SERA
Seismology and Earthquake Engineering
Research Infrastructure Alliance for Europe

Fact sheet 3 I Spring 2020

TA PROJECT SERA-SILOS: SHAKE-TABLE DYNAMIC TESTS ON A FULL-SCALE STEEL SILO FILLED WITH WHEAT

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The structural design of steel flat-bottom ground-supported silos containing granular material represents a challenging issue. They differ from many other civil structures since the weight of the silo structure is sensibly lower than the one of the ensiled particulate material. In case of earthquake ground motion, the particle-structure interaction plays a fundamental role on the global dynamic response. The complex mechanism through which the ensiled material interacts with the silo wall has been studied since the XIX century. Nonetheless, several issues are still to be addressed regarding "grain-silo systems" and structural failures still occur, with potential loss and spread of huge amount of the ensiled content.

An extensive experimental campaign with several parametric shake table tests has been run at EUCENTRE laboratory of Pavia (Italy). A wide spectrum of related aspects has been targeted, such as the dynamic characterization (frequency, damping ratio, amplification) of such complex grain-silo system, the experimental assessment of the static pressure (during and at the end of the filling phase) and the seismic dynamic over-pressures exerted by the ensiled material on the silo wall; furthermore, the assessment of the benefits obtained introducing a seismic isolation system based on curved surface sliders at the base of the silo has been carried out.

Fig. 1: The flat-bottom cylindrical silo on the shake-table

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730900.

The tested specimen is a flat-bottom cylindrical silo; specifically, it is the real full-scale smallest silo manufactured by the Italian company AGI-FRAME.

In addition to the instrumentation typically considered in shake table tests, i.e. uniaxial and multiaxial accelerometers, displacement transducers and strain-gages, a machine 3D vision system based on high-resolution cameras and specific reflective markers have been used to get a mesh of absolute displacements in dynamic conditions (sampling frequency of 200 Hz). Furthermore, since the internal pressure and its variations were an important aspect, 4 pressure sensors specifically designed and manufactured by EUCENTRE were first tested and calibrated, then implemented during all testing phases.

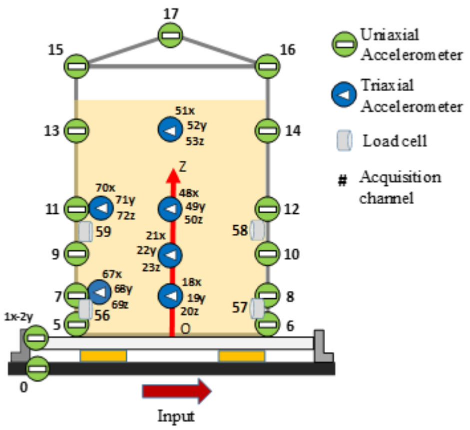

Fig. 2: Accelerometers


Fig. 3: Pressure sensors

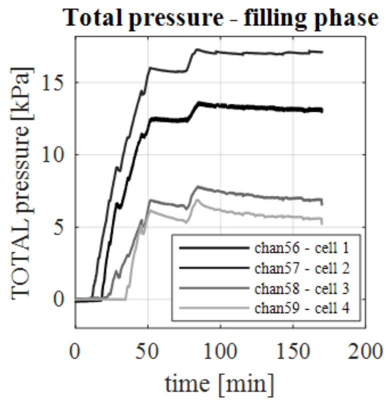

Fig. 4: Horizontal pressure at two different levels during the filling phase

A total of more than 250 shake table tests have been performed to test the dynamic response of the grain-silo system under different conditions. The input signals considered for the ground motion included white noise, low -frequency sinusoidal pattern, artificial and real recorded seismic accelerograms, both far and close to the natural frequencies of the structure. Figure 4 shows the interesting trend of internal pressure during the wheat filling phase, which is relatively far from having a cylindrical symmetry as theoretically expected. Since static pressure is, in some cases, more important than its variation during an earthquake for the design of the structure, this behaviour might give interesting hints on the design of loading conditions.

Peak Table Acceleration	First set of tests before grain compaction		Second set of tests after grain compaction	
RND	Test N.	f (Hz)	Test N.	f (Hz)
0.07 g	1	10.8	88; 89	12.3
0.15 g	20; 21	10.0	90; 91	11.3
0.20 g	39; 40	10.3	92; 93	10.7
0.25 g	-	-	94; 95; 96	10.7

Table 1: Experimental frequencies

Table 1 shows the frequencies as evaluated both before and after the grain compaction. Compaction appeared for table accelerations larger than 0.5 g, almost consistent with the value of the grain-grain friction coefficient (about 0.55): the grain free-surface was monitored during the tests by a visual method and four vertical graduated bars. It can be noticed that the fundamental frequency of the grain-silo system depends on both, the acceleration and the compaction level, it decreases with increasing acceleration (more effective mass) and it increases with increasing compaction (higher stiffness provided by grain material).

This experimental campaign contributes important findings to a field with limited experimental data, particularly considering real full-scale silos and shake table dynamic testing. Important information on the real asymmetrical loading conditions due to the commonly used filling procedures, the dynamic response and the material compaction effects on the dynamic properties of the silo-grain system have been obtained and are currently an object of further investigation, modelling and dissemination. The effectiveness of the silo-system protection obtained by seismic isolation was also effectively investigated. In order to fully exploit the potential of the testing campaign, a fruitful collaboration with world-wide researchers and a specific selection of a variety of input signals was successfully carried out within the preliminary phases of the testing campaign. ■

SlabSTRESS TA project: Slab structural response for European Seismic Design

Georgios Tsionis, Marco Lamperti, Pierre Pegon, Javier Molina, Marco Peroni

European Commission, Joint Research Centre

Fig. 1: The full-scale two-storey test specimen as flat slab structure

Flat slab buildings for commercial, office and residential use are built in many countries. Yet, their performance under seismic and gravity actions is still not very well understood. Many studies have been carried out in North America or Asia, but European research is lagging behind, especially Eurocode 8 does not fully cover the design of buildings with flat slab frames used as primary seismic elements.

The SlabSTRESS Transnational Access project at the ELSA Reaction Wall of the Joint Research Centre studied the response of flat slab reinforced concrete buildings under earthquake and gravity loads. The objective of the project was twofold: to study the ultimate capacity and failure modes of flat slab structures with different layouts of reinforcement and to verify the effectiveness of steel studs for the repair of damaged slab-column connections.

The test specimen was a full-scale two-storey flat slab structure with plan dimensions 9×14 m. Punching shear reinforcement was placed only in the slab of the second storey. In addition, uniformly distributed horizontal reinforcement was placed in half of the slab at each floor, while, in the other half, the same amount of horizontal reinforcement was mostly concentrated close to the columns.

The testing programme included two hybrid simulation pseudo-dynamic tests of the physical specimen with numerical modelling of the shear walls, with input corresponding to the serviceability and ultimate limit states. Quasi-static tests under imposed cyclic displacement with increasing amplitude were also performed. Three slab-column joints were strengthened after the first cyclic test.

The project provided new knowledge on the response of flat-slab structures with different detailing rules that could not be captured in previous tests on column-slab sub-assemblies. The results help to calibrate models, verify the Eurocode and Model Code models for punching shear, and support the development of new rules for the deformation-based design and detailing of flat-slab structures subject to earthquake and gravity loads, as well as to improve the design of flat-slab frames as primary seismic structures.

The results of the project are being exploited by the 14 users of the SlabSTRESS project and by 19 research groups from 13 countries, who participate in an ongoing blind prediction competitions.

More information: www.slabstress.org, www.researchgate.net/project/SlabSTRESS ■

Field testing of Soil-Structure Interaction (SSI) and wave propagation in Euroseistest and EuroProteas (WP16, TA9)

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EUROSEISTEST is a European experimental site established by the Aristotle University of Thessaloniki (AUTH) in 1993 in the tectonically active region of the Mygdonia valley, 30 km outside of the city of Thessaloniki, Greece. It is one of the longest-running test sites worldwide supporting integrated studies in earthquake engineering and engineering seismology. It offers permanent 3D strong motion network and a prototype structure of EUROPROTEAS, a unique large-scale structure for field testing of Soil-Structure Interaction (SSI) in Europe and one of the very few dedicated facilities worldwide. The permanent accelerograph network includes 21 high-resolution digital stations located at the ground and in down-hole arrays. Recorded acceleration time series and metadata are organized in a database that is accessible through the EUROSEISTEST web portal. Currently, the EUROSEISTEST database includes more than 200 recorded events of local magnitude 1.5 ≤ ML ≤ 6.6 at epicentral distances in the range of 1–500 km (mostly near the source).

Fig. 1: The location of the EUROSEISTEST

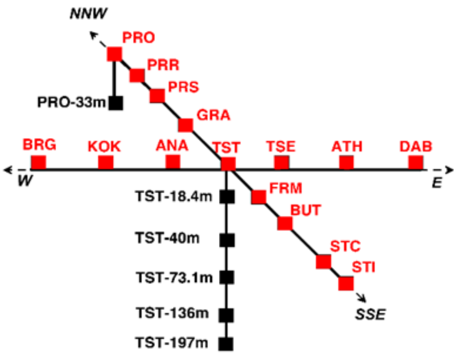

Fig. 2: The permanent accelerograph network

Fig. 3: EUROPROTEAS structure

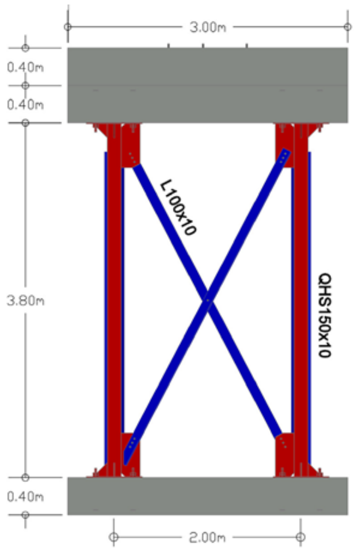

Fig. 4: 2D sketch

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The EUROPROTEAS prototype structure was constructed in the center of the EUROSEISTEST experimental array (TST site). It was particularly designed to trigger soil-structure interaction phenomena and to mobilize the nonlinear behavior of the foundation soil. The X-bracings and the upper RC slab of the perfectly symmetric reconfigurable structure are removable. The outer dimensions of the structure are 3x3x5 m, while its total weight is approximately 28.5 Mg.

User Groups from Centrale Supélec, University of Napoli Federico II, University of Ljubljana, Politecnico di Milano, ETH Zurich, Imperial College, University of Catania, University of Bologna and the University of Strathclyde performed experiments and/or were granted access to EUROSEISTEST and EUROPROTEAS facilities and data. Their studies covered a wide range of scientific topics such as the following:

- Validation of 3D wave propagation models
- Calculation of foundation impedance functions
- Definition of design spectra considering soil-foundation-structure interactions
- Evaluation of 3D complex site effects
- Evaluation of the impact of structural rocking
- Foundation rocking isolation methods
- Investigation of rubber-soil mixtures response as innovative isolation material
- Guidelines for metabarrier seismic materials
- Investigation of scouring effects

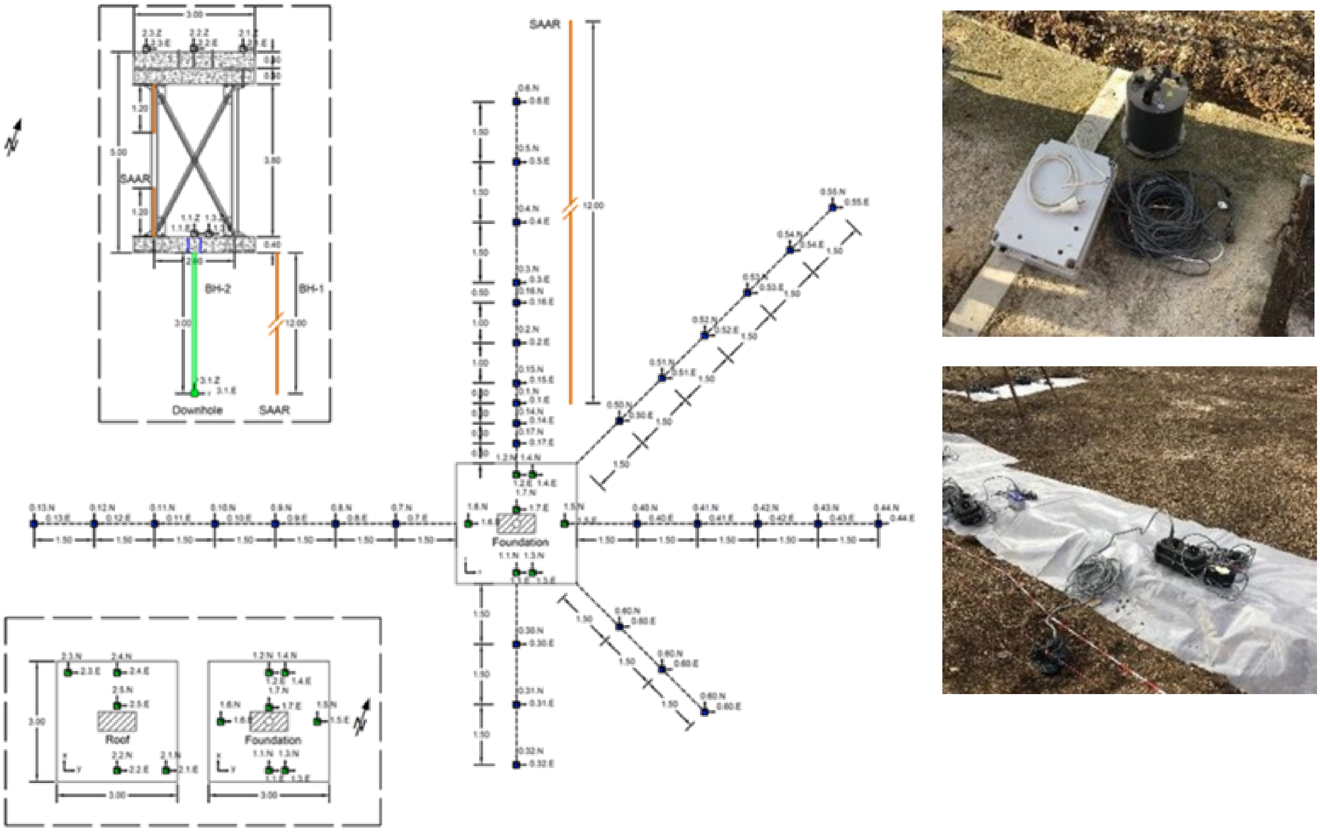

Fig. 5: Instrumentation layout (left), a triaxial accelerograph mounted on the foundation slab (top right) and triaxial seismographs placed on the ground (bottom right)

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A high number (typically more than 80) of various types of instruments was used to monitor the structure and the surrounding soil response, including triaxial accelerometers, triaxial seismometers, borehole triaxial accelerometer, shape acceleration arrays, and laser sensors. Many series of experiments were performed in the prototype structure of EuroProteas, including ambient noise recordings, free- and forced-vibration tests. Specifically, forced-vibration tests were conducted for six of the proposed projects, while free-vibration experiments were proposed only by four user groups. Additionally, ambient noise records were requested by seven user groups.

The forced-vibration tests were carried out by placing a portable uniaxial eccentric mass shaker as a source of harmonic excitation on the roof and the foundation slab of the prototype structure. The tests were performed in the frequency range of civil engineering interest between 1 and 10 Hz and up to forces of 30 kN. In the free-vibration tests, the pull-out forces were applied on the roof of the structure by a wire rope. A load cell was attached to the roof slab and to the one end of the rope, to measure the applied tension force. The other end of the wire rope was attached to a wire rope pulling hoist having a working load limit of 32 kN. Ambient noise was also recorded.

Fig. 6: Eccentric mass shaker

Fig. 7: The connection of the wire rope and the load cell to the roof slab

Most of the experiments performed in the EUROPROTEAS and EUROSEISTEST facility required the measurement of the soil-structure system response under various conditions and excitations. The outcome of this investigation is crucial to the majority of the user groups, as the main goal is to evaluate and implement the effects of soil-foundation-structure interaction in their studies. SSI effects were pronounced in the results of both the free and forced-vibration experiments.

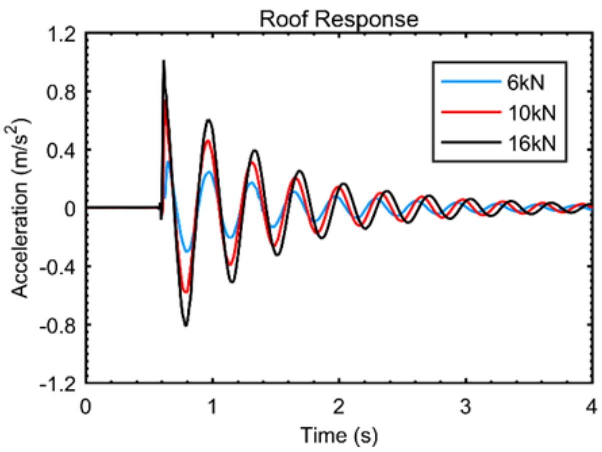

Fig. 8: Recorded acceleration at the roof

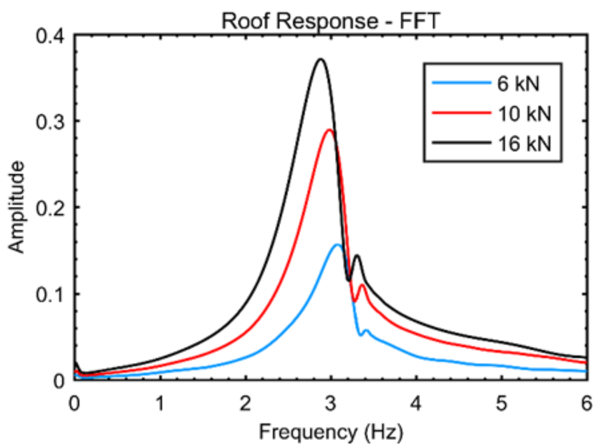

Fig. 9: The corresponding Fast Fourier Transform (FFT) spectra for selected free-vibration tests

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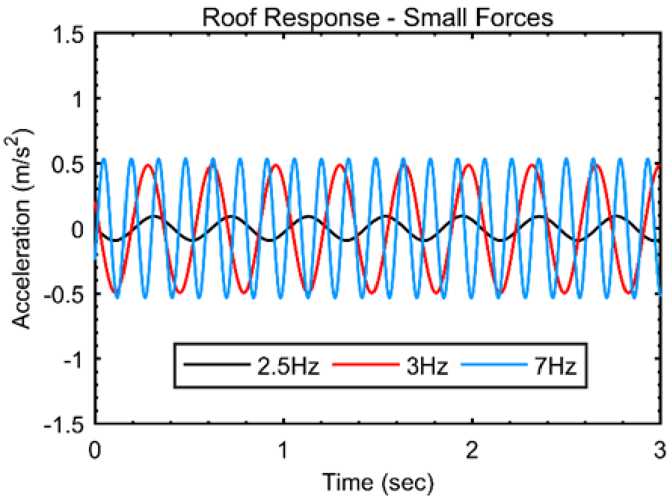

Fig. 10: Recorded acceleration at the roof for small forces

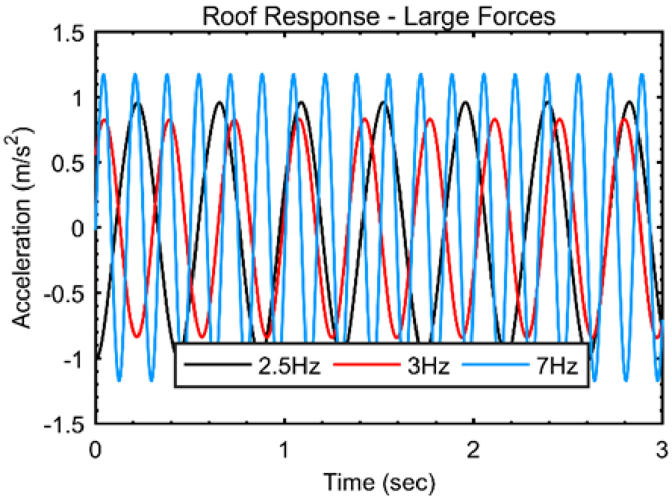

Fig. 11: Large forces for selected forced-vibration tests

Figure 12 shows the achieved comparison between the horizontal impedance functions from experimental recordings and theoretical solutions (Pais and Kausel 1988) for a wide range of frequencies. Convergence is satisfactory especially for frequencies between 2 Hz and 10 Hz.

Figure 13 shows the effect of the implementation of a rubber-soil mixture bellow the foundation on the recorded response at the roof of EuroProteas. The tested configurations have Gravel-to-Rubber ratios equal to 100/0, 90/10 and 70/30 per weight. A 50cm thin layer of the gravel-rubber mixture below the foundation with 30% per weight rubber was found to cause a 60% decrease in the recorded acceleration amplitude at the roof. ■

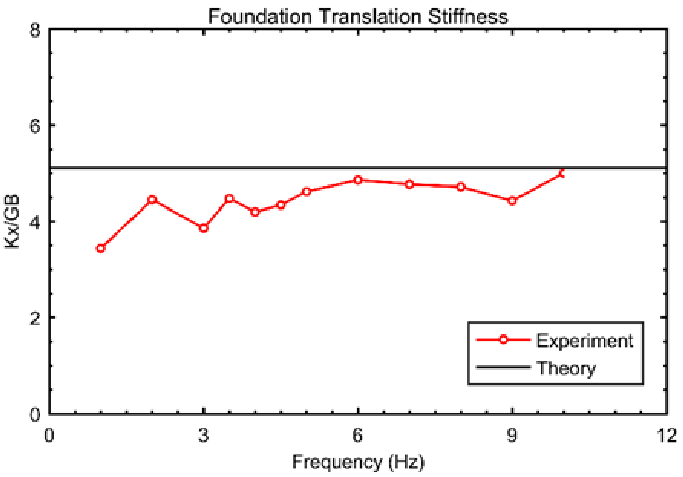

Fig. 12: Comparison of the experimental and theoretical horizontal foundation impedance function

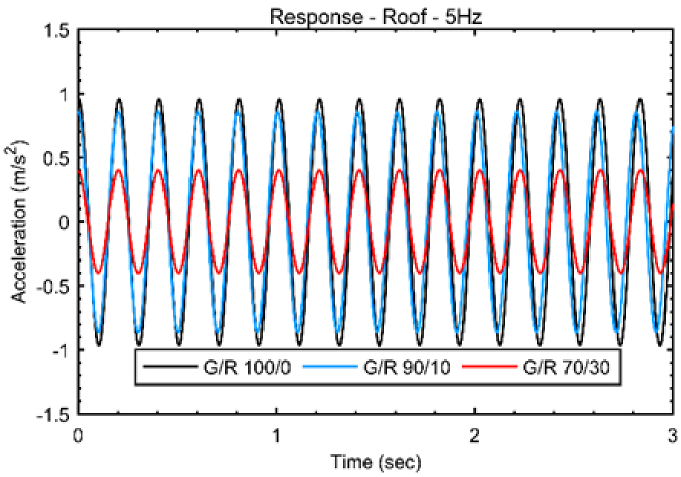

Fig. 13: Influence of rubber-soil mixture configuration in the recorded acceleration response of the roof

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TA Project FUTURE: Full-scale experimental validation of steel moment frame with EU qualified joints and energy efficient claddings under near fault seismic scenarios

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There is a great wealth of numerical and experimental research dealing with the seismic response assessment of new steel moment resisting frames (MRFs). Such research has shown that (i) the seismic behaviour of MRFs is largely influenced by the behaviour of the joints; (ii) the loading protocol adopted to qualify/test beam-to-column joints is representative for the cumulative and maximum rotation demands imposed by far field natural records and; (iii) the design of new steel MRFs according to EC8 is mostly influenced by the serviceability checks (i.e., damage limitation requirements).

It is worth noting that most of the existing studies conducted in the past focused mainly on sub-assemblage tests, without accounting for the response of the building as a whole. Additionally, the loading protocols used for qualifying the joints do not mimic actual earthquake demands at near-collapse conditions. This is also the case of Near Fault (NF) seismic input. Importantly, there is a lack of knowledge about the behaviour of steel joints when subjected to near fault seismic demand. Moreover, earthquake reconnaissance studies have shown that the ratio of vertical-to-horizontal peak ground acceleration can be larger in near-fault than far-fault seismic events. Near fault strong motions tend to increase the inelastic demand on structural steel members and joints. Furthermore, the use of special ductile energy efficient claddings can be beneficial to relax the drift limitations, thus allowing to optimize the structural design (i.e., reducing the design over-strength), reducing the material consumptions, the constructional costs and encouraging the use of more sustainable solutions. The use of such ductile non-structural components also lowers the earthquake-induced losses arising from the claddings.

This project investigates the response of steel moment resisting frames (MRFs) accounting for three different types of bolted beam-to-column joints (i.e., haunched, extended stiffened and dog-bone) as well as the role of energy efficient ductile claddings under near fault (NF) seismic scenarios. The main objectives of the tests can be summarized as follows:

1. To provide design rules for steel frames under combined effects of horizontal and vertical components NF, which are not yet considered in the design standards for new and existing structures;
2. To validate the response of MRFs equipped with EU prequalified joints (i.e., extended stiffened, haunched and dog-bone) under NF earthquakes as well as to demonstrate the effectiveness of the new design rules for joints currently implemented in the draft of the amended EN1993:1-8;
3. To verify the efficiency of slab-to-beam and slab-to-joint details to avoid the composite action at joint level but to ensure effective torsional restraints to the beams;
4. To demonstrate the efficiency of fully detachable dissipative beam-to-column joints, which allow easy replacement after seismic damage;
5. To contribute new background data to the assessment and the repairing/retrofitting of steel frames (e.g. the use of bolted dog-bone joints is representative of potential retrofitting solution) in order to update the next version of EN1998-3;

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6. To verify the revised requirements about P-Delta effects currently proposed by WG2 CEN-TC 250/SC8 and ECCS-TC13 for the amended version of EN1998-1;
7. To validate the use of special energy efficient and extra-ductile claddings for MRFs, characterized by drift limits at DL/SLS larger than 1.5. % of the interstorey height.
8. To develop experimentally-based fragility relationships for such ductile non-structural components, which tend to minimize the earthquake losses due to claddings.

The model has been designed in order to change the joints quite easily. Several sets of beam-to-column assemblies were constructed. The testing of the moment frame includes both horizontal and vertical excitations. For each set of joints, the bare steel (i.e. panel-free) configuration was first tested to a seismic level that allows the joints to exhibit large plastic deformations (i.e. from ultimate to collapse prevention limit states). Afterwards, the damaged joints was replaced, and the panels were mounted to verify the overall behaviour at damage and ultimate limit states. ■

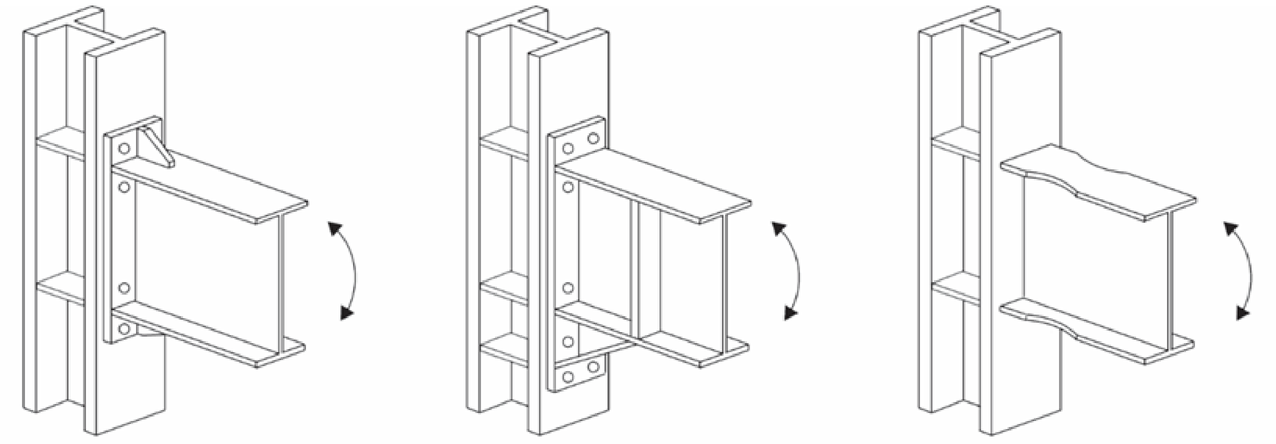

Fig. 1: The three types of detachable beam-to-column joints haunched (left), extended stiffened (middle) and dog-bone (right)

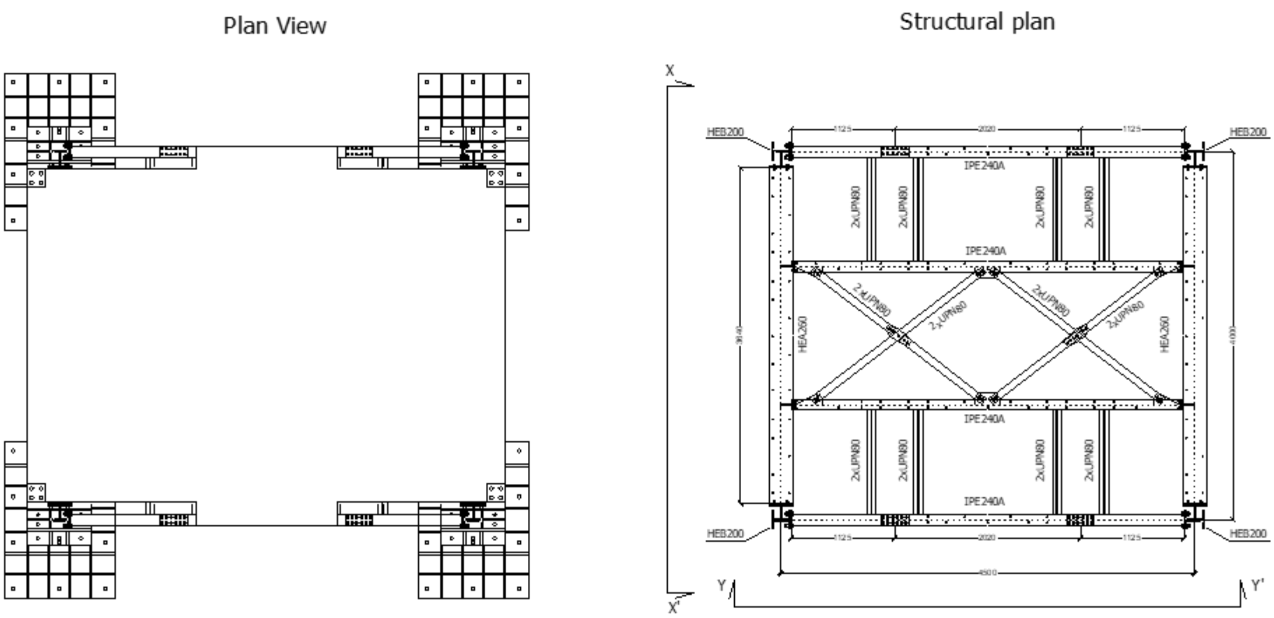

Fig. 2: Structural plan layout of the mock-up: reinforced concrete deck and steel horizontal structure

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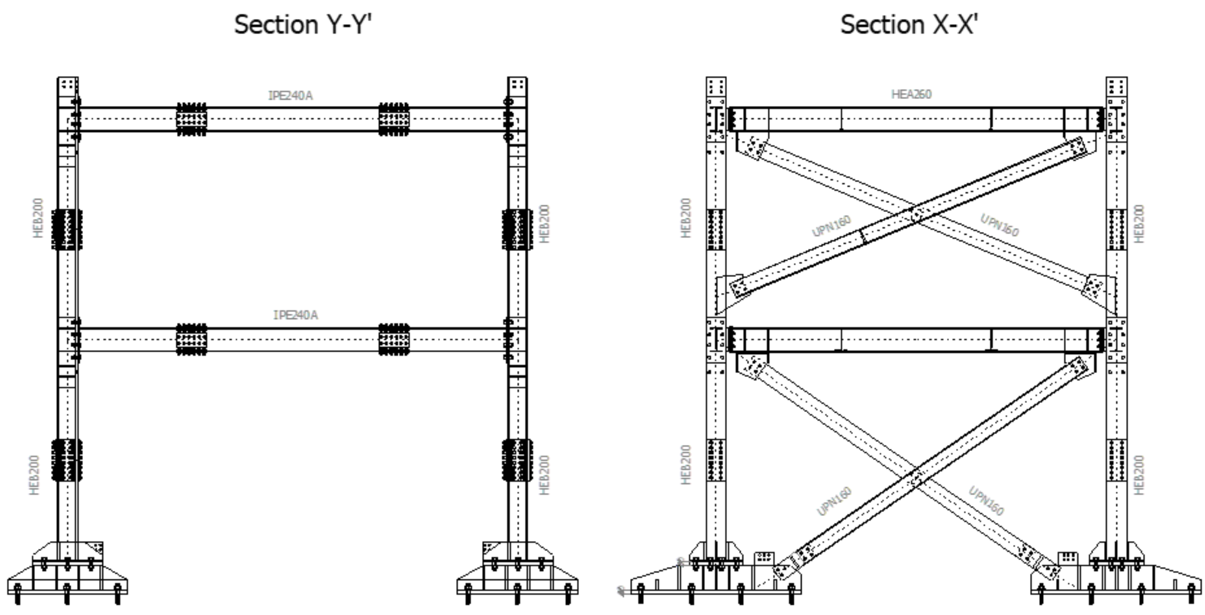

Fig.3: Structural vertical layout of the mock-up: moment frame with detachable dissipative zones and transverse frame to avoid torsional rotation

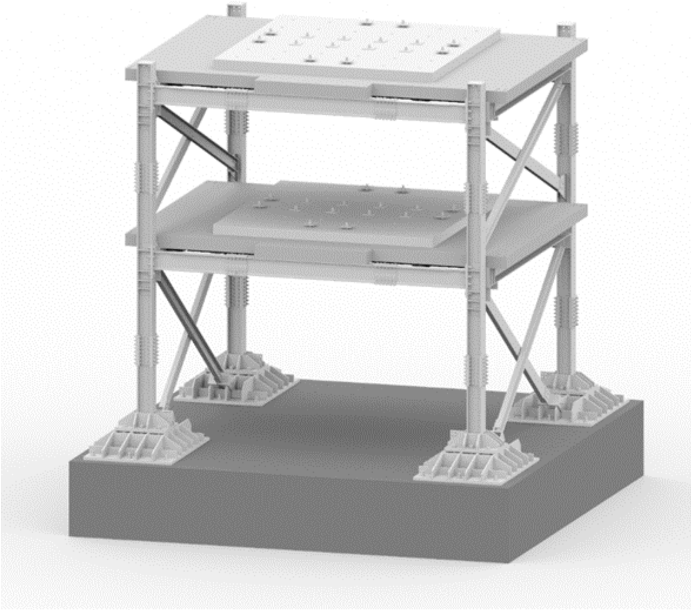

Fig. 4: 3D view of the structure without panels

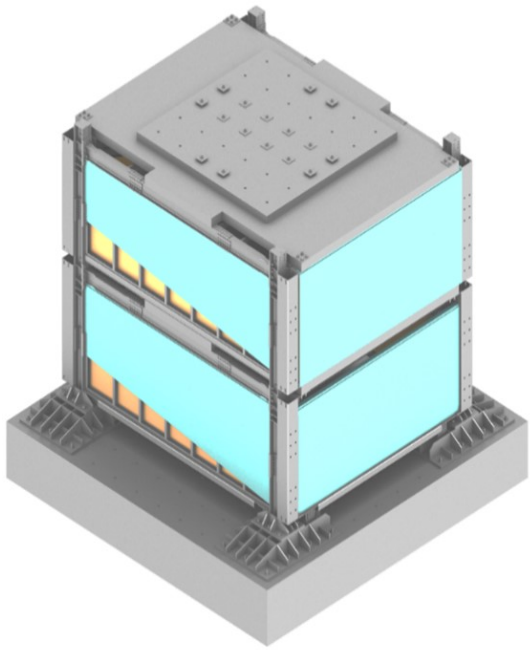

Fig. 5: 3D view of the structure with panels

Roadmap for the integration of data banks and access services from the earthquake engineering (SERIES) and seismology (EPOS) research infrastructures

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The roadmap for the integration of data banks and access services from the earthquake engineering (SERIES) and seismology (EPOS) research infrastructures proposes the integration of the SERIES databases in the existing EPOS service as a new Thematic Core Service (TCS). Possible interoperability with other TCSs (e.g. Seismology) and with international partners is also explored. The first step is to consider the SERIES database as the first service of a new Earthquake Engineering Thematic Core Service (E/ENG TCS) within the EPOS architecture. SERIES will initially provide, through EPOS, integrated access to key data and experimental measures produced in Europe at some of the best facilities for earthquake engineering worldwide. In its mature phase, the integration process will provide advanced interoperability within the earthquake engineering community itself, with the sibling TCS seismology and other TCSs, and with international partners. This objective will be guaranteed by implementing new services and tools for improving user accessibility and experience.

The roadmap identifies the cross-discipline needs in earthquake engineering and seismology data assessed through a questionnaire directed to users and stakeholders operating in the two fields. The questionnaire collected information on requirements and use cases for earthquake engineering and seismological data serving as the basis for the developed roadmap. The metadata structures in EPOS and SERIES were compared, followed by a gap analysis and leading to the requirements for the metadata catalogue development for the proposed new E/ENG TCS.

The roadmap puts forward a strategy with different tasks envisaged to be performed in three steps (short-, mid- and long-term). In the short-term, by the end of the SERA project, a pre-operational access service will be provided to selected SERIES datasets to allow validating identified access technologies and involving the user community, for further implementation in EPOS. The activities performed in the mid-term will include a review if the newly developed services and products are fully compatible with the requirements of EPOS, at a technical, legal, governmental and financial level. Full integration of the earthquake engineering TCS in EPOS will be achieved in the long-term perspective by providing also access to research infrastructures, laboratories and data centres established outside Europe, thus improving the international dimension of EPOS. ■

Access to Array Seismology at NORSAR

Johannes Schweitzer, NORSAR, Norway

Stiftelsen NORSAR or for short NORSAR is a non-profit research foundation located in Kjeller near Oslo (Norway). Under WP17/TA10 of the SERA project, NORSAR is offering access to its infrastructure, which consists primarily of a data centre and field installations on Norwegian territory in Northern Europe, the Arctic and Antarctica. It comprises five seismic and three infrasound arrays (with apertures ranging from 0.5 to 60 km, equipped with 1C or 3C short-period or broadband sensors) and four single 3C broadband stations. Going back to 1971, the continuously growing unique data - base stores more than 55 TByte of seismic data in digital form from NORSAR's arrays and 3C stations as well as from many other (mostly European) arrays and 3C stations, which are all open for research. In addition, NORSAR's staff contributes with its expertise to:

1) Array seismology
2) Automatic online data processing
3) Near real-time seismic monitoring of regional seismicity, aftershock sequences and induced seismicity including microearthquakes associated with natural or anthropogenic ground instabilities, and
4) Seismic hazard and risk assessment as well as earthquake engineering

Until now, six out of eight TA projects at NORSAR have been finalized. The six users visiting NORSAR for these projects are all early career scientists either working on their PhDs (3) or with recently finalized PhDs (3). All finalized projects focused on different aspects of array-data analysis. Four visitors came with their own data, observed with different arrays in different environments:

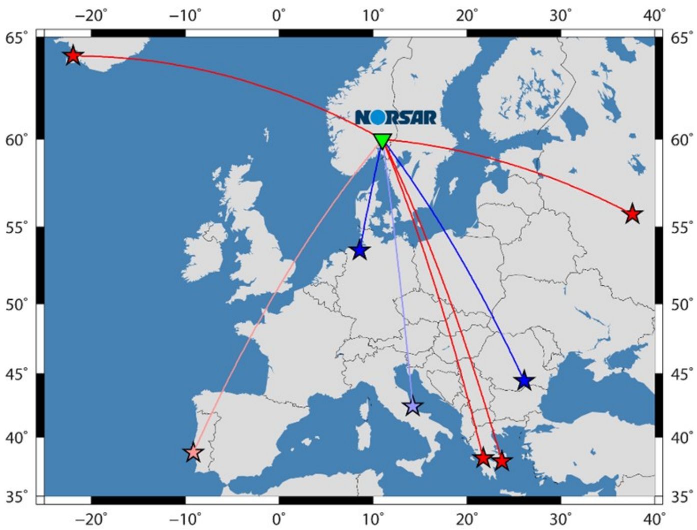
- Infrasound array data from the Romanian infrasound station, to be used as a classifier to distinguish between earthquakes and explosions (quarries, mines)
- Short period data from a temporary small aperture array in Russia, to detect and locate low magnitude seismicity in the Lena trough region, Siberia
- Strong motion accelerometer near field observations from an array in Iceland to investigate the characteristics of a mainshock and aftershock sequence of a magnitude 6.3 earthquake in the South Iceland Seismic Zone
- Broadband data from a small aperture array-like installation on the Peloponnese in Greece to search for seismic tremor signals caused by slow motion earthquakes in the Ionian subduction zone

The two other projects investigated the following:

- The Moho depth and structure of the mantle transition zone (receiver function method) below southern Norway with data observed by the large NORSAR array and other permanent and temporary seismic stations in southern Norway.
- A theoretically developed blind beamforming algorithm, with data from NORSAR's small aperture array ARCES in northern Norway

During their stays at NOSAR, last about one month each, all TA users became familiar with different aspects of seismic array-data processing, the influence of array geometry and instrumentation, the resolution of array specific measurements (backazimuth and slowness), different beamforming techniques, the influence of frequency contents on signal processing results, the separation of seismic signals from noise with arrays, and the importance of including the entire wavefield (vertical and horizontal components) in the analysis.

Results of the different research have been used and published in four conference papers (talks/posters) and one PhD-thesis. ■



Map of European affiliation locations of TA visitors at NORSAR (blue: female, red: male; lighter colors: visits in progress)

TA PROJECT HITFRAMES: HYBRID TESTING OF AN EXISTING STEEL FRAME WITH INFILLS UNDER MULTIPLE EARTHQUAKES

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TA facility: STRULAB Reaction Wall, University of Patras, Greece

Several existing steel multi-storey framed buildings were designed primarily for gravity loads; they exhibit low energy absorption and insufficient dissipation capacity under seismic loadings, as demonstrated, for example, by recent earthquakes which occurred in the Mediterranean regions. The low lateral stiffness and strength of the steel framed structures and the slender masonry infills induce significant lateral drifts, buckling and/or fracture of structural steel members. In addition, beam-to-column connections are weak and do not possess adequate rotation ductility capacity to withstand moderate-to-high magnitude earthquakes. Further, the current standardised provisions for the seismic performance assessment of existing steel structures are scarce and not corroborated by robust experimental evidence. Such provisions do not neither account for the presence of the infills. Infills may endanger the energy global dissipation capacity of structural systems, especially in multi-storey framed buildings. It is therefore mandatory to provide effective methods for the seismic assessment and retrofitting of existing non-compliant steel frames.

Fig. 1: A typical existing steel frame in the municipality of Amatrice, Central Italy, which was damaged during the 2016-2017 Central Italy earthquake sequence

The research project "HybrId Testing of an Existing Steel FRAme with Infills under Multiple EarthquakeS" (HITFRAMES) was led by the Department of Civil Engineering of University of Liverpool, UK. In HITFRAMES project the seismic behaviour of a 2/3 scaled two-storey three-bay steel frame was assessed experimentally through advanced hybrid simulation and substructuring pseudo-dynamic (PsD) method. The case study steel frame was designed for gravity loads only and does not have sufficient seismic detailing. The frame has a rectangular plan layout with a 6.5 m long span and a width of 3.5 m; each storey is 2.5 m in height. Weak and non-ductile beam-to-column connections were intentionally utilized for the tested frames at both floors. To facilitate the PsD tests, an earthquake sequence comprising fore-shock, mainshock and an aftershock was considered. The sample time history is the near-field East-West component recorded at Norcia during the 2016 Central Italy earthquake; the value of peak ground acceleration (PGA) is equal to 0,47 g for the mainshock, as shown in Figure 2.

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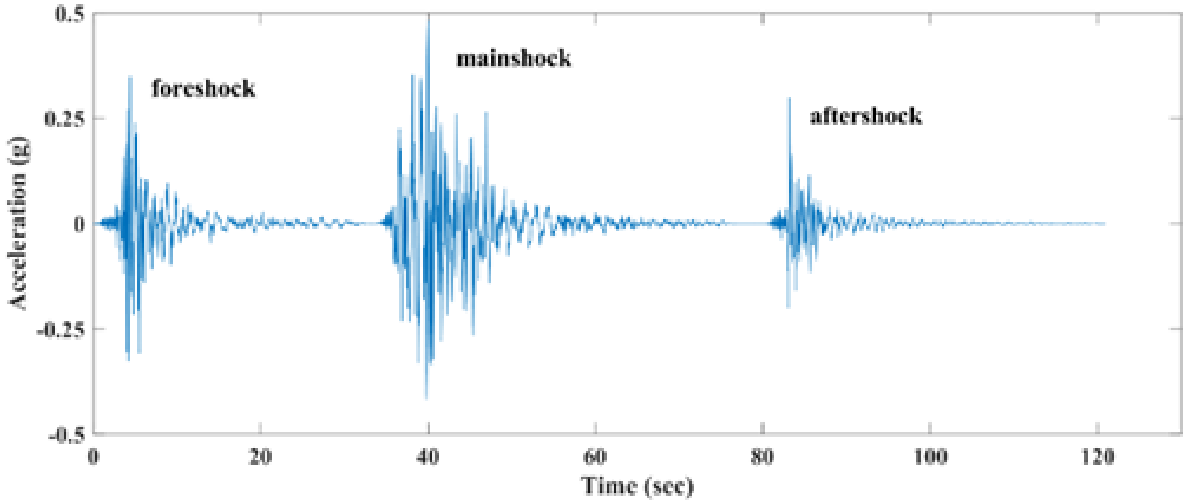

Fig. 2: Time history of the East-West component of the near-field seismic sequence recorded in Norcia during the 2016 Central Italy earthquake (peak ground acceleration of mainshock is 0.47g)

The PsD tests on the case study steel frame were carried out in the StruLab of the University of Patras, Greece; the experimental programme consists of two phases. The first phase included tests on a 2/3 scaled spatial steel building comprising a two-storey one-bay frame, which was sub-structured from an actual existing multi-storey building (see Figure 3). Snap-back free-vibration tests were performed on the frame before and after the installation of masonry infills. Such tests were used to evaluate the dynamic response of the frames. The effects of double-layered masonry infills were thus determined experimentally. The infilled spatial frame was then subjected to the Norcia earthquake sequence (see Figure 2), using scaling factors of 1.0 and 3.0.

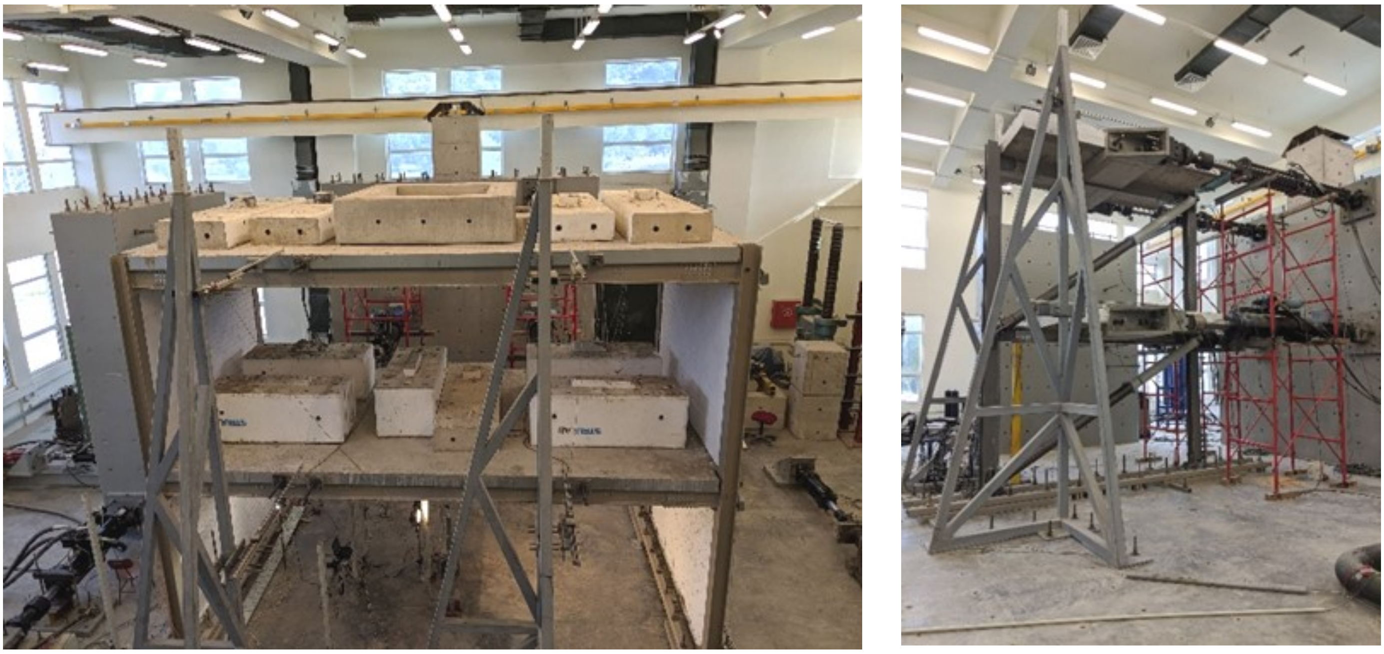

Fig. 3: Three-dimensional (left) and two-dimensional (right) multi-storey 2/3 scaled steel frames tested with the PsD method using the advanced facilities of the StruLab of University of Patras, Greece

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The 3D-steel frame was severely damaged during the tests. Significant yielding was observed on columns, particularly at the column bases and beam-column connections. For the masonry infills, cracks occurred firstly at the corners of infill panels, especially in the area that is in contact with the beam splice connections, where large stress concentration was expected. Secondly, diagonal cracks were observed, followed by horizontal cracks in the middle of infill panels due to shear sliding. It is worth noting that the observed response of the masonry infills, as the lateral drifts increased, appears rather different with respect to the case of the behaviour of the counterpart infills in reinforced concrete framed structures. The latter response is probably due to the different interaction between the steel beams and the masonry infills under larger lateral displacements. At the end of the first testing phase, a partial collapse occurred on the outer side of the double layered infill walls at the first floor, as shown in Figure 4.

Fig. 4: Observed damage on the 3D steel frame after the Norcia earthquake sequence with a scaling factor of 3.0

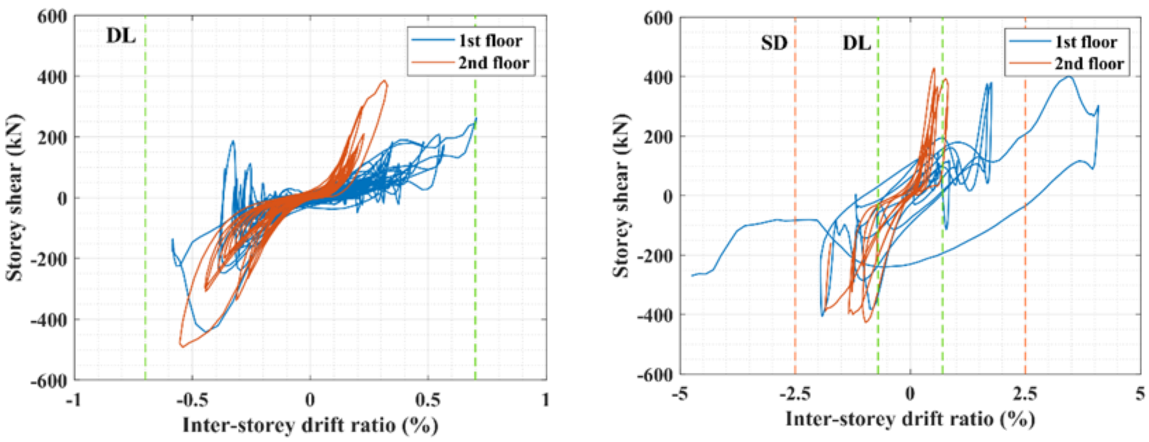

Fig. 5: Cyclic response of 3D steel frame with infills during the Norcia mainshock with scaling factor 1.0 (left) and 3.0 (right). Note: The limit states for the interstorey drifts as in Eurocode 8 – Part 3 have also been included (DL = Damage limitation limit state and SD = Severe damage limit state.

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The global cyclic response (Figure 5) exhibited significant pinching, which is probably a consequence of the opening and closing of cracks on the infill walls. The pinching effects are pronounced at both floors of the tested frame; such response increases as the lateral drifts increase for higher values of peak ground acceleration of the earthquake input.

In the second phase, the behaviour of a two-storey 2D-frame with the same geometry as the 3D-frame was tested; the plane frame was then also retrofitted with typical commercial buckling restrained braces (BRBs). Before the BRBs were installed, a free vibration test was performed on the bare frame to identify the modal properties, which were then utilized as a benchmark for the retrofitted system. The PsD tests were then carried out on the 2D-frame by considering several input ground motions. Initially, the un-retrofitted steel frame was subjected to a foreshock of the Norcia earthquake sequence; a scaling factor equal to 1.0 was utilized to induce slight damage on the frame components. Then the bare frame was retrofitted with BRBs installed on both floors. The retrofitted frame subjected to the foreshock and the mainshock with scaling factor equal to 1.0 (PGA=0.35 g) and 1.5 (PGA=0.72 g), respectively. The maximum drifts recorded were equal to 1.45 % and 2.76 % for the foreshock and the mainshock, respectively.

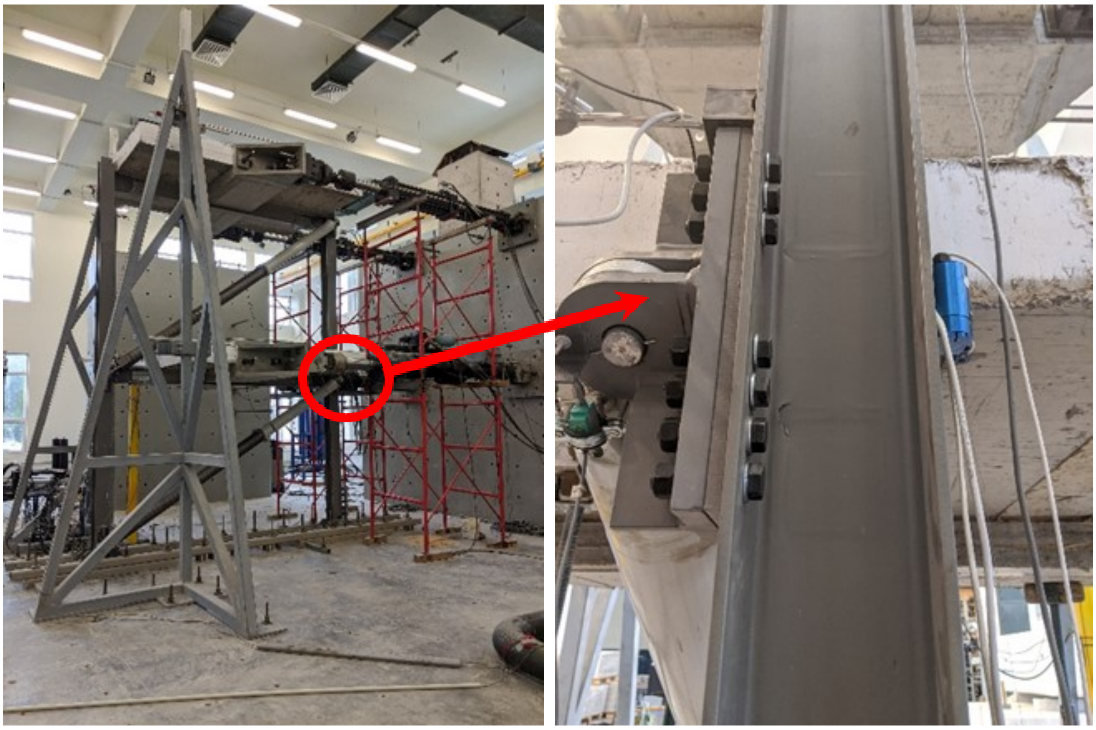

Fig. 6: Observed damage (fracture) on the column web at the first floor of the retrofitted 2D-frame at the end of the 2016 Norcia mainshock with scaling factor equal to 1.5 (PGA= 0.72g)

The PsD tests on the retrofitted 2D steel frame were stopped during the 2016 Norcia mainshock with a scaling factor equal to 1.5 (PGA=0.72 g), because torsion (out-of-plane response) was observed and fractures were detected on the column webs at the connections of the first and second floor (Figure 6). The BRBs exhibited an inelastic response with energy dissipation. However, the connections of the dissipative devices with the column are crucial to prevent local damage to occur and endanger the global dissipation capacity of the retrofitted structural system.

The preliminary conclusions that can be drawn from the response of the tested steel structures in HITFRAMES are as follows:

- Masonry infills significantly augment the lateral stiffness and strength in steel bare frames;
- The response of double-layered infills in steel frames differs from the response of the counterpart infills in reinforced concrete (RC) framed buildings. As a result, existing models used to simulate the response of infills in RC structures are not adequate to reliably predict the response of steel infilled frames;
- Buckling restrained braces are a cost-effective means to retrofit existing vulnerable steel frames, provided that the connections to the beam-column connections are rigid. ■