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Seismic behaviour of steel modular buildings: numerical analysis and comparisons between different design solutions

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Abstract

Recently, there is an increasing interest to develop modular multi-storey structures that can be adapted to any use like hospitals, schools, housing, etc, characterized by versatility and speed of use in several conditions.
Modular buildings may form complete building blocks with structural systems composed by several elements, such as steel frames, X-LAM timber floors and walls. These modular solutions are then completed with suspended ceilings and facilities including electrical and water systems.
This work is focused on the structural behaviour of steel modular buildings with different configurations. To this scope, a case study is considered, characterized by steel elements with connections allowing a rapid on-site assemblage, without any need of skilled workmanship. A comparison among numerical results obtained with time history analyses is shown and discussed.
The work presented is a first part of an on-going research addressed to propose reference solutions for modules, suitable in seismic prone areas and characterized by a low-seismic damage.

Keywords: *Steel–timber connections, green design, modular constructions, seismic analysis.*

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1. Introduction

The modular design is based on a module assigned by the designer (ESU) and on the combination of the various modules (MSU) to create spaces with different uses (MFU).

As for the elements composing the MSU, usually steel is applied for beams and columns, composing 3D frames that may be prefabricated or else assembled directly on-site. Usually these elements are designed only for vertical loads, and the lateral loads resistance is provided to bracing systems made of steel diagonals or, else, of vertical walls.

A critical issue related to this design solution is represented by inter-module connections, playing a central role on the global response of these so-assembled structures. To date few works are available in the literature on the behavior under lateral loads of the modules connections, and on how they govern the global response of assembled structures.

This study presents some preliminary results related to an on-going investigation on the MFU, considering several connections types and structural configurations about floor type and vertical bracing systems, the latter considered with a primary function of resisting to lateral loads (such as wind, earthquake). Numerical simulations about an ideal case study are presented, formed by several MSUs with different characteristics: rigid and deformable diaphragm made with X-Lam elements, steel bracings and X-Lam panels along the height as bracing system. All the numerical simulations are conducted with numerical models implemented within the software Midas Gen (2022). In this phase elastic-linear elements are chosen, so that all the non-linearities are due to the connections adopted. In particular, the results shown in this study refer to the connection proposed by Lacey et al. (2019), where the interlocking elements were included and taken into account to better simulate the current shear-displacement of the connection considered.

The study presented is a preliminary part of an on-going investigation conducted with the aim of proposing modular solutions (made of MSUs for MFUs) as reference solutions, characterized by a low damage in seismic prone areas.

Nomenclature

ESU: Elementary Structural Unit
MSU: Modular Structural Unit
MFU: Modular Functional Unit

2. Case study

In this study an ideal case study is considered, as shown in Figure 1a. Columns and beams are in steel, arranged in plan as indicated in Figure 1b, and composing modules with a 3,00 m inter-story height. The structural elements of the ESU are dimensioned for gravitational loads, assuming permanent (G) and live (Q) loads equal to a value of 3 kN/m2 and 2 kN/m2, using hollow sections for S355 steel columns (SHS 100x100x8) and beams (RHS 250x100x10). A design solution with diagonal elastic bracings and X-LAM panels as floor elements is chosen in study (Figure 1b).

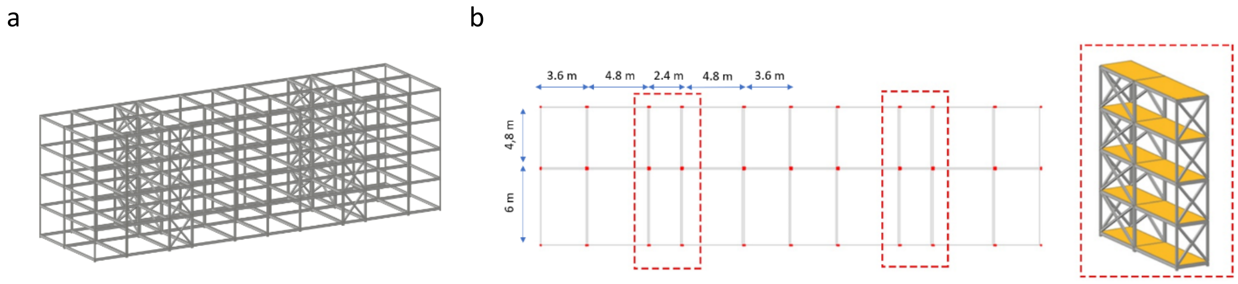

Fig. 1. Case study considered in this study

2.1. Modules connection (A)

In this work the connection investigated by Lacey et al (2019), Lacey et al (2020a), Lacey et al (2020b) is considered. The choice to consider this study is due to the presence of bolts and interlocking elements allowing the modules to be centered during the assemblage phase, with an advantage in terms of speed. A detail of the connection chosen, named in this study as connection 'A', is reported in Figure 2. In particular, the connection consists of: a horizontal connection with plate (plate 2); a vertical connection with structural bolts (bolt); positioning pins to improve shear stiffness (locating pin welded to plate).

As proposed in Lacey et al (2019), Lacey et al (2020a), Lacey et al (2020b) the Connection 'A' is characterized by the relationships indicated in Figure 3. In detail, the shear behavior of the Vertical Connection (VC) has a quadrilinear law in two shear directions (dir. 1 and dir. 2) and depends on the yield strength of the bolts and of positioning pins (Figure 3a). Whereas, Horizontal Connection (HC, Figure 3b) depends on the size and characteristics of the Plate 2 connection plate, having a different shear law along the two directions, and includes also the plate axial behavior.

The inter-module connection, referred to two adjacent modules (Figure 5a), is modelled with the links scheme as shown in Figure 5b. Two general links are modelled for each HC (a-d, b-c) with the relationships for shear and axial force previously described (Figure 3b). Whereas, each VC (a-b and d-c) may be modelled in general as reported in Figure 5c, where also rotational and the axial springs may be included. Preliminarily, in this study the latter are assumed with an infinite stiffness, so that only the shear law (Figure 3a) is taken into account.

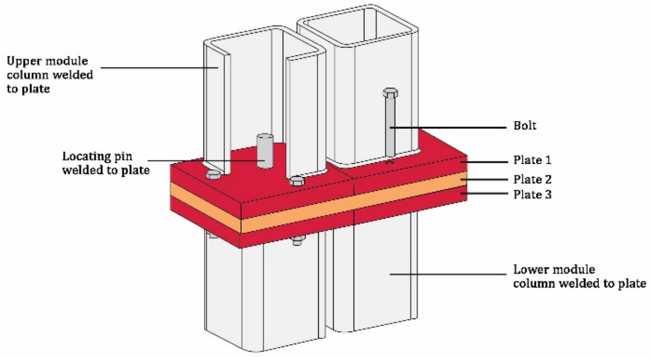

Fig. 2. Illustration of interlocking inter-module connection

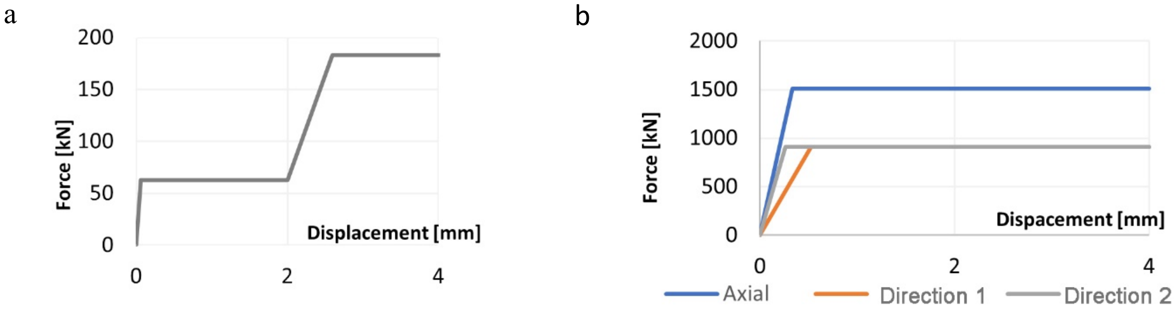

Fig. 3. VC and HC connection's behaviour

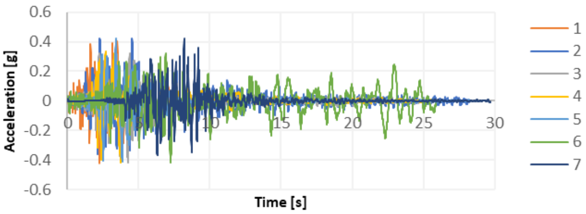

Fig. 4. Accelerograms assigned in the TH analyses

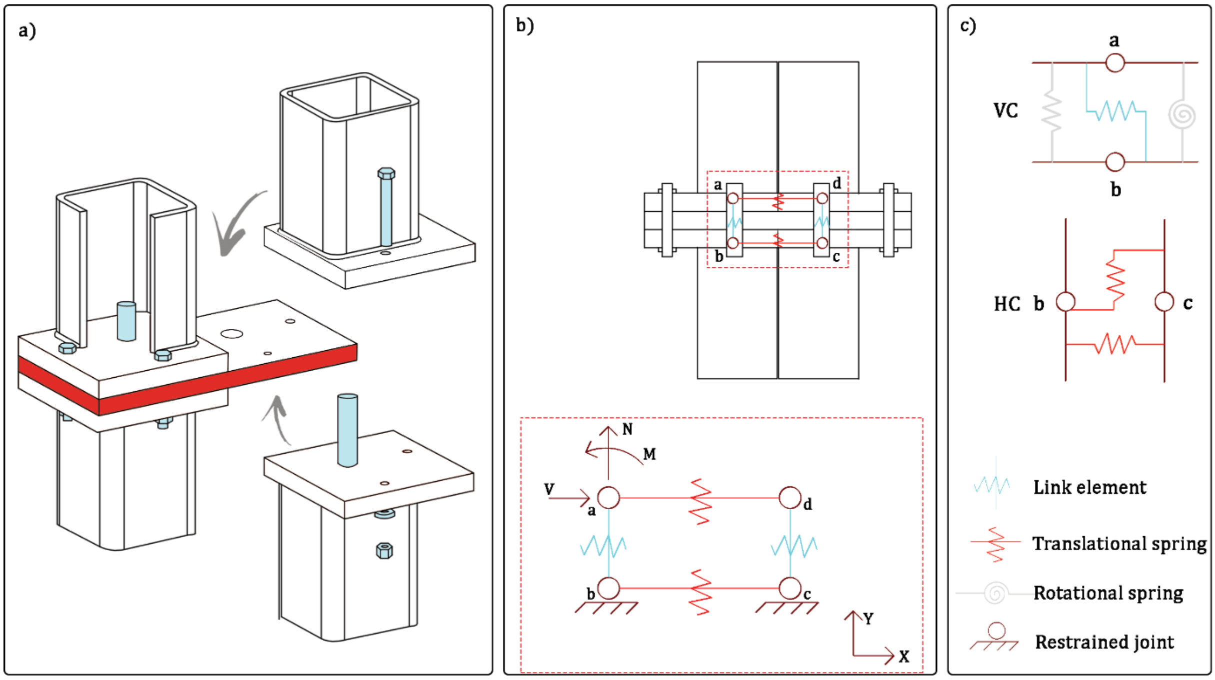

Fig. 5. (a) Interlocking inter-module connection; (b) Link schematization; (c) Vertical and horizontal springs components

3. Numerical analysis

In this study the preliminary results obtained by conducting Time-History (TH) analyses are shown. A set of 7 accelerograms are considered, applied along the two in-plane directions X and Y, spectrum-compatible with a design spectrum of Italian Design Code (2018) for a ground type B with ag=0.35g. The accelerograms are derived with REXEL V 3.5 software (2014).

Figure 6 shows the case study considered in four different structural configurations, considered for the following comparisons, that are:

- Model 1: Rigid diaphragm and steel bracing (Figure 6a);
- Model 2: X-Lam floor and steel bracing (Figure 6b);
- Model 3: Rigid diaphragm and structural X-Lam panels (Figure 6c);
- Model 4: X-Lam floor and X-Lam structural panels (Figure 6d)

As for the Model 1, three different relationships are considered for the VC, namely Connection A, Connection B and Connection C (Figure 7a). Connection A indicates the quadrilinear shear-displacement relationship as proposed in Lacey et al (2019), Lacey et al (2020a), Lacey et al (2020b). While, the Connection B has a bilinear law with the stiffness corresponding to the one of the Connection A third branch. Finally, Connection C is a simplified bilinear law, with a secant stiffness at the connection yielding point. The structural response in terms of average of inter-story drifts, by varying the connection is depicted in Figure 7b and Figure 7c, and numerically summarized in Table 1. One may observe that, for each connection type, higher values of drifts are obtained along the X direction (the shortest direction of each module). Among the connections, the Connection A having a quadrilinear law accounting for the shear-slip between bolt-plate provides the lowest drifts in both directions. By reducing the inter-story drifts, the seismic damage on non-structural elements (such as partitions, facilities) would result consequently reduced. Figure 8 shows the resulting VC force-displacement laws of a VC connection (link a-b\d-c of Figure 5b), located at the base of first floor where the steel bracing is positioned, at the end of a TH performed. Figure 8a-c refers to the resulting VC force-displacement along the X direction when accelerograms are applied along the same direction, for the three Connections (A, B, and C). Whereas, Figure 8d-f plots the force-displacement curves for VC along the Y direction when accelerograms are considered along the same direction. One may observe that all the connections reach higher displacements along Y direction, as proof of the fact that, as observed in Figure 7, drifts along Y directions are lower and more uniform than the ones obtained in the direction X.

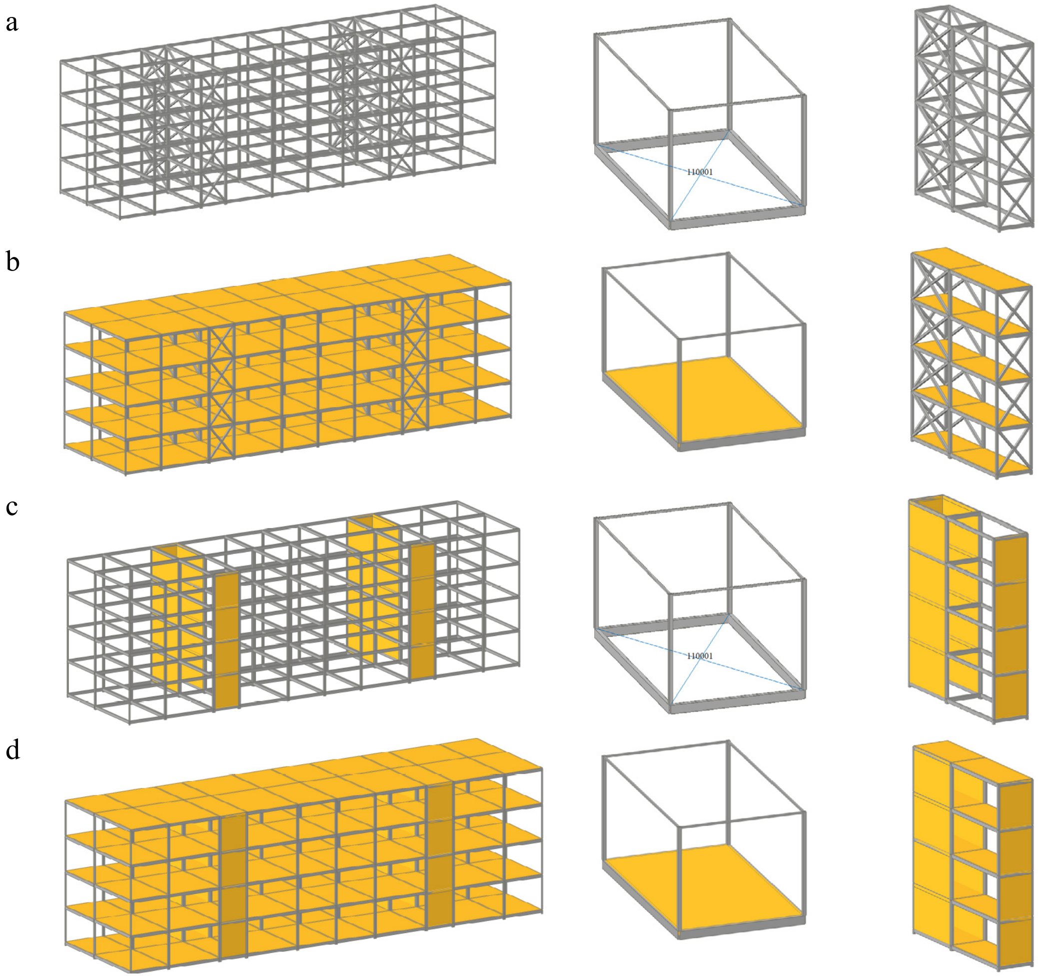

Fig. 6. Structural configuration: (a) Model 1: rigid diaphragm and steel bracing (b) Model 2: X-Lam floor and steel bracing; (c) Model 3: Rigid diaphragm and structural X-Lam panels; (d) Model 4: X-Lam floor and X-Lam structural panels

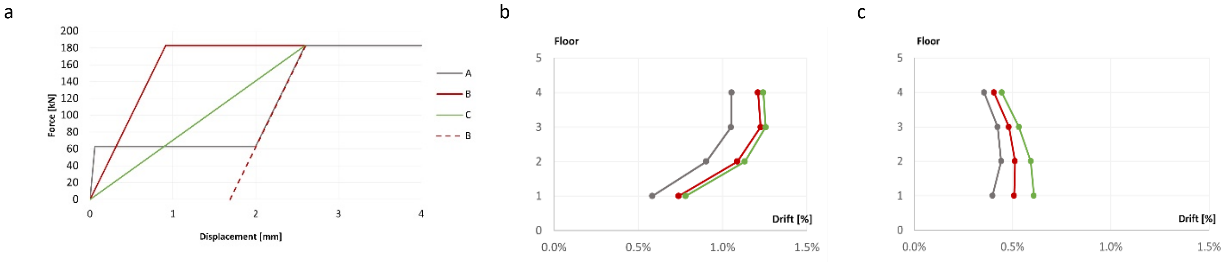

Fig. 7. (a) Time History analysis with different connections; structural response: (b) direction X and (c) direction Y

Table 1. Model 1: Drifts (%) obtained with the TH analyses

Floor	Drift-X [%]			Drift-Y [%]		
	A	B	C	A	B	C
4	1.05%	1.21%	1.24%	0.35%	0.41%	0.45%
3	1.05%	1.25%	1.26%	0.42%	0.48%	0.53%
2	0.91%	1.09%	1.13%	0.44%	0.51%	0.59%
1	0.58%	0.74%	0.78%	0.39%	0.51%	0.61%

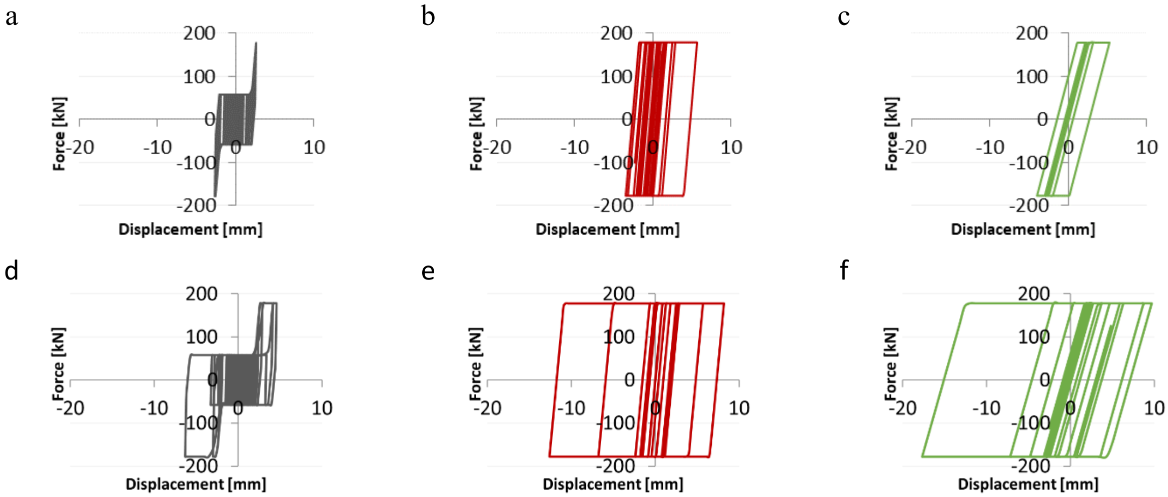

Fig. 8. VC force-displacement output of Connection A, B, C: (a), (b), (c) along X direction; (d), (e), (f) along Y direction

Afterwards, in this study also the influence of the structural configuration on the ideal case global response is investigated. To this aim, as previously introduced, four different configurations are considered, indicated as Model 1, Model 2, Model 3 and Model 4, and illustrated in Figure 6. Again, 7 TH analyses are carried out along the in-plan directions X and Y, by assigning the same spectrum-compatible accelerograms considered for the previous investigations (Figure 4). In this case, the Connection A is considered only.

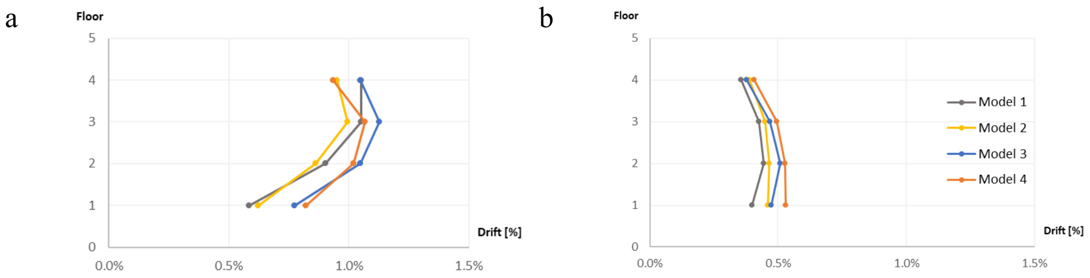

Fig. 9. Time History analysis: structural response (a) direction X and (b) direction Y

Similarly to the previous results, also in this case the structural response is reported in Figure 9, illustrating the average of inter-story drifts among the 7 TH analyses along X (Figure 9a) and Y direction (Figure 9b). Again, higher values of drifts are obtained along the X direction (the shortest direction of each module) in all the structural configurations. Whereas lower and more uniform drifts along Y directions are obtained. Among the structural configurations, it does not exist a clear correspondence between drifts measured along the two directions. If one would assume the drift limit value equal to 1%, for limiting damage of infills, this limit would not be respected along the X direction. This would imply the need of increasing the number of bracing elements, such as X-Lam walls or steel bracings considered in this study. Among these, it seems that their effectiveness is almost similar.

Table 2. Maximum drift (%)

Floor	Drift-X [%]				Drift-Y [%]			
	1	2	3	4	1	2	3	4
4	1.04%	0.95%	1.05%	0.93%	0.36%	0.39%	0.37%	0.41%
3	1.05%	0.99%	1.13%	1.06%	0.42%	0.45%	0.47%	0.49%
2	0.90%	0.86%	1.05%	1.08%	0.44%	0.47%	0.51%	0.53%
1	0.58%	0.62%	0.77%	0.82%	0.40%	0.46%	0.47%	0.53%

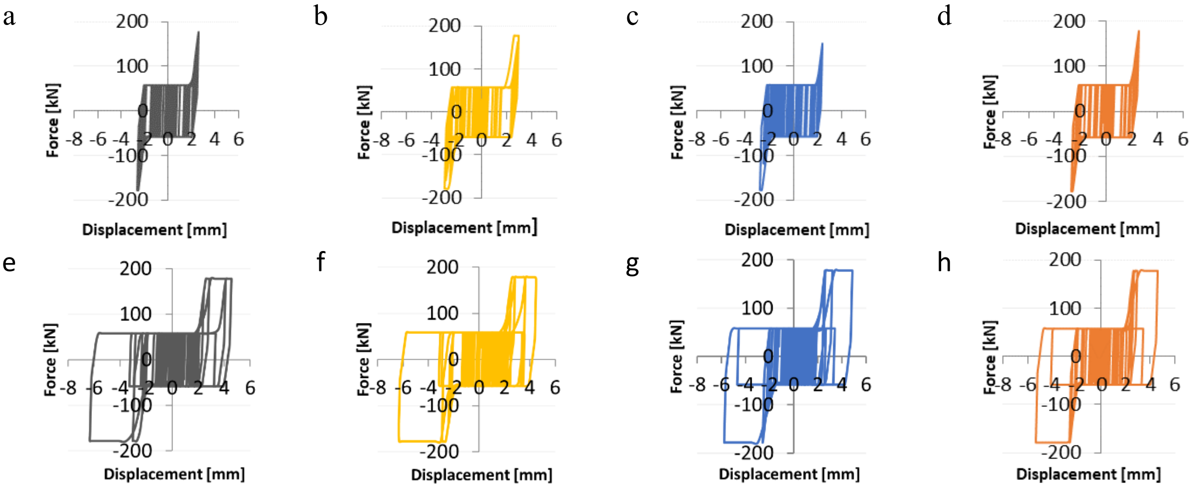

Fig. 10. VC force-displacement output of one inter-module connection, for a) Model 1, b) Model 2, c) Model 3, b) Model 4 along X direction; and for e) Model 1, f) Model 2, g) Model 3, h) Model 4 along Y direction

As for the connection behaviour, as example, Figure 10 plots the resulting VC force-displacement laws of a VC connection (link a-b\d-c of Figure 5b), located at the base of the bracing system considered. More in detail, Figure 10a-d depicts the resulting VC force-displacement along the X direction when accelerograms are applied along the same direction, for the four structural configurations considered. Whereas, Figure 10e-h plots the force-displacement curves for VC along the Y direction. Also in this case, for the structural configuration considered higher displacements are reached along Y direction, demonstrating again why drifts along Y direction are lower and more uniform than the ones obtained in the direction X (Figure 9b).

4. Conclusion and future developments

In this study preliminary results of an on-going investigation addressed to propose reference modular solutions have been shown. To this scope, three types of connections and four structural configurations have been considered. Their structural response has been evaluated through TH analyses along the principal directions, referring to an ideal case study made of steel elements, with an inter-modules connection according to the work proposed in Lacey et al. (2019).

The numerical results clearly show that the shear-slip of the connection considered reduces inter-story drifts along the Y direction (the shortest in-plan dimension). In this case connections results yielded. As far as the bracing system is concerned, relatively to the obtained results, it seems that the two solutions considered are quite similar in terms of global response. Therefore, if one would reduce the seismic damage of non-structural elements, following a traditional design approach, additional bracing systems may be added.

The main goal of this research is to identify seismic-resistance modules characterized by a low seismic-damage in seismic prone areas, so that the elements and components (partitions, facilities) integrity is guaranteed. To this regard, starting from the obtained preliminary results, further investigations will be carried out. Moreover, other additional design techniques will be considered for satisfying the low-damage design requirement. For instance, once suitable modular solutions will be proposed other design techniques may be considered, such as for instance the seismic isolation at base, or else, at a certain level realizing in this way a non-conventional TMD. In this way, an interval of seismic hazard will be identified, where reference modular solutions may be applied without additional design techniques. On the contrary, additional design techniques may be required when the reference modular solutions are applied starting from a certain seismic action.

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