ASSOCIAZIONE NAZIONALE ITALIANA DI
INGEGNERIA SISMICA
ANIDIS
Italian National Association of Earthquake Engineering

XVIII CONVEGNO ANIDIS
L'ingegneria sismica in Italia
ASCOLI PICENO 2019
15-19 Settembre

Seismic performance of a hybrid frame equipped with Innovative plug-and-play joint

Arash poursadrollah [a], Mario D'Aniello [a], Raffaele Landolfo [a], Attilio De Martino [a],

[a] *Department of Structures for Engineering and Architecture, University of Naples "Federico II", Via Forno Vecchio 36, 80134 Naples, Italy*

Keywords: hybrid system; joint; nonlinear time history; numerical modeling

ABSTRACT

Hybrid structures are highly efficient and economical. In particular, modular solutions with tubular columns combined with horizontal light-weight girders made of cold-formed steel sections may provide a cheap and efficient system. In order to simplify the on-site erection phases, a novel plug and play joint has been proposed within the RFCS INNO3D joints project to enable industrialized and modular solutions that ensure fast-track construction and increase the quality of the finished product. In this paper, the nonlinear dynamic behavior of a frame equipped with the proposed joint is investigated. The nonlinear numerical model that simulates the hysteresis behavior of the Innovative frame is presented and the results obtained from nonlinear time history analyses are also discussed

1 INTRODUCTION

There is a growing interest in developing new design and construction approaches that are more efficient, safer, environmentally friendly, less labor intensive, and can lead to buildings that are of higher standards and can be constructed in a compressed schedule. The construction industry is still mostly dominated by conventional construction practices, which may lead to less efficient and economical solutions. To meet the needs of client and communities of future it is required to rethink the design and construction processes and develop appropriate responsive strategies. Improved accuracy and quality, fast on-site installation, and lower final cost of construction are the main motivations for owners to turn to modular constructions. In modular construction, the potential in saving time and costs results from simultaneous module construction and site preparation which leads to reducing the overall completion schedule.

Currently, the overall cost of steel frame structures is highly influenced by the cost of steel joints. Hence, innovative solutions aiming for ease of erection will contribute significantly to a cost reduction in the construction site, increasing the safety levels for the workers

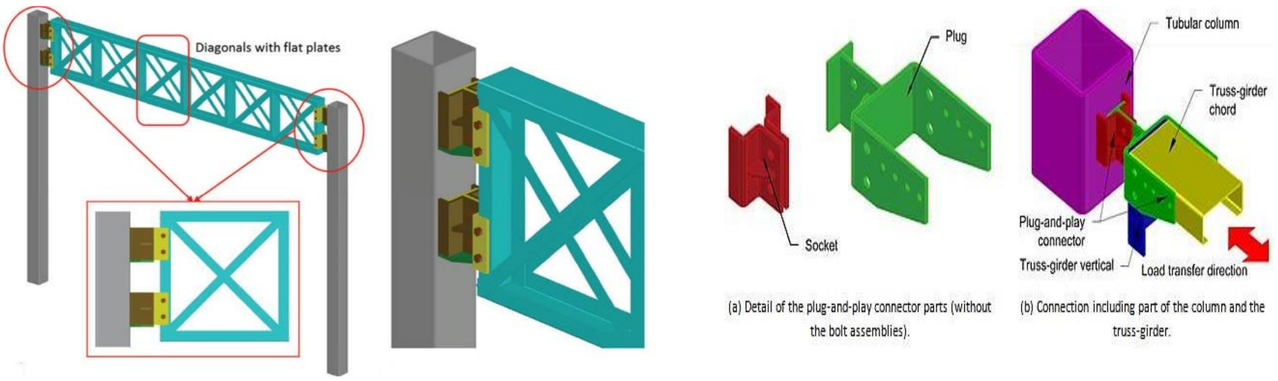
By reducing the man-hours invested in a project and at the same time by reducing the cost of their structures, an economic solution is achieved. In INNO3DJOINTS (acronym of "Innovative 3D joints for robust and economic hybrid tubular construction"), the first issue is solved by providing the designer with a simple and reliable design, whereas the second issue is solved by developing an innovative and competitive structural solution, not only lightweight but also easy to erect.

There have been various projects dealing with light-weight steel systems and prefabricated steel buildings and integrating it with steel skeletal system (e.g. ETHICS; InFaSo; FrameUp; PRECASTEEL). However, there are only a few projects where the system developments have been so influenced and optimized in respect to execution technique, except in FrameUp where the rolled sections are considered in the skeletal system. Interlocking moment resistant joints, "drop and click beams" have recently been developed in the USA for fast execution of steel skeletal system. Plug-and-play connections are also typical in steel to concrete and precast structures (Bijlaard et al. 2008, Maquoi et al. 1998)

This project addresses the development of innovative plug-and-play joints for hybrid tubular construction, whereby tubular columns are combined with cold-formed lightweight steel profiles to provide a highly efficient structural system. Such efficient joints are essential to enable industrialized and modular solutions that ensure fast-track construction and increase the quality of the finished product. Moreover, these types of joints shall be easily demountable (Brekelmans et al. 2000).

2 DEFINITION OF THE HYBRID SYSTEM

The main goal of INNO3DJOINTS is to develop innovative plug-and-play joints for hybrid tubular construction, whereby tubular columns are combined with cold-formed lightweight steel profiles to provide a highly efficient structural system. The hybrid system is a robust solution for carrying gravity loads and lateral forces in lightweight construction. Figure 1 illustrates the configuration of the hybrid frame. Using two separate joints for connecting the truss at different level of the column, provide the primary lateral resistance for the system. The plug and play joint is composed of different components as illustrated in Figure 1. The main components are socket, and plog. Socket is made of two identical S-shape paltes, welded to the column's face at one end, while serves as a host for the plug on the other end. Plug is made of a T-shape and U-shape plates, reinforced by stiffener plates at both side. Clearly on one end the plug is connected to the truss and on the other end will be locked in the socket.



(a) Detail of the plug-and-play connector parts (without the bolt assemblies).

(b) Connection including part of the column and the truss-girder.

Figure 1. left: Structural system Right: Details of the hybrid connection

3 CASE-STUDY

In order to ensure that research is focused on a practical solution, an existing residential building was identified and used as benchmark archetype to define the new hybrid system. The plan was adjusted to be compatible with modular construction. The structure is designed in accordance with the requirements of Eurocode 3 (EC3) part one and part three. A live load value of 2.00 kN/m^2 and 1.00 kN/m^2 for floors and roofs of residential buildings were considered, respectively. These types of frames are meant to be used in low seismicity area. Therefore, 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 inplain rigidity. The columns of the frame are strengthened by a vertical truss. Square hollow section 200x200x8 are considered for all the columns and beams are a truss girder made of C 200x75x25x3. In Figure 2 the tri-dimensional view of the structure is illustrated.

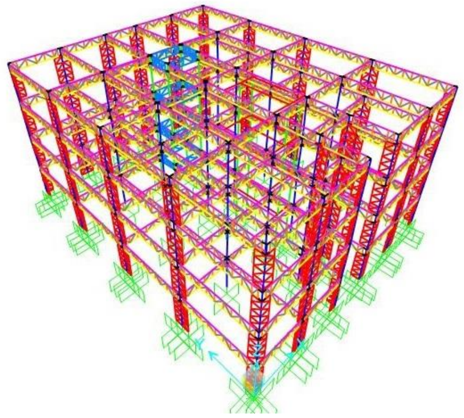


Figure 2. 3D Model in sap2000

4 EXPERIMENTAL TEST

The detailed drawing of different components of the INNO3D joints are shown in **Errore. L'origine riferimento non è stata trovata.**. To characterize the behaviour of the T-stub in tension it was used an experimental test conducted at the

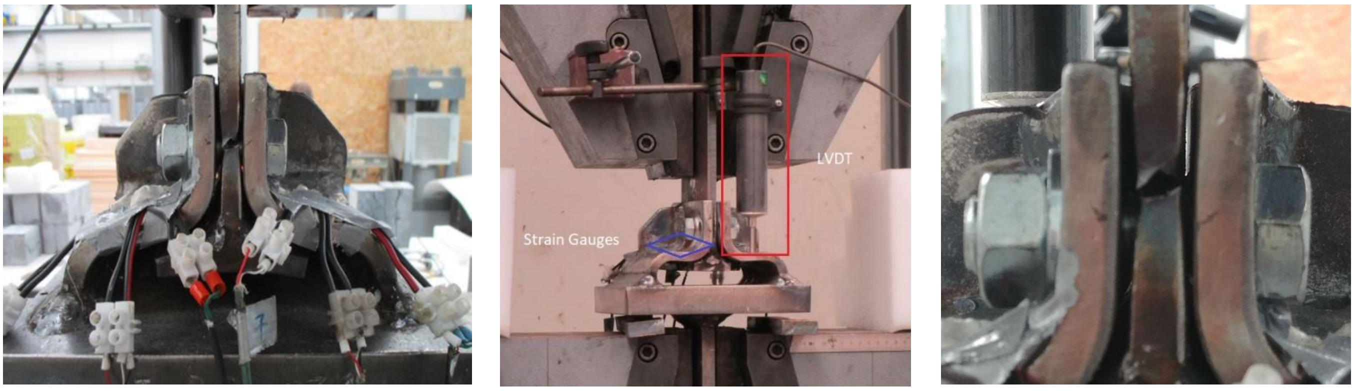


Figure 3 Test on the plug-and-play connection carried out at University of Coimbra: Position of the strain gauges (left); The test setup (middle); Failure mode (right)

University of Coimbra, as illustrated in **Errore. L'origine riferimento non è stata trovata.**.

The T-stub tested at Univ. of Coimbra was subjected to a monotonic axial tensile laod. The test was caried out by MUE 404 Servosis testing machine capable of applying 3000 KN load; in displacement control with a constant rate of 0.01 mm/sec. Seven strain gauges were attached at the bend part of the T-stub to measure the variation in resistance and one LVDT were employed to obtain the axial deformation of the T-stub. A rigid plate with the thickness of 30 mm was used to simulate the face of the column. Figure 3 also shows the failure mode of the T-stub in the experiment.

5 FINITE ELEMENT MODEL OF THE PLUG AND PLAY JOINT

This section presents the method utilized to simulate the behaviour of the proposed joint as a component of the 3D frame developed in the previous section. In order to incorporate the behaviour of the joint in the structural model, a finite element model of the joint has been developed. The monotonic and cyclic behaviour of the joint was simulated by employing finite element method (FEM) in Abaqus. Figure 5 shows the 3D view of the developed model in Abaqus

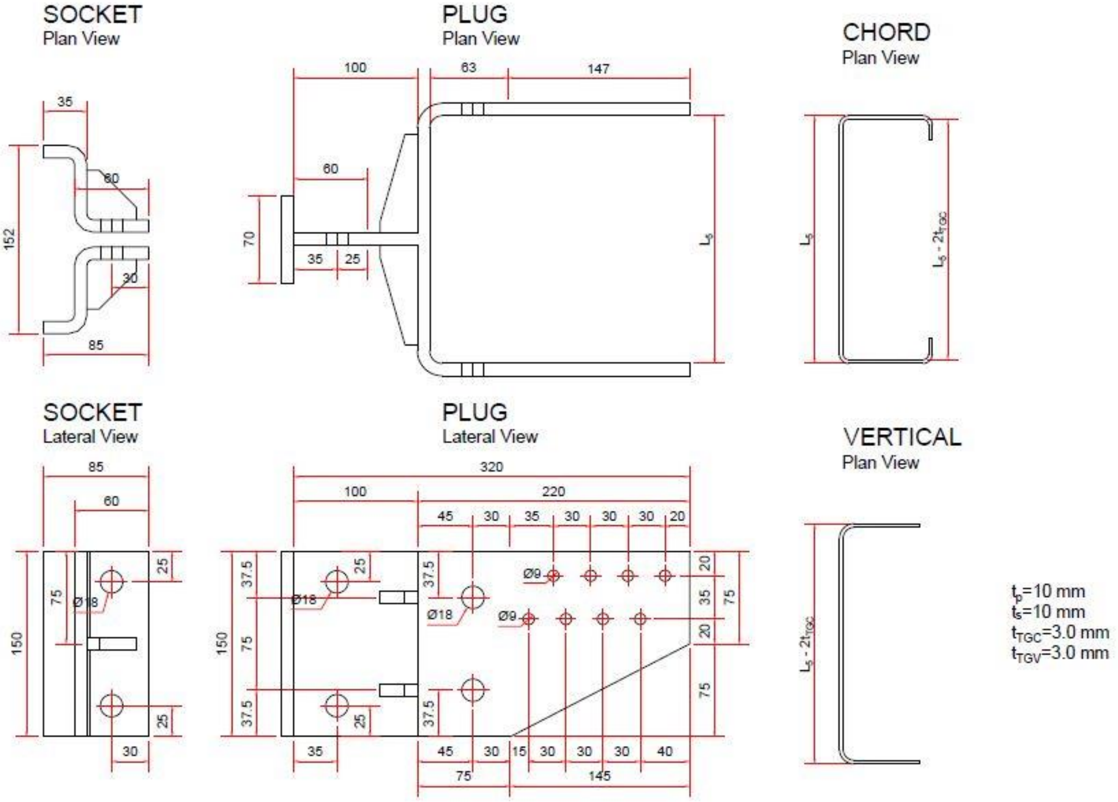


Figure 4 The detailed drawing of different component of the INNO3D joint

platform.

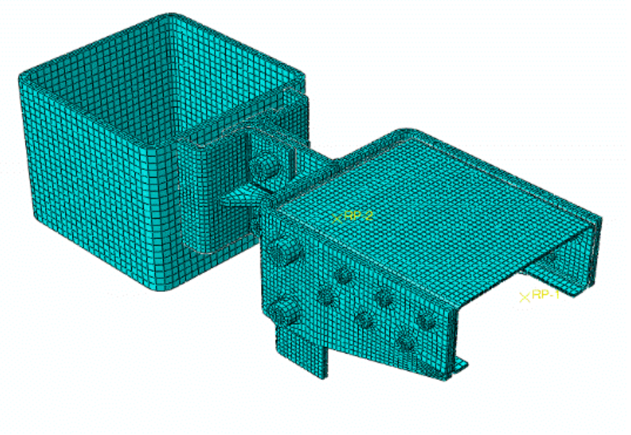


Figure 5 The FEM of the plug-and-play joint

The joint is modeled entirely using eight node reduce integration solid elements (C3D8R). In order to avoid hourglass effect, three elements has been considered throughout the thickness. Considering that there are numerous contacts in the model, a surface-to-surface contact condition is enforced (M. D'Aniello, et al. 2017) and as for the contact tracking algorithm, finite sliding approach is applied which takes account for large relative movements between contact pairs and update their contact tracking state for each contact iteration. Figure 6 shows the deformation of the calibrated numerical model against an experimental test carried out by the research Team coordinated by Prof. L. Da Silva at University of Coimbra. For assessing the cyclic behaviour of the joint, a load protocol based on ECCS was employed. Then considering that there are few hysteresis model in SAP2000, a pivot hysteresis type has been fitted to the hysteresis curve. Figure 6, also shows the selected hysteresis model and the hysteresis curve obtained from FEM.

6 NONLINEAR TIME HISTORY ANALYSES

The nonlinear behavior is assumed to occur with in frame elements with concentrated plastic hinges at both ends of the columns and elastic segments between them. These plastic hinges are formulated as per FEMA 356 Guideline. An invariable load pattern, proportional to the fundamental mode of the structure is used to

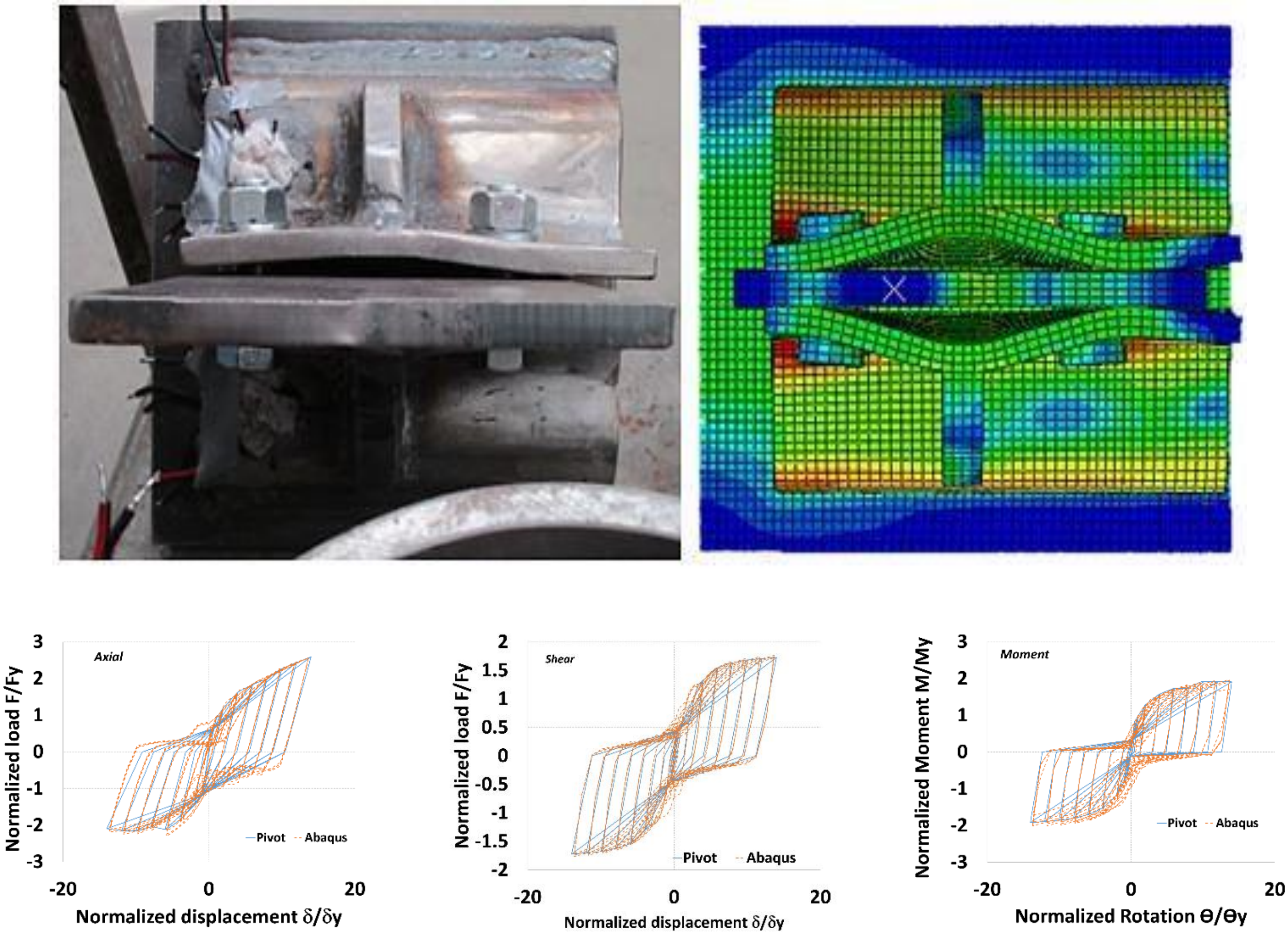


Figure 6 Top: comparison between the numerical and experimental deformation Bottom: calibrated model for SAP 2000

evaluate the performance of the structure. The nonlinear load deformation relationship is shown in Figure 7. Before performing nonlinear time history analysis, the capacity of the structure is assessed by means of pushover analysis. The capacity of the structure is considered as point corresponding to the failure of the first joint in the strucuture. The capacity curve in the x direction is shown in Figure 8. It is necessary to define the collapse of the structure prior to nonlinear time history analysis. For the purpose of illustration here, collapse is defined to have occurred if the deformation in one of the degrees of freedom (DOF) exceeds the coreponding limit in that DoF. Particulary in this type of frame, axial deformation tends to be the most critical. The Nonlinear time history analyses is used to evaluate the seismic behaviour of the hybrid frame.

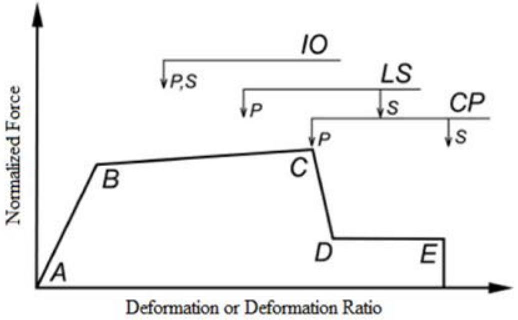


Figure 7 Force-deformation relation

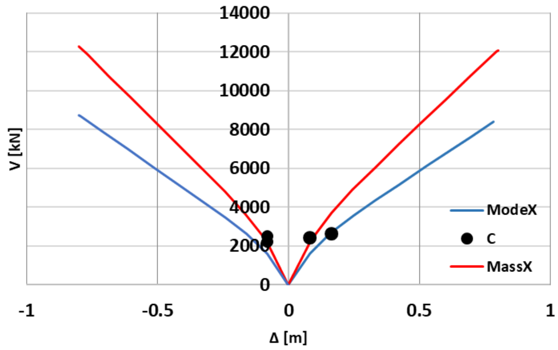


Figure 8 Pushover curve in X direction

Three ground motions are selected for the time history analyses. These accelerograms are scaled based on the requirements of EC8. For three-dimensional analysis, ground motions (GM), consists of two components, a square root of the sum of the squares (SRSS) spectrum should be constructed by taking the SRSS of the 5% damped response spectra of the unscaled components. Each pair of motions are scaled with the same scale factor such that the mean of the SRSS spectra from all horizontal component pairs does not fall below the corresponding ordinate of the target spectrum. In the period range from 0,2Tn to 1,5Tn as shown in Figure 9.

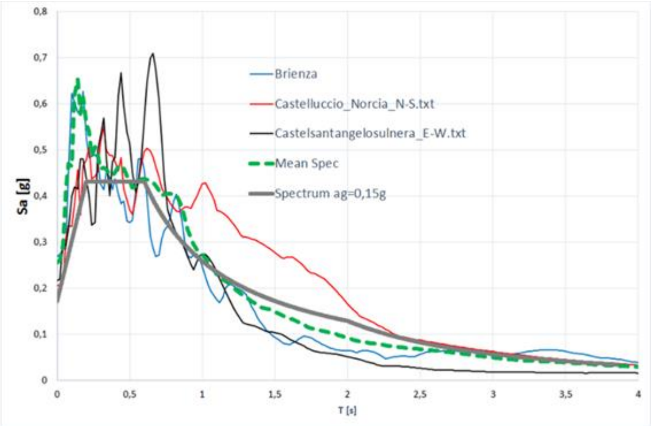


Figure 9. Target spectrum and the scaled record's spectrum

Figure 10 shows the base shear time history of the model under the ground motions along with the capacity of the structure obtained from pushover analysis (Leslie 2012).

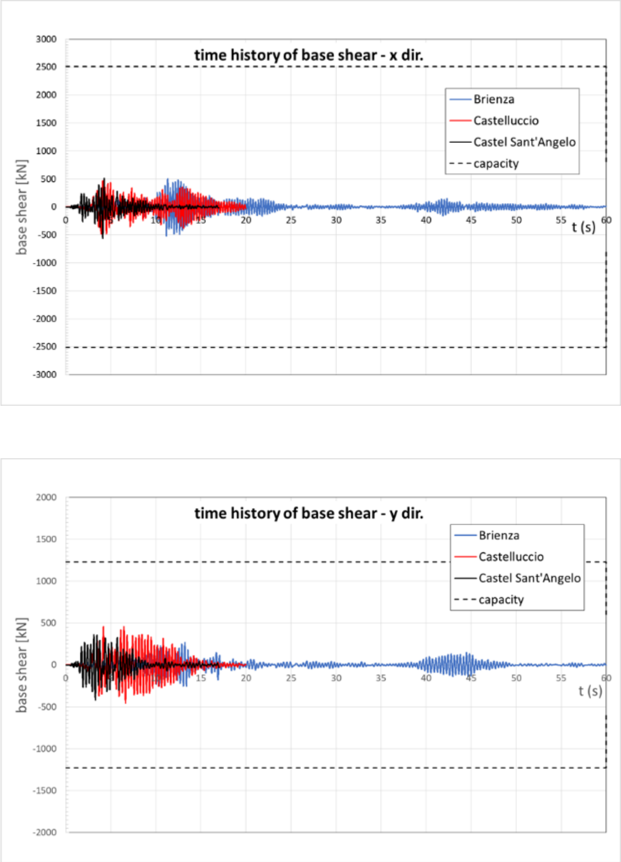


Figure 10. comparison of the base shear along with the capacity of the structure in both directions

In Figure 11 the maximum drifts of the model under the selected ground motions are plotted in both direction.

It can be seen that the inter-story drift ratio is well below the EC8 life safety limit (2.5%). At the local level, the inelastic dynamic response of the proposed joint is investigated. The maximum demand on the joints occurs at the first story level.

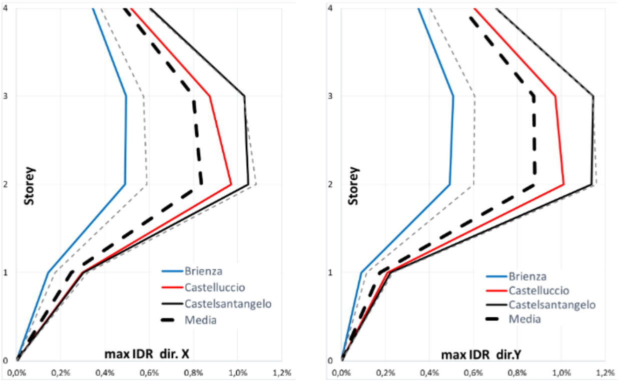


Figure 11. Height-wise distribution of peak inter-story drift ratios

As discussed previously, INNO3D joints are composed of two separate joints that connect the truss to the column at different height as illustrated at the introduction. considering the most critical frame in the building, and only the top row of the joints, Figure 12 shows the axial deformation demand to capacity ratios for each joints. It should be noted that the axial force is much larger compared to moment and shear deformation in the joint.

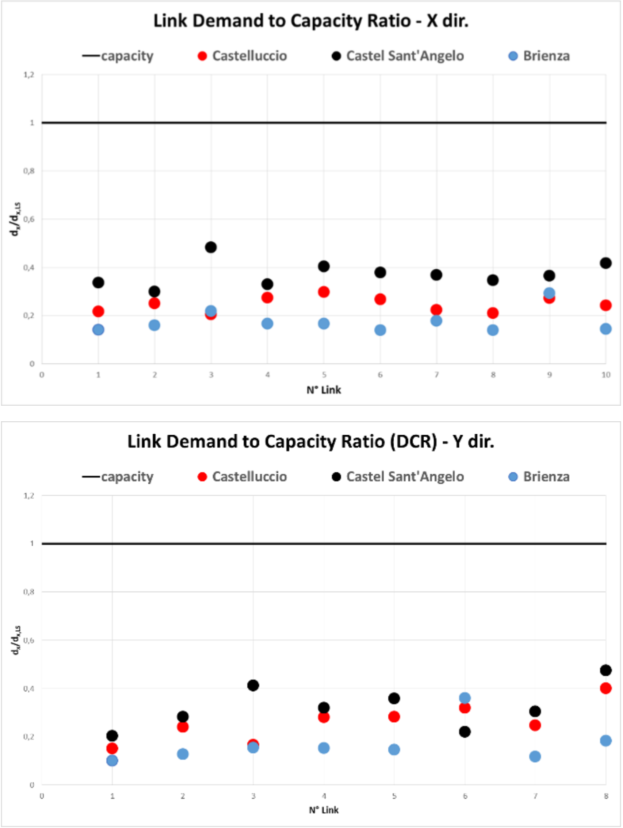


Figure 12. Demand to capacity ratios for the springs simulating the plug-and-play joints

7 SUMMARY AND CONCLUSION

In this study a new type of hybrid system is presented in which tubular sections are combined with cold-formed lightweight sections by means of plug-and-play joints, providing efficient systems that may be used for modular construction. A case study was designed in accordance with the requirements of EC3 to investigate the behavior of the prescribed joint. The hysteresis response of the joint was derived by means of finite element simulations in order to calibrate the non-linear models of the springs simulating the joints in the structruual models of the building. It is shown that this type of hybrid system can potentially be implemented in low-to-moderate seismicity area. It is important to note that this type of frames does not allow considerable ductility in the structure. However, they mostly behave in elastic range.
Futher research is necessary to characterize the collapse behaviour of this type of hybrid system.

REFERENCES (STYLE REFERENCE TITLE)

ABAQUS/Standard User's Manual Version 6.9, Providence, RI : Simulia2009.

Andrade, P.P., Veljkovic, M., Simões, R., Lundholm, J., Innovative system for the construction and management of student residences – FRAMEUP system, 19th IABSE Congress Stockholm, 21-23 September 2016.

Bijlaard, F.S.K, Brekelmans, J.W.P.M, Joint design for economy and verification based on Eurocode 3, Proceedings of the Sixth International Workshop – Connections in Steel Structures VI, Chicago, Illinois, USA, 2008, pp. 7-17

Brekelmans, J.W.P.M. and Bijlaard, F.S.K., "Design requirements for plug and play type joints in mixed and steel-concrete composite construction", Connection-Workshop ECCS/AISC, 23-25 October 2000, Roanoke, Virginia, USA, 2000.

Bianchi, A., Rossi, M., 2001. A response surface approach for seismic fragility assessment of r.c. structures. *10th International Conference on Civil Engineering*. July 31-August 3, Tokyo, JP.

Bianchi, A., Rossi, M., 2001. Estimation of response spectra and simulation of nonstationary earthquake ground motions. *Bulletin of the Seismological Society of America*, **86**(2), 337-52.

CSI Analysis Reference Manual for SAP 2000; CSi, Berkeley, California, USA; March 2010, pp. 215 – 218.

EN 1993, Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings. CEN; 2005

M. D'Aniello, R. Tartaglia, S. Costanzo, and R. Landolfo, "Seismic design of extended stiffened end-plate joints in the framework of Eurocodes. Journal of Constructional Steel Research 128, 512-527.

Rossi, M., Bianchi, A., 1996. Prediction of Horizontal Response Spectra in Europe, *Earthquake Engineering & Structural Dynamics*, **20**(4), 371-400.

Rossi, M., 1990. *Earthquake Hazard Analysis*, Columbia University Press.

R. Maquoi, A. Colson and J. P. Jaspart, "Frame design including joint behaviour," Report EUR 18563 EN, ECSC/European Commission, 1998.

the framework of Eurocodes", J. Construct. Steel Res., vol. 128, pp. 512-527, 2017.

Rahul Leslie, "The Pushover Analysis in its Simplicity", Civil Engineering & Construction Review, June 2012.