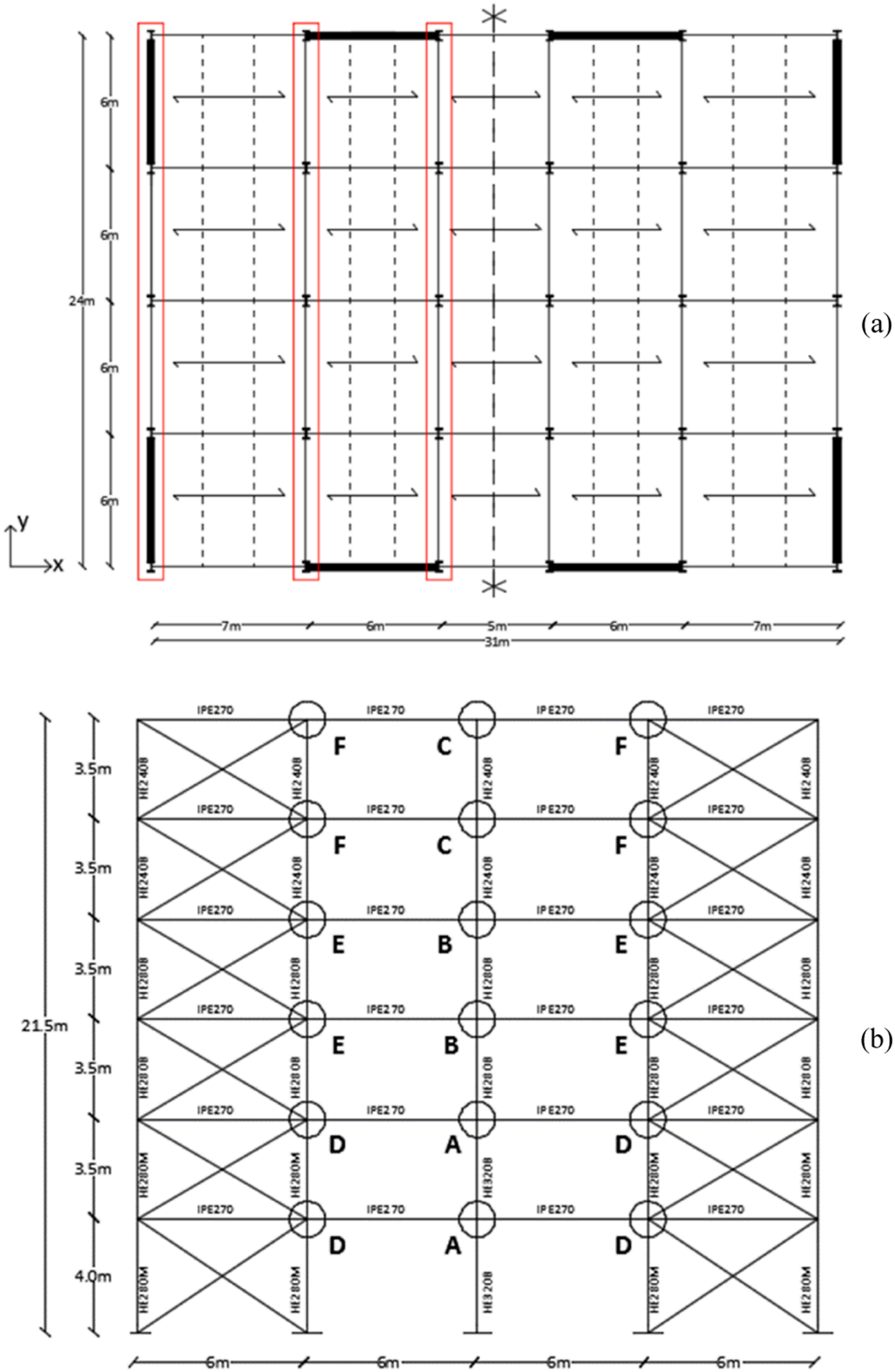


Fig. 16. Examined steel-concrete composite frame layout: (a) plan and (b) side views.

Table 5
Cross-section properties for the X-concentric bracings.

Story	Cross-section properties	Size [mm]
1	Rectangular (hollow)	180 × 80 × 16
2	Rectangular (hollow)	150 × 100 × 16
3	Rectangular (hollow)	150 × 100 × 14.2
4	Rectangular (hollow)	150 × 100 × 12.5
5	Rectangular (hollow)	140 × 80 × 8.8
6	Tube	114.3 × 5

from pushover analyses can be seen in Fig. 19.

In particular, it is worth to note that the frame with isolated slab (JB joint type) is characterized by a global response that is structurally efficient, and mostly comparable to the hinged configuration. The JA type solution, while associated to higher stiffness and resistance, is typically characterised by lower ductility.

More in detail, it was already shown in Section 3 that the fully isolated joints (JB type) perform similarly to a continuity solution (JA), under symmetric (gravitational) loads. At the same time, under anti-symmetric (seismic) loads, the isolated JB joints behave similarly to ideal hinges. Overall, additional structural benefits deriving from the choice of JB joints can be achieved from their use in combination with vertical bracing systems for the specialisation of structural components, as shown in the present case-study example.

At the global level, see Fig. 19, the JA configuration is in fact associated to higher initial stiffness (which involves a lower fundamental period T1 and a higher input seismic action for the structure). The higher resistance, compared to the JA solution, is not compensated by the reduced ductility.

Further effects of joint detailing can be seen in Figs. 20–21, in Damage Limit State (DLS), Service Limit State (SLS) and Collapse Limit State (CLS) conditions. The reference limit conditions for structural performance assessment were detected on the base of the measured inter-story drift, such as 0.8 % for DLS, 2 % for SLS and 3 % for CLS respectively.

The comparative results further enforce that the frame performance is implicitly affected by the mechanisms and interactions of joint components. At the DLS configuration (with the 1st mode proportional distribution of loads), the JB joint is less stiff and more resistant than JA and ideally hinged configurations (Fig. 20). With the mass proportional loading distribution, JA and JB results are mostly identical, but the JB configuration is comprised between JA and ideal hinges. In terms of CLS, see Fig. 21, the numerical results show that the isolated slab (JB) has more ductility than JA, and is rather in line with the performance of the ideally hinged frame.

6. Conclusions

The optimal seismic design of steel-concrete composite joints and frames is a rather challenging task, due to several geometrical and mechanical interacting parameters that need to be addressed. In this sense, the use of computationally efficient numerical strategies can provide a robust support in the analysis of components and even complex systems.

In this paper, the attention was given to the implementation of a computational efficient, rotational-spring component-based modelling strategy that has been elaborated on the base of the guideline document developed by the Italian DPC-ReLUIS tasks, for the design of seismic

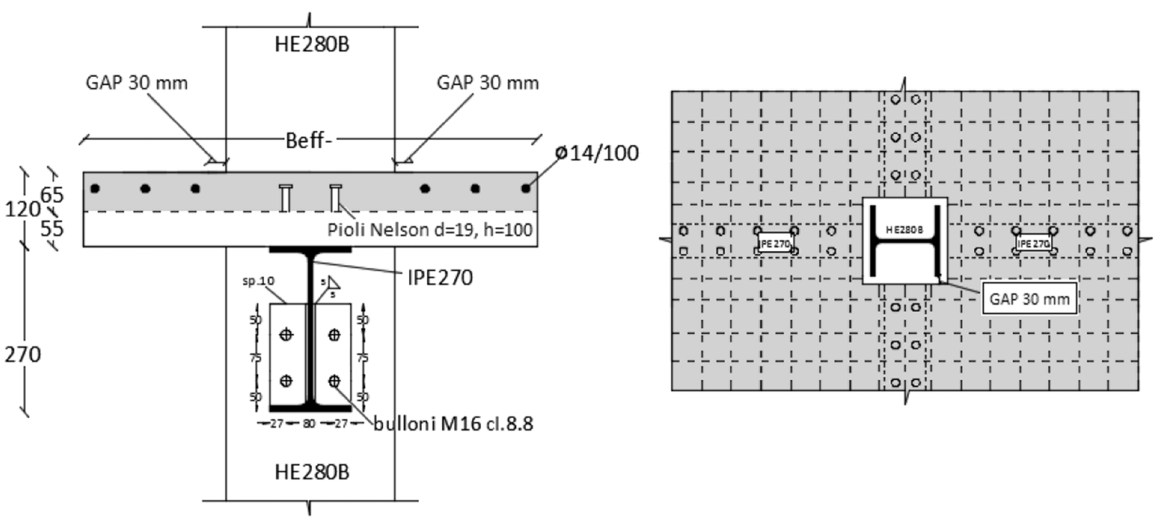


Fig. 17. Reference steel-concrete composite section: cross-section and plan view.

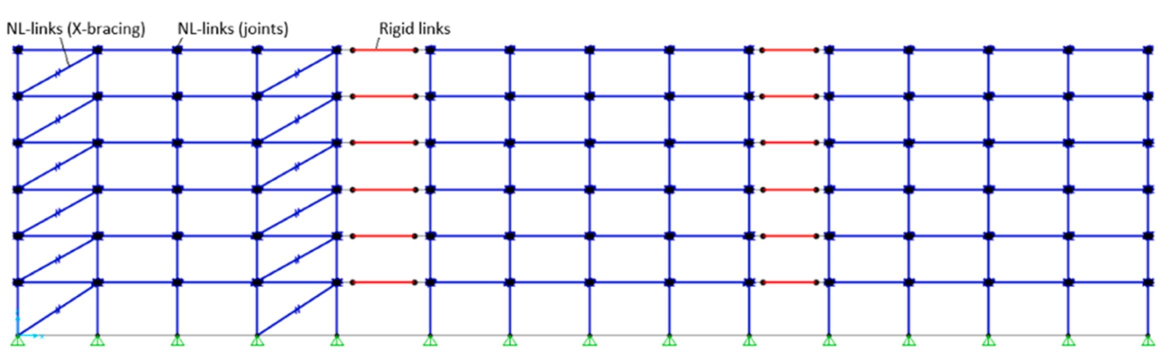
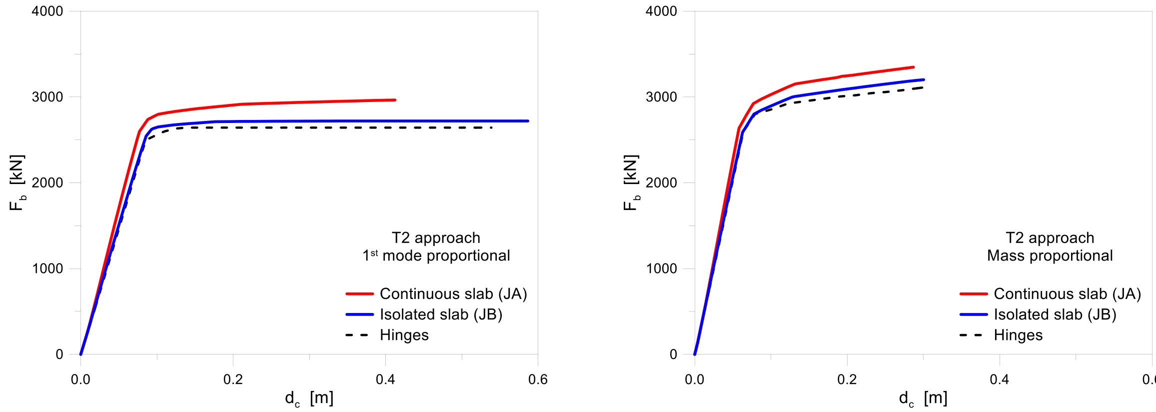
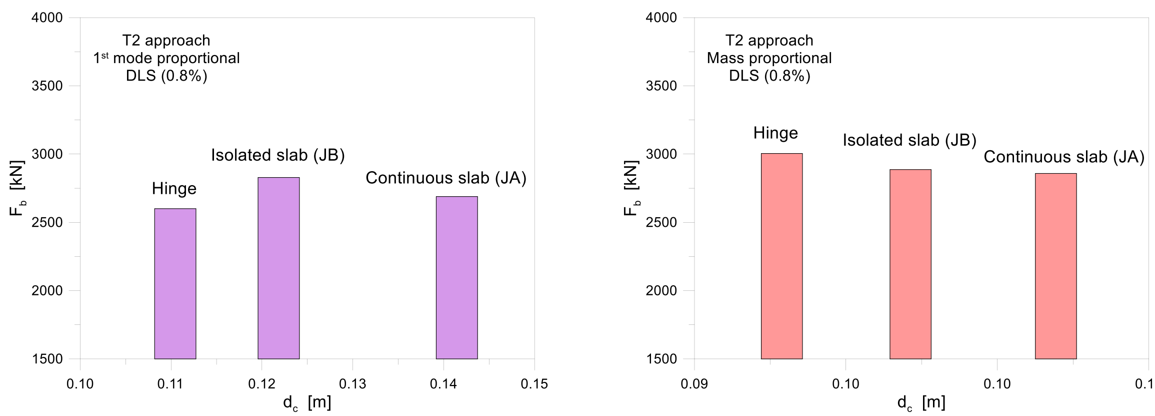


Fig. 18. Numerical model of the steel-concrete composite frame with fully isolated slab (JB joint) and X-bracings (Sap2000).



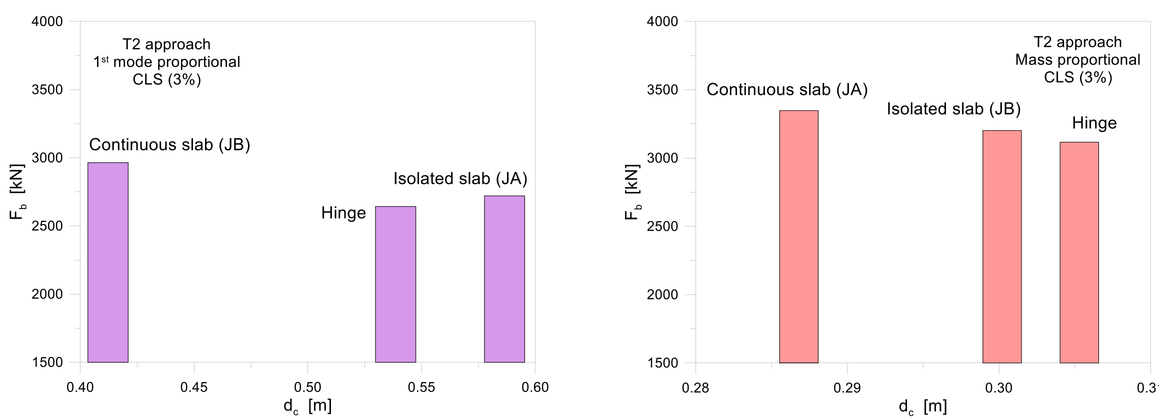
(a) (b)

Fig. 19. Pushover analysis results (Sap2000) based on (a) 1st mode and (b) mass proportional distributions of loads.



(a) (b)

Fig. 20. Pushover analysis results for DLS (Sap2000) based on (a) 1st mode and (b) mass proportional distributions.



(a) (b)

Fig. 21. Pushover analysis results for CLS (Sap2000) based on (a) 1st mode and (b) mass proportional distributions.

resistant steel-concrete composite frames.

As known, the most important mechanisms and behaviours of single members, but also the interaction of components, should be properly taken into account and numerically reproduced under general loading configurations. The attention was given in this study to beam-to-column joints in steel-concrete composite frames with X-concentric bracings. Two different modelling strategies were addressed for the calibration of joint components. The first one ("T1″ model) consisted of the traditional non-linear axial springs (according to the DPC-ReLUIS guidelines and [5]). Beam-to-column joints with continuous (JA joint) or fully isolated slab (JB joint) were properly examined.

To further optimize the computational efficiency of typical numerical models, non-linear rotational springs were proposed to simplify the T1 strategy, and account for the moment-rotation behaviour of the same components and joints (T2 model). The validation of T2 models to past literature results proved the rather good accuracy and high efficiency of this new strategy, compared to more refined full3D models. As such, the T2 approach was used to investigate the performance of a 2D composite frame, which was designed – according to standard requirements for Zone 1 seismicity in Italy – with X-concentric bracings. The seismic analysis of the case-study frame (and the associated interaction of components) proved that isolated joints (with bracing systems) can offer improved performances especially in terms of global ductility of the system, which is particularly important for seismic resistant constructions.

In particular, the T2 strategy offered remarkable benefits to support an optimized design and analysis process, not only at the joint level, but also for full complex structures and steel-concrete composite frames. In this sense, further efforts will be spent for the application of the same modelling strategy to different configurations and frames, as well as for a robust validation and parametric analysis inclusive of several solutions and technologies of technical interest.

CRediT authorship contribution statement

Maria Rosaria Pecce: Writing – original draft, Methodology, Investigation. **Chiara Bedon:** Writing – original draft, Supervision, Methodology, Conceptualization. **Marco Fasan:** Writing – original draft, Methodology, Formal analysis, Conceptualization.

DDeclaration of Competing Interest

The authors declare there is no conflict of interest with the publication of present research study.

Acknowledgements

DPC-ReLUIS is gratefully acknowledged for facilitating, in the years, a fruitful scientific networking of the involved authors with several esteemed experts, and for providing financial support to the team members of University of Trieste research unit. This article is dedicated to the memory of our respected mentor and colleague Prof. Claudio Amadio.

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