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PRELIMINARY STUDY ON THE SEISMIC PERFORMANCE OF HYBRID STEEL STRUCTURES WITH TRUSS LIGHTWEIGHT GIRDERS AND PLUG-AND-PLAY CONNECTIONS

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SUMMARY: *Hybrid structures are efficient and economical systems that can be successfully adopted for modular buildings. Novel hybrid industrialized and modular buildings with truss girder made of lightweight steel profiles and connected to tubular columns by means of innovative plug-and-play joints has been recently proposed within the RFCS INNO3DJOINTS with the aim to develop solution ensuring fast-track construction and increasing the quality of the finished product. In this paper, a preliminary study on the seismic behaviour of these innovative hybrid frames equipped with plug-and-play joints is summarized. Nonlinear static and dynamic analyses were performed on 2D models of a reference structural archetype. The obtained results showed that this type of structure may also be used in low seismicity zones.*

KEYWORDS: *INNO3Djoints, ADRS, numerical modelling, hybrid structures,*

1 Introduction

In the last decade, there has been a growing interest in the development of new constructional systems such as modular constructions in order to improve the efficiency, decrease the cost, and limit environmental impact [Jeng, B. DiGiovanni D., and Wan A., 2011; Smith, R. E., 2010]. Furthermore, modular systems can improve the overall quality of buildings that should be constructed in a tight schedule, because buildings are produced in "modules" that are assembled together on-site, thus saving time and costs thanks to the simultaneous module construction in the shop and on-site preparation. Modular systems can be effectively prefabricated using lightweight steel modules to be assembled on-site to steel skeleton systems (e.g., ETH-ICS, 1990, InFaSo, 1990, FrameUp [Andrade, 2016]).
Another key issue to reduce the constructional costs of steel structures is related to the cost of joints. Hence, innovative solutions with cheap connections that facilitate erection will contribute substantially to a cost reduction in the construction site and increasing the safety levels for the workers. In the light of these considerations, innovative modular constructions with hybrid systems made of lightweight steel truss girders connected to tubular columns by means of plug-and-play joints have been developed within the recent INNO3DJOINTS (acronym of "Innovative 3D joints for robust and economical hybrid tubular construction") project in order to ensure fast-track construction and increase the quality of the finished product. This novel system has been initially conceived for applications in non-seismic areas, but thanks to the large ductility provided by the plug-and-play connections as well as the considerably lightness (e.g. 30% less structural mass) of the structures as respect to conventional steel structural systems for multi-storey buildings [Dell'Aglio et al. 2017,

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Giordano et al. 2017, Montuori et al. 2016, 2017, Nastri 2018, Tartaglia et al. 2018, Costanzo et al. 2019], it can be interesting to verify the potential use of these systems in low and moderate seismic zones. With this regard, a preliminary numerical study has been carried out. The seismic performance has been investigated by means of non-linear static and dynamic analyses on 2D models extracted from a reference structural archetype and the main results are summarized hereinafter. This paper is organized in three parts, namely (i) the first part described the main features of the hybrid system, (ii) in the second part the mechanical response and the modelling of the plug-and-play joints is described; (iii) the third part focuses on the non-linear analyses of the structures.

2 Definition of the hybrid system

The hybrid structural system developed within INNO3DJOINTS project combines cold-formed lightweight steel profiles (i.e. class 4 elements in accordance with EC3 definition) to ductile tubular members (i.e. class 1 or 2 according to EC3). Figure 1 (a) illustrates the configuration of such hybrid frame. Using two separate joints for connecting the truss at the level of each horizontal chord to the column is the strategy to restrain flexurally the truss girder and to guarantee the primary lateral resistance. Theses joints are detailed to be plug-and-play and are composed of different components, as illustrated in Figure 1 (b). The main components are the socket and the plug. The socket is made of two S-shape plates that are welded to the column's face at one end, while serves as a host for the plug on the other end. The plug is made of a T-shape and U-shape plates, and it is reinforced by stiffeners at both sides. In addition, the plug is connected to the truss on one end and it will be locked in the socket on the other end. This configuration results in a shear connection. However, using one connections per horizontal chord of the beam provides an equivalent moment connection that guarantees the lateral stiffness of the frame as it will be discussed hereinafter. It is noteworthy to mention that, due to the cold-formed characteristics of the columns, the joint is connected to the column at the end of the corner radius of the column. this details improves the connectivity of the joint to the column, since the corner of this type of profiles cannot be welded properly.

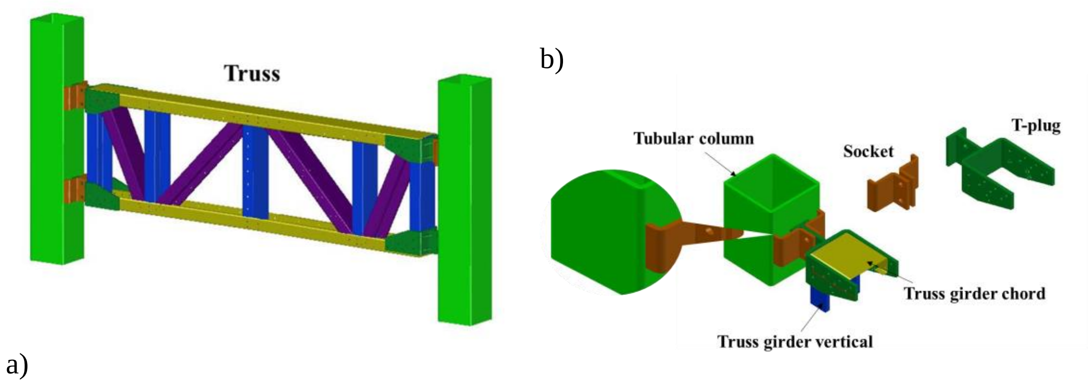


Figure 1 - *Structural system (a); Details of the plug-and-play connection (b)*

3 Numerical modeling of the joint

The mechanical response of the plug-and-play connection was characterized on the basis of experimental tensile tests performed at the University of Coimbra [Da Silva et al. 2018]. On the basis of the experimental results it was possible to develop and calibrate finite element models that allowed investigating the local and overall behaviour of the connection. The geometrical details of the joint are shown in Figure 2.

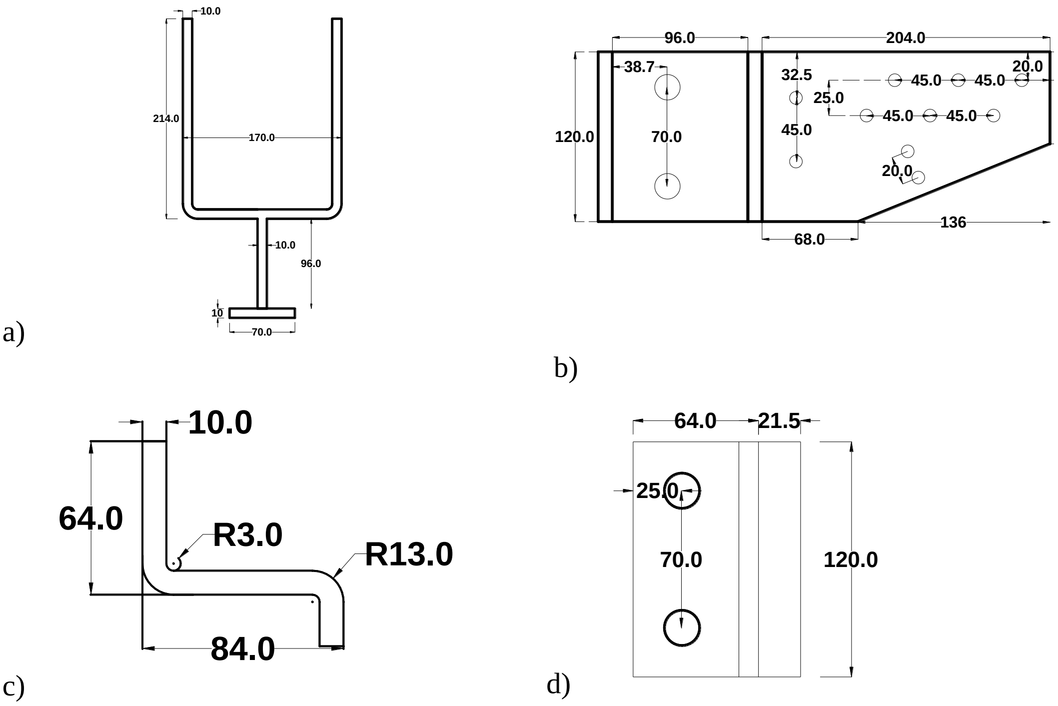


Figure 2 - *Geometry of the component of the joint: T-plug Top view (a); T-plug side view (b); single socket top view (c) single socket side view (d)*

The finite element (FE) model of the joint was developed in Abaqus. The main modelling assumptions are the following:

(i) material nonlinearity of the components of the joint was obtained through tensile coupons test.

(ii) surface-to-surface contact between all surfaces in contact and the finite sliding approach was applied. The surface contact properties between the plate elements were modelled as a tangential behaviour using penalty formulation with friction coefficient equal to 0.3. The socket is tied to the face of the column.

(iii) the bolt-head were considered as a single body with bolt-shank together on both ends of the bolt. The threaded part of the bolt-shank and the extended length of the bolt beyond each nut were ignored;

(iv) the joint is entirely modelled using eight-node reduce integration solid elements (C3D8R). The details of the finite element mesh are shown in Figure 3a. Structure mesh techniques are used for all parts of the assembly. A global seed of 3 is applied for the components, while, the bolt and the bolt-hole region were meshed with a local seed of 1.

In order to simulate the displacement history applied during the test, the load is applied at a reference point that is highlighted in yellow in Figure 3a. Figure 3 shows the deformation of the calibrated numerical model against an experimental test carried out by Da Silva et al. (2018).

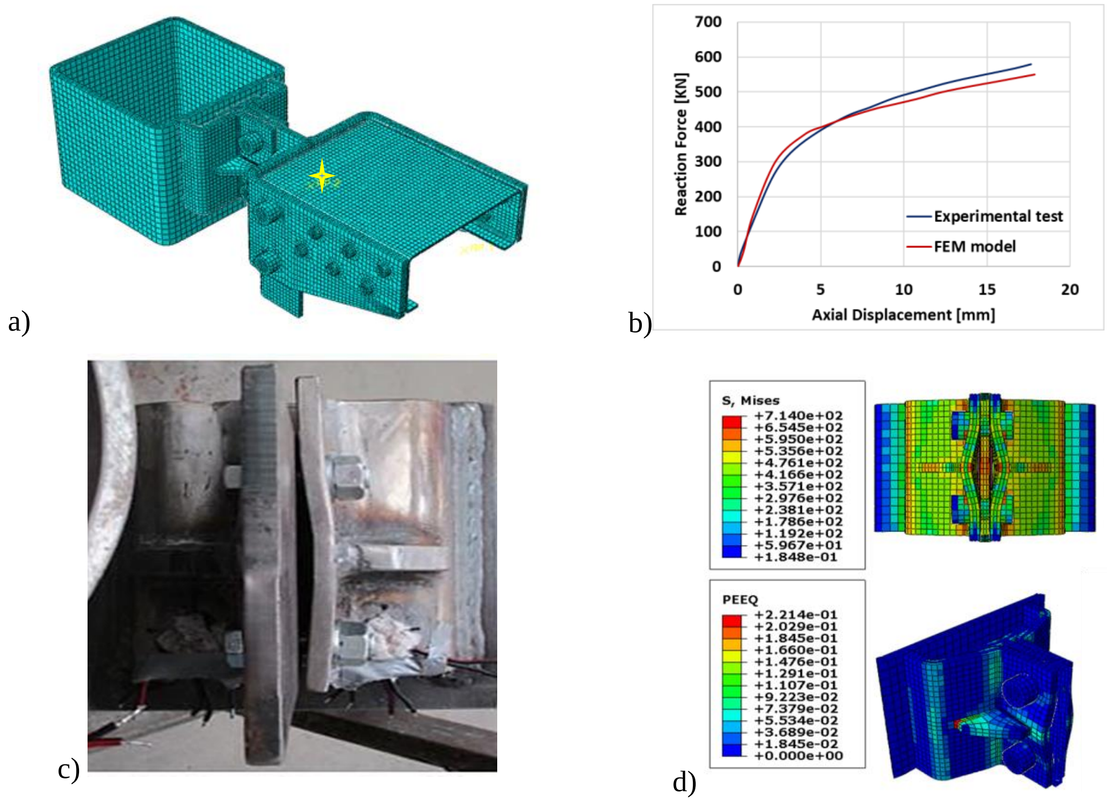


Figure 3 – *The finite element model of the joint (a); comparison between the experimental and FEM response curves (b); experimental deformed shape of the joint (c); deformation of the FEM model (d)*

4 Case study

An existing residential building was identified and used as a benchmark architectural archetype to study the considered hybrid system. The plan was adjusted to be compatible with modular construction. The structure was designed under the requirements of Eurocode3 [EC3, 2004] parts one and three. The case study has a rectangular plan view without any irregularity in the plan or elevation, and one frame in each direction was selected to be the representative of the structure in that direction. Since all frames in each direction are contributing to the lateral resistance of the structures, the behavior of each frame is fairly similar to the overall behavior of the structure in that direction. A typical elevation view of the case study, including its geometric properties, is shown in Figure 4.

Since these types of frames are meant to be used in low seismicity areas, the reference peak ground acceleration (PGA) was set equal to 0.1g that corresponds to the upper limits for DCL in accordance with EN1998-1. The soil type was assumed as type C according to EN1998-1. The floor system of the building is Cross-Laminated Timber (CLT). This system is fairly a lightweight system while providing adequate in plain rigidity [Ceccotti *et al.*, 2007]. The columns of the frame are strengthened by a vertical truss. The structural and non-structural permanent loads of 0.56 KN/m^2, 1.4 KN/m^2 are assigned to each story respectively, while, a

live load of 2.5 KN/m^2 is assumed in accordance to Eurocode. The mass of the structure is lumped into floor levels and computed based on the applied loads. The Rayleigh damping matrix is specified with 2% damping at the first and second periods, which are equal to 0.35 sec and 0.11 sec, respectively.
The two-dimensional nonlinear model was developed using Sap2000 [CSI, 2020]. The nonlinear behaviour of the plug-and-play connections was simulated using lumped plasticity springs with three degrees of freedom (DOF), whose hysteretic response curves were obtained from the finite element models described in Section 3. In particular, the ECCS loading protocol was applied to the calibrated FE model, and the hysteretic response curves for bending moment, shear and axial forces were extracted. The hysteretic curves show a fairly amount of pinching mainly due to the opening and closing of the bolts in the joint. The obtained cyclic curves were simulated in SAP200 by means of non-linear link elements (i.e. lumped plasticity springs) using Takeda-Pivot hysteretic model, as shown in Figure 5. Also, the parameters of the spring are listed in Table 1. The plastic hinges in the columns are formulated in accordance with FEMA356 [FEMA, 2000] guideline.

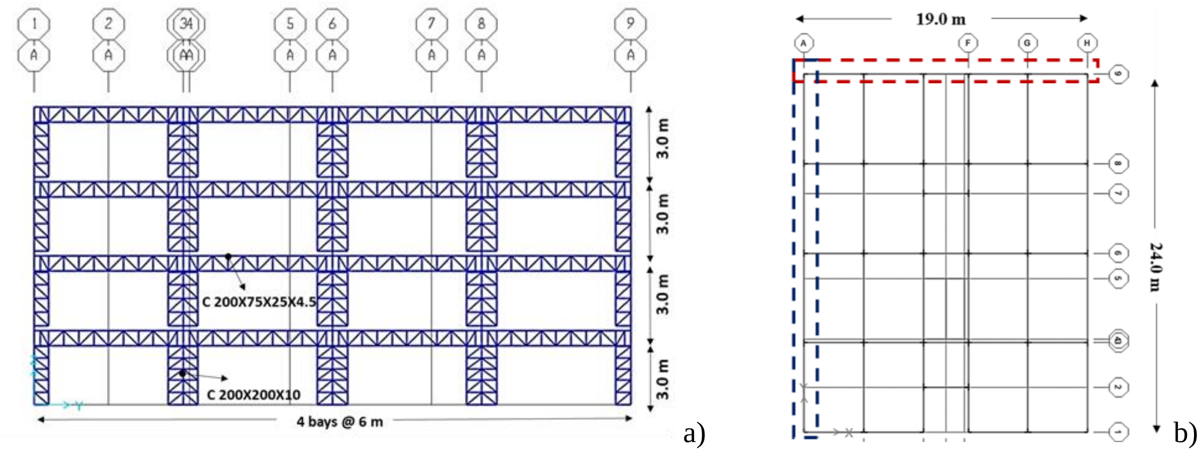
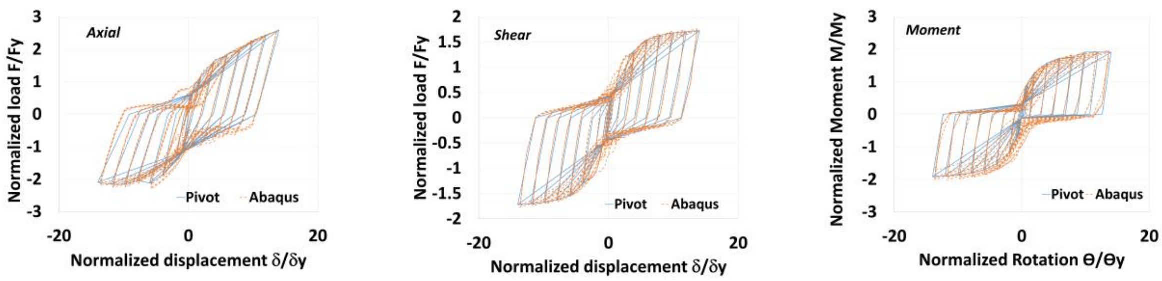


Figure 4 - *Plan view of the building (a); Typical elevation of the building (a)*

Table 1 - Parameters of the Pivot model used to simulate the hysteretic behavior of the joints

	α_1	α_2	β_1	β_2	η
Axial	40	5	0.7	0.7	1
Shear	45	45	1	1	0
Rotation	200	100	0.2	0.4	0



a) b) c)

Figure 5 - *Calibrated models for a) Axial spring, b)shear spring, c) rotational spring*

5 Pushover analysis

Nonlinear static (pushover) analysis is conducted for the 2D frames by using both the first mode lateral pattern and the pattern proportional to the masses at each story [Krawinkler, et al. 1998]. Figure 6 shows the global pushover curves for the selected frames.
Global collapse may imply dynamic instability in a sidesway mode, usually triggered by large story drifts, which are amplified by P-Δ effects and deterioration in strength and stiffness of the components of the system. In this special case, collapse is assumed to be associated with losing a joint in the structure, which was defined when the tangent stiffness in any DOF in the joint is less than 20% of the initial stiffness. The pushover curve is cut off at this state.
The seismic assessment of the structure was carried out using the N2 method as recommended by EN1998-1, namely as follows:

1. The initial Acceleration Displacement Response Spectrum (ADRS) of demand is formed for 5% damping. For developing the S_a- S_d graph, the spectral displacement, S_d corresponding to each point of the Response Spectra (Initial RS) (S_a/g vs. T); the following relation is used:
$$S_d = \frac{T^2}{4\pi^2} S_a \tag{1}$$
2. Defining an equivalent single degree of freedom (SDOF) corresponding to the Multi-degree of freedom (MDOF) model using the following formula:
$$F^* = \frac{V_b}{\Gamma} \quad d^* = \frac{\Delta_{rt}}{\Gamma} \tag{2}$$
3. For each point on the converted capacity curve, the yield points (F_y*,d_y*) are determined by equivalent bilinear representation of the curve in a way that the area under the original a bilinear curve will be equal. using the following formula, the yield displacement of the bilinear curve can be computed as:
$$d_y^* = 2(d_m^* - \frac{A_{tot}}{F_y^*}) \tag{3}$$
4. The equivalent pushover curve in F*, d* is converted into corresponding acceleration and displacement capacity curve using the following equation:
$$S_a = \frac{F^*}{m^*} \tag{4}$$

The pushover curve and the idealization of the curve based on the EC method is shown in Figure 6. As expected, tt can be observed that all examined frames have limited ductility. The EC8 spectrum type 1 with reference peak ground acceleration (PGA)=0.15g and soil type C is selected as the target spectrum throughout the study. In addition to the spectrum, a set of three ground motions are used for the seismic assessment. The characteristics of these accelerograms are listed in Table 2. These natural records are scaled to match the response spectrum at ultimate limit state (475 return period) in accordance with Eurocode 8. Therefore, the record scaling involved two steps. First, individual records are normalized by their respective peak ground acceleration. Then they are scaled in such a way that the average of their spectrum does not fall below the corresponding ordinate of the target spectrum. in the period range from 0,2T_n to 1,5T_n, being T_n the period of the first mode of vibration of the structure. The target response spectrum and the spectra of the scaled ground motions are depicted in Figure 7. Figure 8 shows the capacity and the demand curves along x and y directions in the acceleration-displacement response spectrum space (ADRS) for both load patterns. Although the ductility provided by these frames is quite limited, the demand is in elastic range, as it can be observed in Figure 8. Therefore, it seems feasible the application of these structures in low seismicity zones.

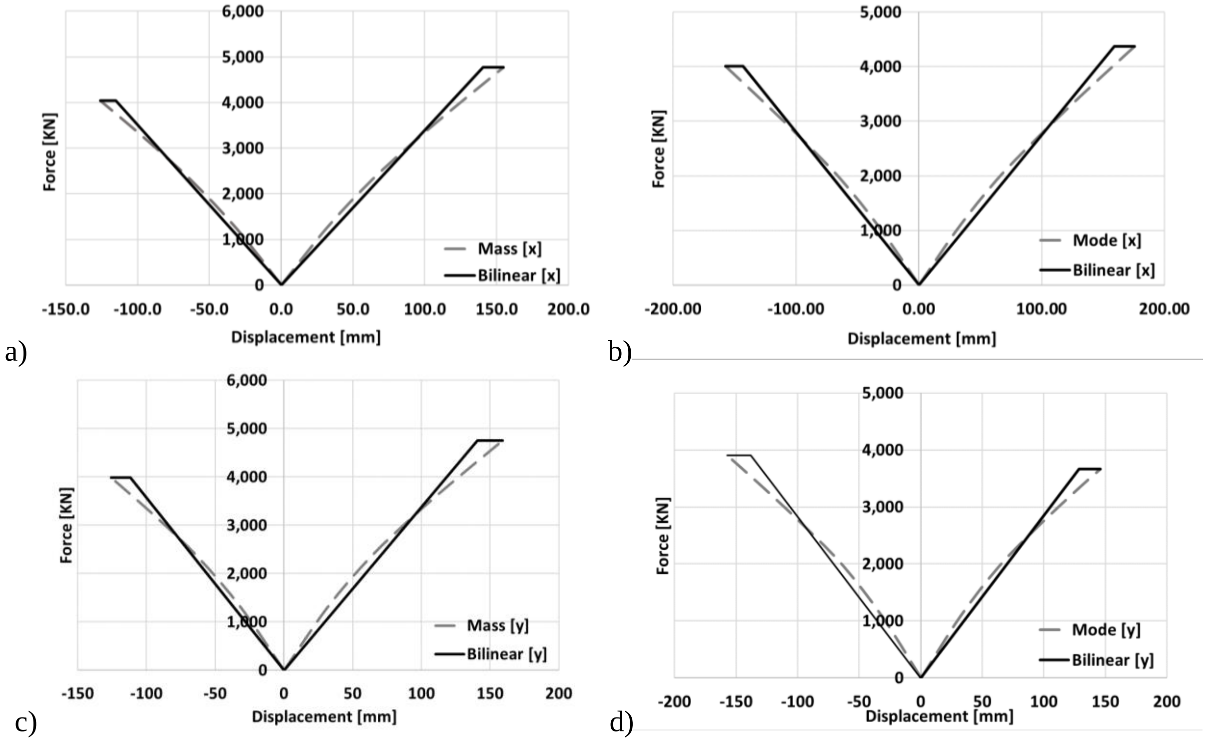


Figure 6 - *Pushover curves and their idealization for X-direction (a,b) and for Y-direction (c,d)*

Table 2 - *Properties of the considered accelerograms*

Earthquake name and date	Selected component	Duration	Station	Magnitude Mw	PGA (cm/s^2)	Scale factor
Brienza 23.11.1980	N-S	78.33	Brienza (Italy)	6.9	213.532	16.82
Castelluccio_Norcia 30.10.2016	N-S	59.995	Castelluccio (Italy)	6.5	571.424	6.52
Castelsantangelosulnera March 1990	E-W	100.00	Castel Santangelo Sul Nera (Italy)	6.5	466.718	2.52

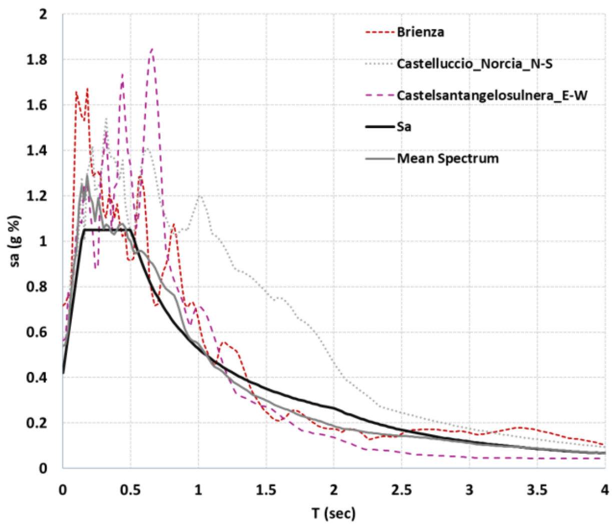


Figure 7 - *EC8 response spectrum along with the GMs set response spectrum*

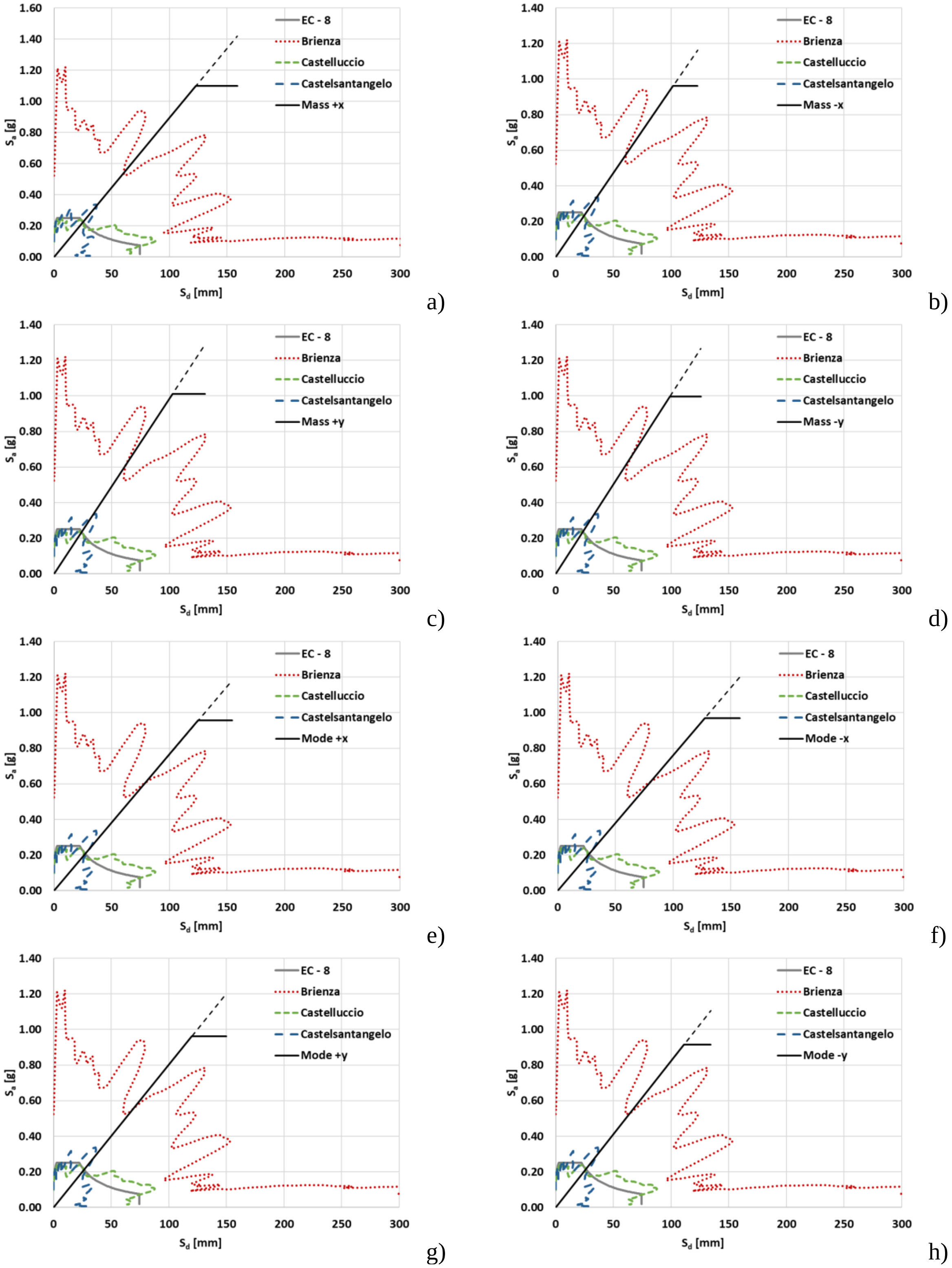


Figure 8 - *Capacity and demand curves in ADRS format: a,b) Mass X; c,d) Mass Y; e,f) First Mode X; g,h) First Mode Y*

6 Nonlinear time history analyses

In the following section, the case study is evaluated by the means of time history analyses. For the time history analyses, Rayleigh damping is used to obtain a damping ratio of 2% at the first mode period of the structure T and $0.1T$.

The maximum drifts of the model under the selected ground motions are plotted in Figure 9. It can be seen that the inter-story drift ratio is well below the life safety limit (2.5%).

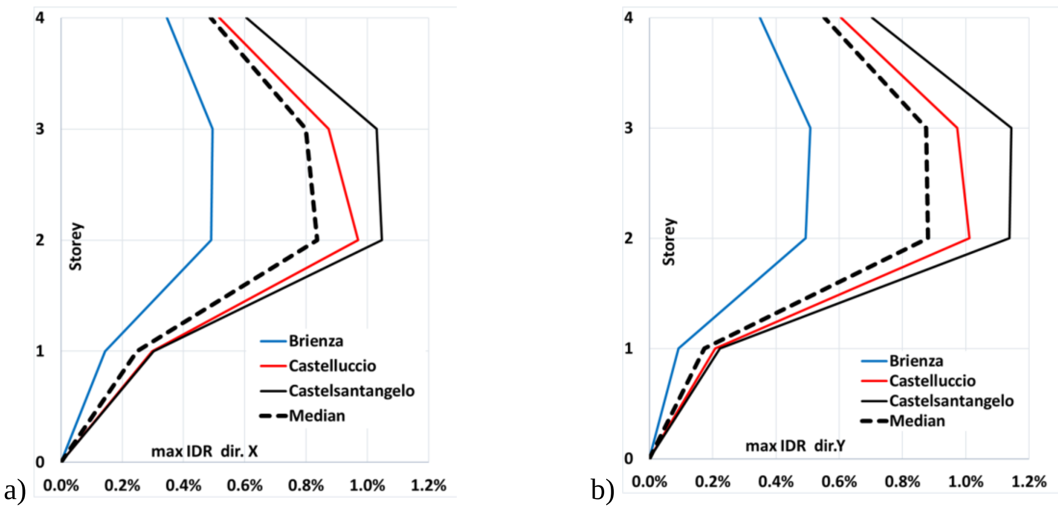


Figure 9 - *Height-wise distribution of peak inter-story drift ratios a) X direction b) Y direction*

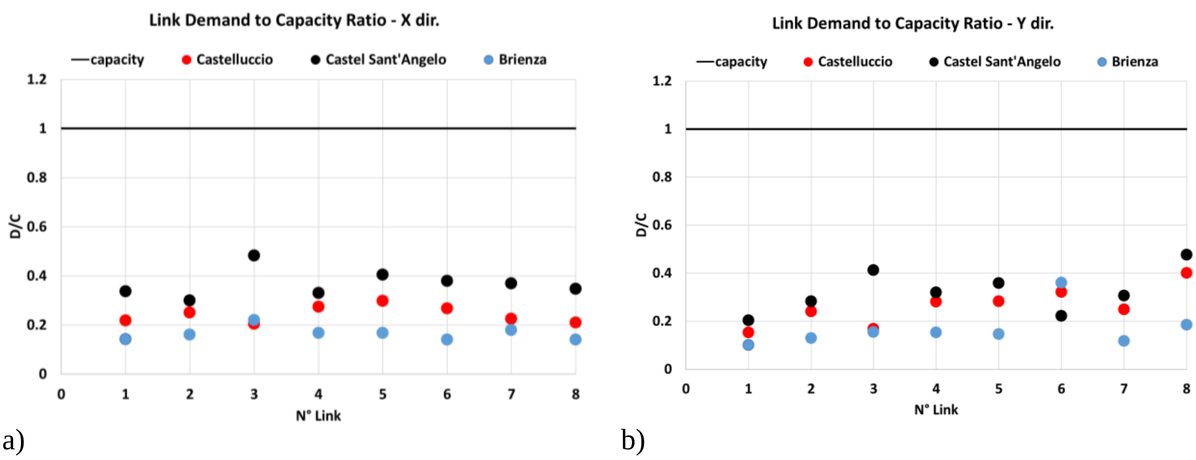


Figure 10 - *Demand to capacity ratio for the first story joints*

The inelastic dynamic response of the hybrid system was also investigated at local level. The maximum demand on the joints occurs at the first story level. Figure 10 shows the axial deformation demand to capacity ratios for each joint. As it can be observed, all joints behave elastically without damage. Anyway, it is interesting to observe that the axial force is much larger compared to moment and shear deformation in the joint.

As also observed from pushover analyses, the dynamic analyses confirm that this structural system behaves elastically under seismic actions at ultimate limit state. The reason for this performance is mainly due to the very low mass of the system and its relative large period of vibration that mostly help minimizing the seismic induced effects.

7 Conclusions

In this study, an innovative modular construction with hybrid systems made of lightweight steel truss girders connected to tubular columns by means of plug-and-play joints is presented and the preliminary study to investigate the feasibility of its use in low and moderate seismic zone is carried out. A case study was designed following the requirements of EC3 to investigate the behavior of the prescribed joint. A numerical model was calibrated with available experimental data to simulate the hysteretic behavior of the joint.

Pushover analyses showed that the main lateral resistance in the frame is provided by the special configuration of the joint. In addition, plastic hinges are mainly formed in the base columns. As expected, this type of special frame has low ductility at global level. However, the comparison between capacity and demand in ADRS space show that demands intersect the capacity curve in the elastic branch for all the lateral load patterns. Furthermore, the time history analyses were conducted to assess the lateral behavior in more detail. It was shown that the frame behaves elastically in both global and local levels. Based on the results, it seems that these modular structures can be used in low seismicity areas. The inherent lateral resistance within the frame; due to the configuration of the components; without any further detailing or additional elements, e.g. braces, is highly advantageous.

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STUDIO PRELIMINARE SULLA PRESTAZIONE SISMICA DI STRUTTURE IBRIDE DI ACCIAIO CONTRAVI RETICOLARI LEGGERE E COLLEGAMENTI PLUG-AND-PLAY

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SOMMARIO: *Le strutture ibride sono sistemi efficienti ed economici che possono essere proficuamente impiegati per edifici di tipo modulare. Edifici modulari con soluzioni ibride innovative realizzati con travi reticolari costituite da profili leggeri di acciaio collegati a colonne tubolari con collegamenti innovativi "plug-and-play" sono stati recentemente sviluppati nell'ambito del progetto europeo RFCS INNO3DJOINTS con la finalità di sviluppare soluzioni costruttive che garantiscano sia tempi rapidi di montaggio che elevata qualità. In questo articolo sono sintetizzati I risultati di uno studio preliminare volto alla caratterizzazione del comportamento sismico di questa tipologia di edifici ibridi con nodi smontabili plug-and-play. Le analisi non-lineari sia statiche che dinamiche sono state condotte su modelli 2D estratti da un archetipo strutturale di riferimento. I risultati ottenuti hanno mostrato che questo tipo di strutture può essere usato in zone di bassa e moderata sismicità.*

PAROLE CHIAVE: *INNO3Djoints, ADRS, numerical modelling, hybrid structures*

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