SERA
Seismology and Earthquake Engineering
Research Infrastructure Alliance for Europe

DELIVERABLE

D17.1 - Overall summary of TA for public outreach

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Summary

The SERA project, funded by the European Union within the Horizon 2020 Research and Innovation programme under grant agreement No.730900, involved in the Transnational Access (TA) activities 44 User Groups composed by 261 EU and extra-EU talented researchers out of more than 500 of them involved in the three calls for proposals.

TA Users are integrated in the scheduling of the Research Infrastructure (RI) during the execution programme of each project, from the design and construction of the specimen, to instrumentation, experimental testing and interpretation of the experimental results, receiving from the staff of the RI all the support needed to carry out their project. A support team is allocated to each user on a daily basis, to develop and execute the test programme, including appropriate technicians for test model fabrication, instrumentation, etc. The infrastructure facilities are well prepared for hosting external researchers who, during their stay, are integrated with the permanent staff, from whom they receive technical and scientific assistance. After receiving the necessary training, users are able to fully participate in the test preparation, execution, data acquisition and results interpretation.

Figure 1: SLABSTRESS project @JRC Research Infrastructure

Figure 2: SERA-SILOS project @EUCENTRE Research Infrastructure

The 1st year of SERA has been characterized by several activities related to the Transnational Access (TA) framework, such as the implementation of the web portal for the proposal management, the definition, publication and advertising of the first 2 calls for proposals, the nomination of the TA Selection and Evaluation Panel (TA-SEP). A tight schedule was imposed both to the Research Infrastructures (RIs) and to the first born User Groups in order to have a sustainable activities calendar in the next phases of SERA TA. All projects within each call required, in fact, the constitution of a strong User Group, the definition and preparation of an innovative proposal, the evaluation and selection of the best projects and the real campaign implementation. The evaluation criteria considered to select the best proposals are listed hereafter:

- Fundamental Scientific and Technical value and interest
- Originality and innovation
- Quality of proposing team
- Importance for public safety
- Importance for European standardisation
- Importance for European integration and cohesion
- Importance for sustainable growth
- Importance for European competitiveness
- Importance and relevance to TA facility's own scientific interest
- Synergies and complementarities with other TA tests
- Previous use of TA facility by any in the user team
- Cost and feasibility according to TA facility
- Availability of similar infrastructures in any of the users' countries

SERA TA FACILITIES
• ELSA Reaction Wall, JRC, Ispra (IT)
• Shake Lab Bearing Tester and Shake Table, EUCENTRE, Pavia (IT)
• AZALEE Shake Table TAMARIS/CEA, Paris (FR)
• LNEC-3D Shake Table LNEC, Lisbon (PT)
• STRULAB Reaction Wall, University of Patras, Patras (GR)
• EQUALS Shake Table, University of Bristol, Bristol (UK)
• DYNLAB Shake Table IZIIS, Skopje (MK)
• Centrifuge University of Cambridge, Cambridge (UK)
• EUROSEISTEST and EUROPROTEAS, Aristotle University, Thessaloniki (GR)
• Array Seismology NORAR, Kjeller (NO)

Table 1: SERA TA Research Infrastructures

The 3rd call for proposals was launched in 2018, leading to the allocation of all remaining resources initially foreseen. Announcing the last call at about half-way of SERA produced a one year and a half time frame before the project conclusion, allowing the last involved User Groups to effectively coordinate with the RIs, define in detail the research to be implemented and carry out the experimental tests. Unpredictably, the world sanitary emergency referred as COVID-19 exploded in the city of Whuan, in the Hubei province of the People's Republic of China in December 2019 (month 32 out of 36 of SERA). The disease expanded and evolved in pandemic, progressively involving also EU countries starting from the last week of January 2020. Such world emergency produced delays in some of the final activities, therefore, some RIs, at the time of editing of this document, are still dealing with the last experimental activities, data-processing and experimental results interpretation, while access to the facilities is in most of the cases still not possible. In order to make available a complete and detailed description of all the activities carried out within the SERA TA framework, possibly not compatible with the submission date of this document, an integrated and open-access publication will be produced in the next months. The publication will be the “Proceedings of the Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe – SERA Project –“, published by EUCENTRE and advertised through the SERA (http://www.sera-eu.org/en/home/) and SERA TA (https://sera-ta.eucentre.it/) web portals.

In the following tables, the projects selected across the three calls for proposal and the hosting infrastructure are listed.

PROJECTS SELECTED IN THE 1st CALL FOR PROPOSALS

Number of Project	Title of Project	Hosting Research Infrastructure
1	EQUFIRE – Multi-hazard performance assessment of structural and non-structural components subjected to seismic and fire following earthquake by means of geographically distributed testing	JRC
2	SLAB STRESS – SLAB STructural RESponse for Seismic European Design	JRC
3	Dynamic testing of variable friction seismic isolation devices and isolated systems	EUCENTRE
4	SE.RE.M.E. – SEismic REsilience of Museum contEnts	CEA
5	FUTURE – Full-scale experimental validation of steel moment frame with EU qualified joints and energy efficient claddings under near fault seismic scenarios	CEA
6	(Towards the) Ultimate Earthquake proof Building System: development and testing of integrated low-damage technologies for structural and non-structural elements	LNEC
7	Seismic Response of Masonry Cross Vaults: Shaking table tests and numerical validations	LNEC
8	ARISTA – Seismic Assessment of ReInforced Concrete frames with SmooTh bArs – Proposals for EC8-Part 3	STRULAB
9	ARCO – Effect of Axial Restraint on the Seismic Behaviour of Shear-Dominated COupling Beams	STRULAB
10	Seismic Response of Novel Integral Abutment-Bridges	University of Bristol
11	Statistical verification and validation of 3D seismic rocking motion models	University of Bristol
12	RE-BOND – REsponse of as-Built and strengthened three-leaf masONry walls by Dynamic tests	University of Bristol
13	Influence of the floor-to-wall interaction on the seismic response of coupled wall systems	IZIIS
14	Seismic behaviour of anchored Steel Sheet-Piling (SSP) retaining walls: experimental investigation, theoretical interpretation and guidelines for design	University of Cambridge
15	STILUS – Structure-Tunnel Interaction in LiqUefiable Sand	University of Cambridge
16	IMPEC – On the broadband synthetic sIgnals enhanceMent for 3D Physic based numerical analysis, the EUROSEISTEST Case study	EUROSEISTEST and EUROPROTEAS
17	Blind beamforming in array processing	NORSAR

Table 2: Projects selected within the 1st call for proposals

PROJECTS SELECTED IN THE 2nd CALL FOR PROPOSALS

Number of Project	Title of Project	Hosting Research Infrastructure
18	SEismic Response of Actual steel SILOS (SERA-SILOS)	EUCENTRE
19	Seismic Testing of Adjacent Interacting Masonry Structures (AIMS)	LNEC
20	HybrId Testing of an Existing Steel FRAme with Infills under Multiple EarthquakeS (HITFRAMES)	STRULAB
21	NSFuse: Ductile steel fuses for the protection of critical nonstructural components	University of Bristol
22	SEeismic BEhavior of Scaled MOdels of groin VAults made by 3D printers (SEBESMOVA3D)	University of Bristol
23	Investigation of Seismic Deformation Demand, Capacity and Control in a Novel Self-Centring Steel Braced Frame (SC-CBF)	IZIIS
24	Seismic Behaviour of Rigid Pile Inclusions	University of Cambridge
25	COSMO:Change Of Seismic MOtion due to pile-soil kinematic interaction	University of Cambridge
26	Dynamic Soil Structure Interaction: Three-dimensional Time-domain Analysis of Field Model Scale Experiments	EUROSEISTEST and EUROPROTEAS
27	"SISIFO"Seismic Impedance for Soil-structure Interaction From On-site tests	EUROSEISTEST and EUROPROTEAS
28	Ambient and forced vibration techniques for improving design and performance assessment of structures with consideration of soil-structure interaction	EUROSEISTEST and EUROPROTEAS
29	Seismic SITE effects in sedimentary basins from 3D physics-based numerical modeling (SITE3D)	EUROSEISTEST and EUROPROTEAS
30	Comparison of rocking on rigid and compliant base using the EUROPROTEAS real-scale facility	EUROSEISTEST and EUROPROTEAS
31	Seismic tremor detection in Greece using small aperture arrays	NORSAR
32	The velocity model up to 300 km deep using NORSAR array data (Baltic Shield) based on P and S receiver functions	NORSAR
33	Joint processing of seismo-acoustic array data as tool to discriminate between man-made explosions and earthquakes	NORSAR

Table 3: Projects selected within the 2nd call for proposals

PROJECTS SELECTED IN THE 3rd CALL FOR PROPOSALS

Number of Project	Title of Project	Hosting Research Infrastructure
34	Seismic performance of multi-component systems in special risk industrial facilities	EUCENTRE
35	SHAking Table testing for Near Fault Effect Evaluation (SHATTENFEE)	University of Bristol
36	SSI-STEEL: Soil-Structures Interaction effects for STEEL structures	University of Bristol
37	INfills and MASonry structures protected by deformable POLyurethanes in seismic areas (INMASPOL)	IZIIS
38	Resonant metamaterial-based earthquake risk mitigation of large-scale structures and infrastructure systems: assessment of an innovative proof-of-concept via medium-size scale testing	EUROSEISTEST and EUROPROTEAS
39	"DYMOBRIS" Dynamic identification and Monitoring of scoured BRIdgeS under earthquake hazard	EUROSEISTEST and EUROPROTEAS
40	SOil Frame-Interaction Analysis through large-scale tests and advanced numerical finite element modeling (Acronym: SOFIA)	EUROSEISTEST and EUROPROTEAS
41	Earthquake Spectral Provisions and Urban Fragility Evaluation	NORSAR
42	Beamforming of aftershock strong-motion time-histories recorded on the ICEARRAY for earthquake source studies	NORSAR
43	Investigation of (micro)seismicity of the Laptev Sea using a small-aperture array	NORSAR
44	Design, location and processing of a regional array in SW Portugal - Europe	NORSAR

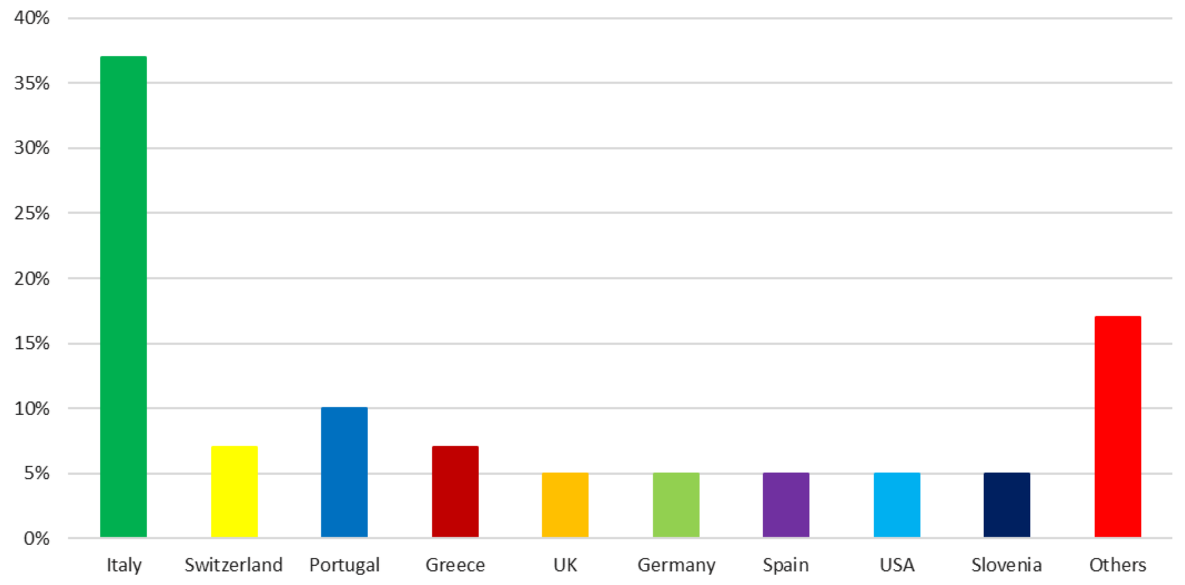
Table 4: Projects selected within the 3rd call for proposals

Research Infrastructure	Facility	Total TA Projects	Projects Assigned in the 1st call	Projects Assigned in the 2nd call	Projects Assigned in the 3rd call
JRC	ELSA	2	2	0	0
EUCENTRE	SHAKE LAB	3	1	1	1
CEA	AZALEE	2	2	0	0
LNEC	LNEC-3D	3	2	1	0
University of Patras	STRULAB	3	2	1	0
University of Bristol	EQUALS	7	3	2	2
IZIIS	DYNLAB	3	1	1	1
University of Cambridge	Centrifuge	4	2	2	0
Aristotle University of Thessaloniki	Euroseistest & Europroteas	9	1	5	3
NORSAR	Array seismology	8	1	3	4
		44	**17**	**16**	**11**

Table 5: Distribution of projects per TA facility

Proposals have been submitted by heterogeneous User Groups, composed by both universities and private companies often in joined applications, coming from 31 different countries. In the following graphs, the percentages of the candidate User Groups for the involved countries are shown. Data refer to all received projects, i.e. the sum of accepted, reserve and not accepted.

Proposing Researchers (261) origin in the 1st call



Others (<5%): Belgium (0,38%), Denmark (0,77%), China (0,38%), Cyprus (0,77%), France (3,07%), Netherlands (1,53%), Luxembourg (0,77%), New Zealand (1,15%), Turkey (0,77%), Croatia (4,21%), Camerun (0,77%), Austria (0,38%), Romania (1,92%)

Figure 3: Proposing Researchers origin – 1st call

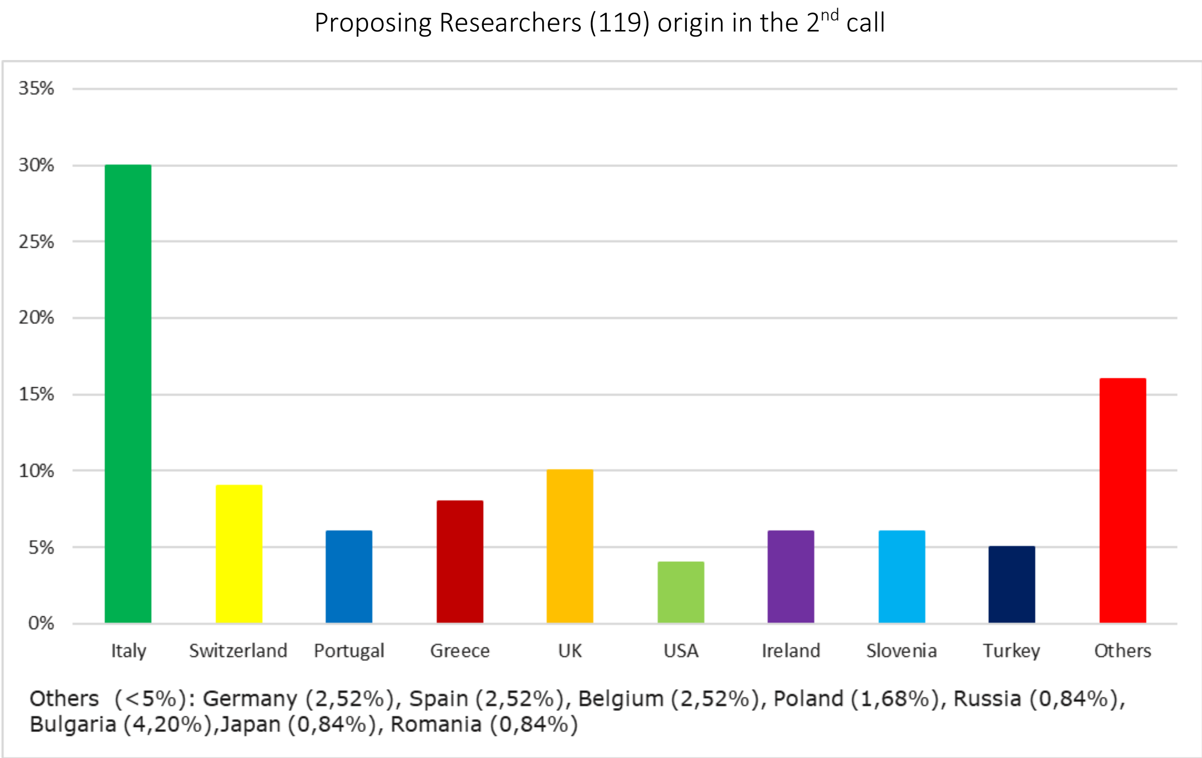


Figure 4: Proposing Researchers origin –2nd call

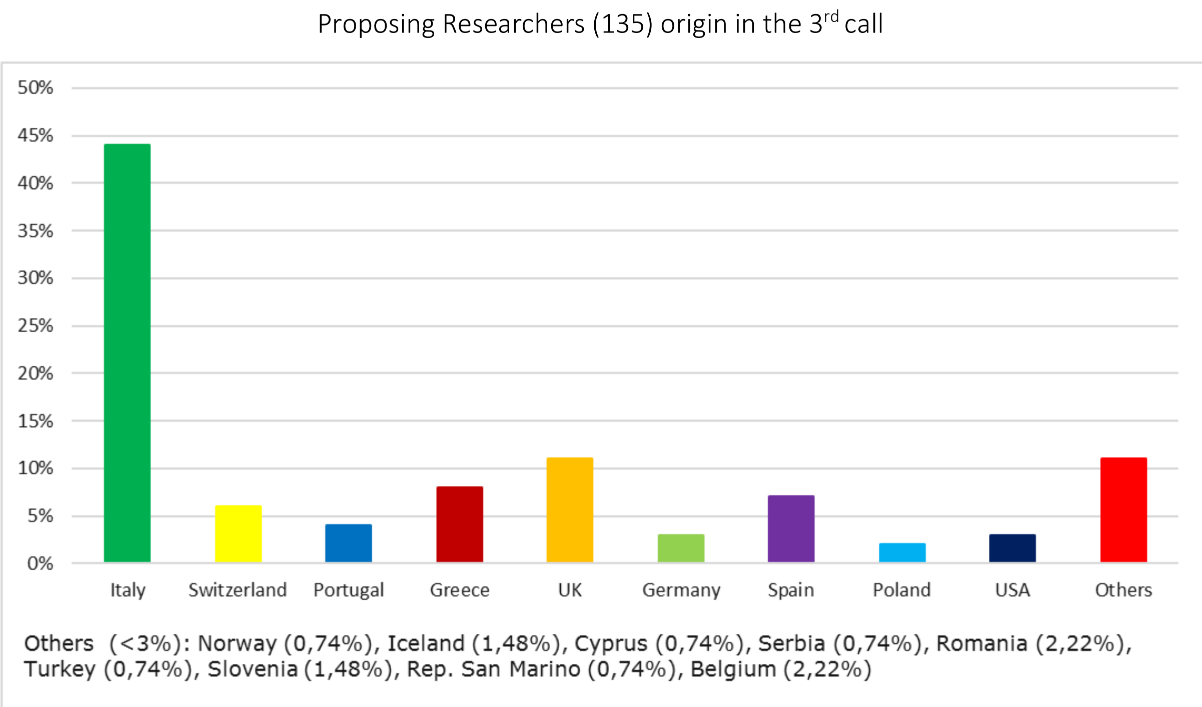


Figure 5: Proposing Researchers origin – 3rd call

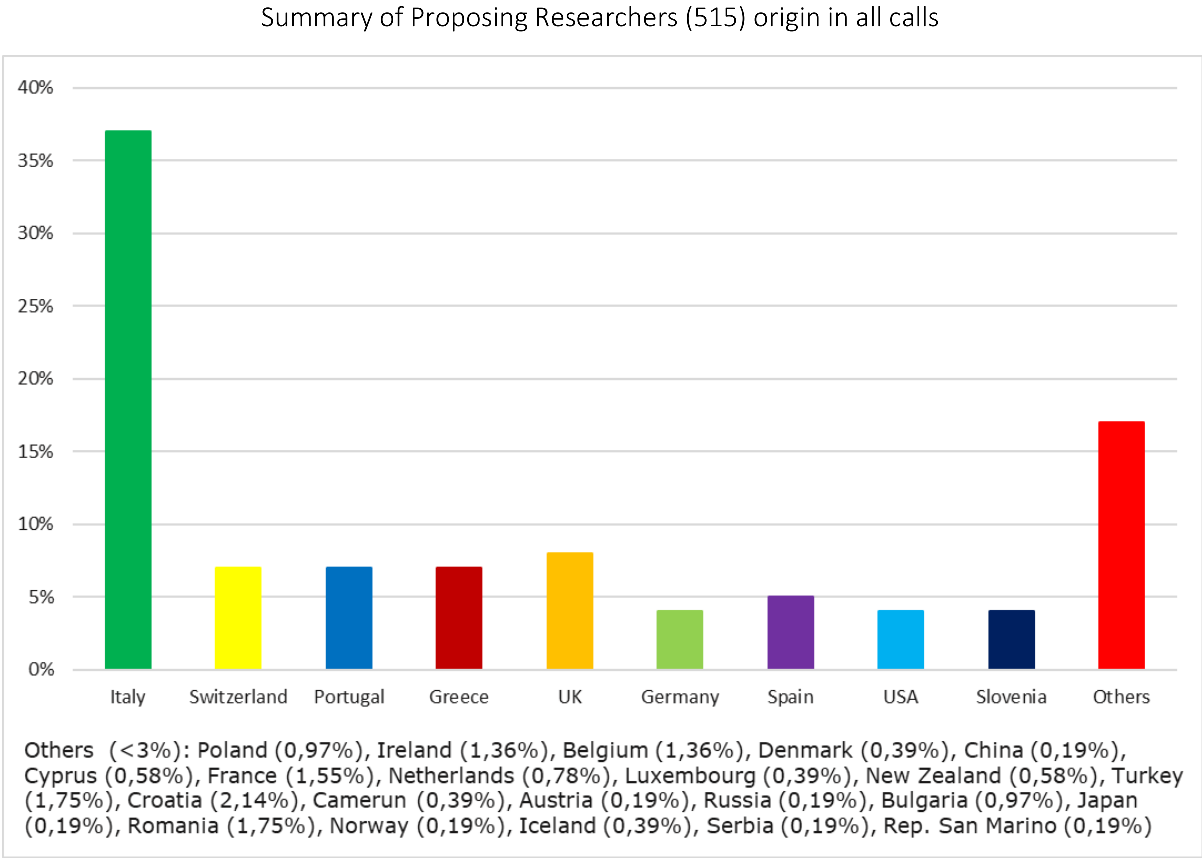


Figure 6: Proposing Researchers origin – all calls

As shown in the projects overview in the next chapters, the selected proposals addressed a very wide spectrum of topics, ranging from the development and implementation of the most advanced testing techniques, such as dynamic hybrid and geographically distributed testing, to the vulnerability of existing historical buildings, industrial facilities, bridges, to design code improvement and large database analysis. From Figure 7 to Figure 12, few pictures of some of the implemented activities are shown.

Figure 7: Full-scale grain steel silo tested both in fix base and seismic isolated configuration on the shaking table

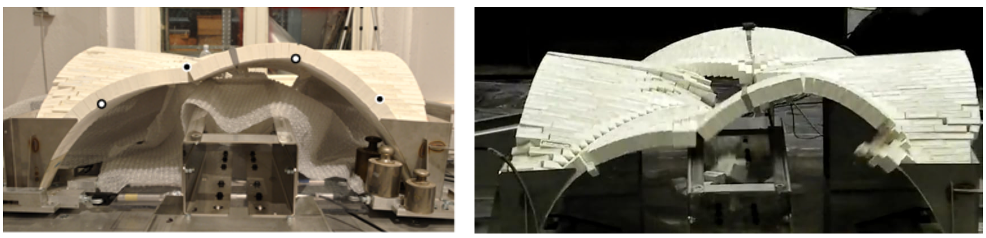


Figure 8: Masonry cross vaults shaking table tests

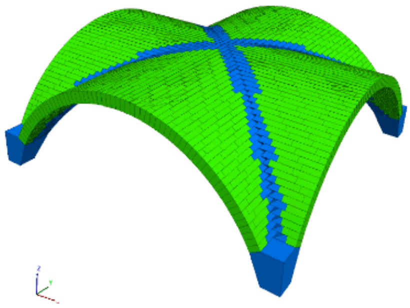


Figure 9: Masonry cross vaults numerical modeling

Figure 10: Investigation of the seismic resilience of museum contents through shaking table tests

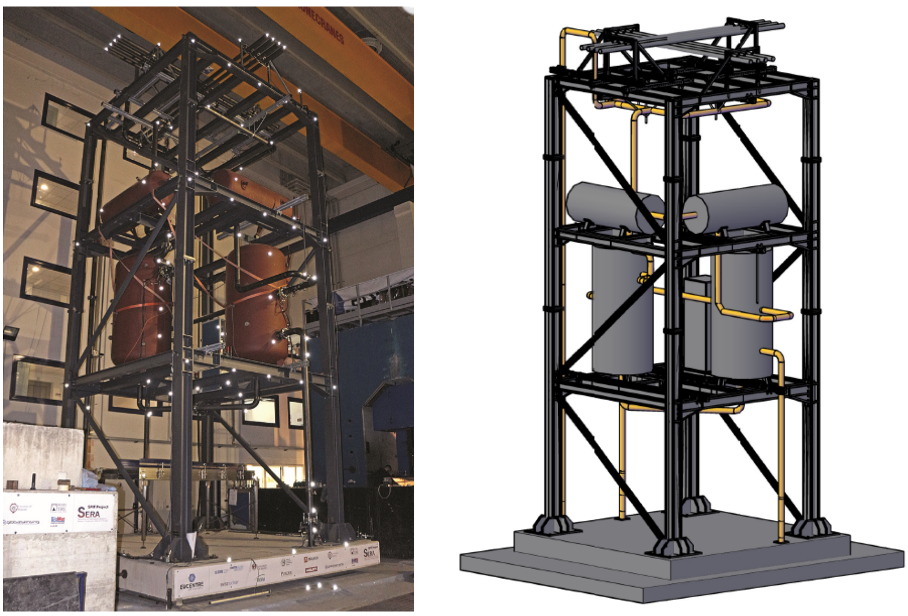
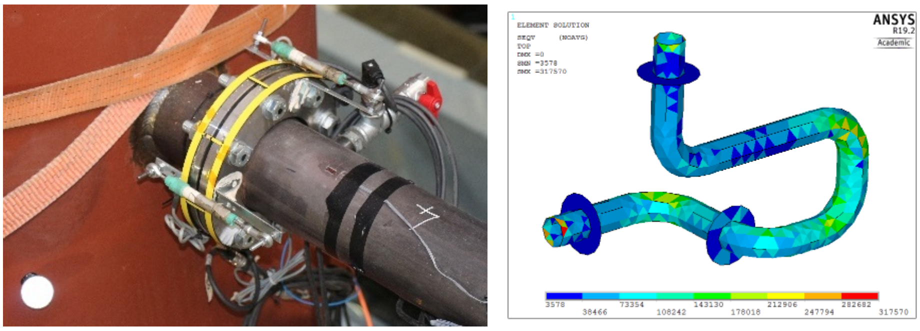


Figure 11: Investigation of the seismic performance of multi-component systems in special risk industrial facilities



(a) (b)

Figure 12: (a) Traditional (potentiometers, strain gages) and innovative (optic fibers, optical markers) instrumentation applied to a tank-piping-flange system; (b) 3D numerical modeling of a piping trunk

In Table 6 and Table 7, all received proposals have been categorized by the testing technique considered, and by type of specimen or analysis. While the testing technique is pretty related to the number of available facilities offering a certain equipment and their foreseen access units, the type of specimen is very well balanced among 8 categories.

TESTING TECHNIQUE

	1st call	2nd call	3rd call	Total
Shaking Table	15	9	9	33
Reaction Wall	12	1	0	13
Numerical Simulation	1	3	4	8
Centrifuge	2	3	0	5
Bearing Tester System	1	0	0	1
Field	1	7	3	11

Table 6: Received proposals organised by testing technique

TYPE OF SPECIMEN/ANALYSIS

	1st call	2nd call	3rd call	Total
Mixed	8	0	0	8
Reinforced Concrete	6	0	1	7
Steel	3	3	0	6
Masonry	5	2	1	8
Anti-Seismic Devices	2	2	2	6
Waves Propagation	3	4	6	13
Soil-Structure Interaction	2	9	3	14
Non-Structural	3	3	3	9

Table 7: Received proposals organised by type of specimen/analysis

As shown in Table 7, all main typologies have been considered, ranging from existing structures to innovative proposed concepts, and to non-structural elements too, in line with the progressively increasing attention of the last years. Non-structural elements represent in fact most of the construction cost of typical buildings. Such components constitute a relevant portion of the losses in recent earthquakes worldwide. Moreover, there is in many cases still lack of seismic design provisions, resulting in damage at early stages for shakes of smaller magnitude compared to the design level of the structure itself. Their damage or failure can still result in the reduction or total loss of usability of the building, thus indicating the extreme importance of a proper consideration and design of such non-structural elements.

Across the implemented projects, new as well as existing and historical structures have been considered. It is worth to remember that more than half of the existing structures in Europe are nowadays more than 40-50 years old, thus characterized by poor or absent seismic design, and likely with a not negligible resistance reduction due to ageing and natural and artificial repeated stresses.

The Transnational Access of SERA has been also the occasion to implement, test and improve the most advanced testing techniques representing the state-of-the-art of the laboratory capabilities. Hybrid testing, i.e. the test of a whole structural system split in a numerical sub-system and one or more physical specimens, has been implemented in many different projects. The implementation was done in different fashions, such as with fast dynamic test execution, to effectively consider the response of rate-dependent physical components (e.g. curved surface isolation devices), or with geographically distributed test conduct, taking advantage of numerical and experimental capabilities of more than a single Research Infrastructure. Furthermore, not only the seismic loading, but multi-risk scenarios which included fire loading have been successfully implemented.

Not only common and most advanced testing techniques have been considered within the projects; also the use of innovative metamaterials, currently used and still object of research in different fields, have been recently investigated and implemented for seismic protection. Metamaterials based elements have been recently considered for isolation of building against bulk waves in vertical direction, for which traditional isolation systems might not fulfill the requirements, by the implementation of so-called metafoundations. In the TA framework, metabarriers have been investigated and tested, aiming at reducing the Rayleigh seismic waves thus protecting buildings and aggregates.

Finally, TA researches addressed topics from other perspectives too, from the analysis of large existing seismology databases, to the current design provisions and their improvement, which is one of the main connection points between research and design in the everyday practice.

In the following chapters, a brief overview of all selected projects carried out within SERA TA framework is reported. More details and the whole projects and results description will be available in the next months in the open-access "Proceedings of the Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe – SERA Project –", published by EUCENTRE, which will be advertised through the SERA (http://www.sera-eu.org/en/home/) and SERA TA (https://sera-ta.eucentre.it/) web portals.

Project #1 – JRC RW – EQUFIRE – Multi-hazard performance assessment of structural and non-structural components subjected to seismic and fire following earthquake by means of geographically distributed testing

Many historical events (e.g. the 1096 San Francisco, 1923 Tokyo, 1995 Kobe, 1999 Turkey, 2011 Tohoku and 2011 Christchurch earthquakes) have shown that, after an earthquake, fire may be triggered by earthquake-induced rupture of gas piping, failure of electrical systems, etc. The structural fire performance can then deteriorate because the fire acts on a previously damaged structure. In addition, the earthquake may have damaged fire protection elements and the fire can spread more rapidly if compartmentation walls have failed. This is particularly relevant for steel structures as the high thermal conductivity of elements with small thickness entails quick temperature rise with consequent fast loss of strength and stiffness.

The effects of seismic and fire actions have been traditionally studied separately because: i) the inherent issues related to each action are quite complex per se; ii) researchers and practitioners are typically specialised in one particular field; iii) experimental facilities have been conceived to reproduce one of the two actions; iv) full-scale tests are very expensive and feasible in very few facilities; v) there is lack of numerical codes capable of performing fire following earthquake (FFE) analysis at low computational cost.

Most of the works in literature involve numerical simulations on steel moment resisting frames (CEN EN 1998-1, 2004; Kinnunen and Nylander, 1960; Nielsen, 1998; Muttoni, 2008) and only a few of them are dedicated to buckling-restrained and conventional brace systems, e.g. CEN, EN 1992-1-1 (2004) and Pinto et al. (2007) that developed a framework for evaluating the post-earthquake performance of steel structures in a multi-hazard context that incorporates tools for probabilistic structural analysis under fire and seismic loads. Experimental studies have been performed on single elements (Fardis, 2009), beam-column joints made of filled steel tubes (Hueste and Bai, 2007), and full-scale reinforced concrete frames (ACI-ASCE Committee 421, 2015). The study of literature reveals that several numerical studies on the post-earthquake fire behaviour of structural components have been carried out without being supported by comprehensive experimental research. Moreover, works on non-structural components are also very limited.

Therefore, the EQUFIRE project aimed to provide experimental data to study the post-earthquake fire performance of steel frame structures. The project studied a steel frame building with concentric bracings by seismic pseudo-dynamic tests of a real-scale one-storey frame at the ELSA Reaction Wall and tests of single elements subjected to fire following earthquake at the furnace of the Federal Institute for Materials Research and Testing. The experimental results serve to study the response of structural and non-structural components, and their interaction with different fire protection systems, to scenarios of fire following earthquake, with a view to providing sound experimental evidence and knowledge for improving existing design guidelines and future standards.

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Project #2 – JRC RW – SlabSTRESS – SLAB Structural RESponse for Seismic European Design

Flat slab concrete buildings for office, commercial and residential use are built in many countries, but their behaviour under seismic and gravitational action is not yet fully understood. Many studies have been undertaken in North America and Asia, but European research is lagging behind and the current version of Eurocode 8 (CEN EN 1998-1, 2004) does not cover the design of buildings with flat slab frames used as primary seismic elements. The SlabSTRESS (www.slabstress.org) project was therefore launched at the ELSA Reaction Wall of the Joint Research Centre, within the Transnational Access activities of the SERA project.

Design of flat slab frames in Europe developed mainly in North-European non-seismic countries (Kinnunen and Nylander, 1960; Nielsen, 1998; Muttoni, 2008). The specifications of Eurocode 2 'Design of concrete structures' (CEN EN 1992-1-1, 2004) consider the design of flat slabs and punching verifications for the effects of gravity loading. Eurocode 8 'Design of structures for Earthquake resistance' (CEN EN 1998-1, 2004) does not include specific rules for flat slabs. The scientific community has expressed the aspiration to advance the knowledge and develop adequate code provision (Pinto et al., 2007; Fardis, 2009).

For the time being, design is carried out considering the provisions given by Eurocode 8 for secondary elements coupled with a primary dissipative earthquake resistant system; the former must bear gravity loads at the maximum design lateral deformations reached by the latter. These deformations are calculated for the design actions on the primary system, multiplied by the behaviour factor. In addition, the code specifies that the secondary elements must give a contribution lower than 15 % of the total stiffness of the structure.

Research in North America produced a wide database of tests and code specifications for flat slab design for gravity combined with seismic loads. A set of results is shown in Figure 13 for tests on interior slab-columns connections.

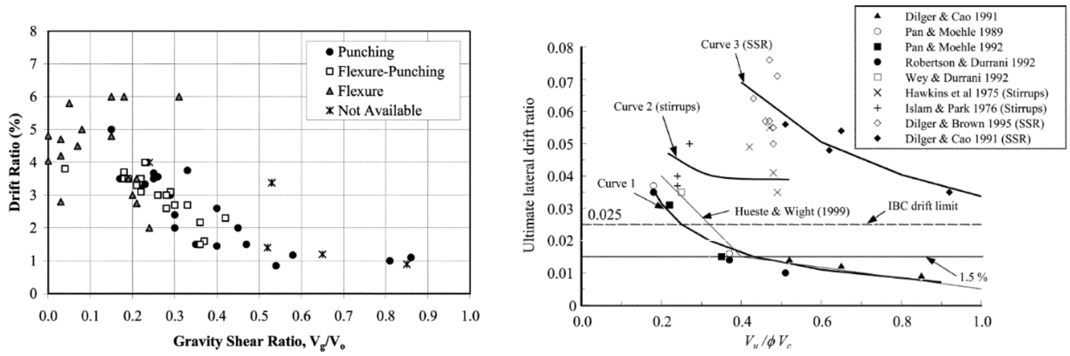

Figure 13: Ultimate drift capacity and gravity shear ratio. Test results for interior connections without transverse reinforcement (left) (Hueste MB, Bai JW, 2007) and test results without and with transverse reinforcement (ACI-ASCE Committee 421, 2015) (right)

Experimental activity in Europe started on slab-column connections under cyclic loading. Research at EPFL (Drakatos et al., 2016) tested full-scale slab-column connections without transverse reinforcement to compare the effects of monotonic and cyclic loading, different gravity shear ratios and reinforcement ratios. For slabs subjected to low gravity loads, and for lower reinforcement ratios in particular, lateral drift cycles led to reduction of flexural strength and ultimate drift capacity when compared to monotonic tests.

Researchers at FCT/UNL in Portugal have developed a test setup (Almeida et al., 2016) to test flat slab-column connections, with realistic conditions of slab continuity, under combined gravity loading and reversed horizontal cyclic drifts. Besides specimens without punching shear reinforcement, a series of specimens with punching shear reinforcement and solutions to enhance the deformation capacity, such as stirrups (Almeida et al., 2019), headed studs (Isufi et al., 2019; Isufi et al., 2020), post-installed bolts (Almeida et al., 2019), fibre-reinforced concrete (Gouveia et al., 2019) and high-strength concrete (Inácio et al., 2020) have been tested with promising results. Isufi et al. (2020) studied the numerical models of flat slab frames calibrated on these experimental results. Although the test setup of FCT/UNL overcomes some of the limitations of past tests on specimens that represent only the hogging moment region of the slab, testing full-scale specimens is more realistic. Furthermore, the tests at FCT/UNL have been limited to interior slab-column connections.

Previous tests of real-scale multi-storey flat-slab buildings are very limited. Coelho et al. (2004) carried out pseudo-dynamic tests at the ELSA laboratory on a three-storey building with only one bay in each direction (7.0 m and 4.0 m respectively). The connections had overhangs along two of the four sides (1.5 m and 1.25 m respectively) and the floors were 0.3 m thick waffle slabs with thick slab around the columns extending in plan four times the slab thickness. The columns were rectangular, 0.3 m × 0.5 m reduced to 0.3 m × 0.4 m at the last floor. For the 475 years return period earthquake (ultimate limit state) the structure reached a displacement of 162 mm at the second storey (1.64 % drift) with cracking around the columns. In a following test for the 2000 years return period earthquake, a failure in the test set-up caused the jacks to pull the structure to failure and a drift capacity of 4.3 % was reached. Heavy damage in the slab around the columns was accumulated at different floors and the top floor slab was nearly detached from the column at two connections.

Fick et al. (2017) tested under cyclic lateral loading a flat-slab structure with two floor panels in plan and three storeys (plan dimensions: 9.1 m × 15.2 m, height: 9 m, slab thickness: 0.18 m). The spans measured 6.1 m in each direction, with 1.5 m overhangs all around the perimeter. The columns were square (46 cm × 46 cm). This resulted in a structure with only two types of connection, edge and corner, with an important influence of the overhangs. The test was stopped after a connection punched at 3.3 % drift.

The North-American code ACI318 (ACI-ASCE Committee 421, 2015) and design philosophy (Hueste and Bai, 2007) are based on a database of results mainly on individual connections, with or without shear reinforcement (Figure 13). A central aspect for slabs without transverse steel is that ultimate drift ratio reduces with increasing gravity shear ratios (GSR). The GSR is the ratio between the acting vertical shear force and the punching shear resistance according to ACI318 (Hueste and Bai, 2007). Transverse steel increases the ultimate drift ratio of connections, with some reduction of ultimate drift capacity with the gravity shear ratio. Hence, the results for the two tests above must be compared considering the gravity shear ratio ensuing from the specimen design and the gravity loading. Fick et al. (2017) report a GSR value of 0.21, while a nominal value close to 0.4 is calculated for Coelho et al. (2004). For a gravity shear ratio of 0.21 in Fick et al. (2017), ultimate drift values in the database (Hueste and Bai, 2007) range from 2.7 to 3.6 %. For gravity shear ratio 0.4 in Coelho et al. (2004), the ultimate drift is between 1.5 and 2.6 %. It should be considered that the structure in Fick et al. (2017) had a particular geometric configuration and a part of waffle slabs.

This experimental background shows the need for a comprehensive experimental study on a real scale structure. The SlabSTRESS programme was proposed with the aim of providing support for the European design codes by studying the response of a full-scale two-storey building for seismic and gravity actions, different types of connections (corner, edge and interior), the redistribution of load effects in floors with realistic boundary conditions, different longitudinal reinforcement layouts, with and without transverse steel reinforcement. The aim of the testing phases presented here is twofold: first to verify, for actions corresponding to the serviceability and ultimate limit states, the seismic performance of flat slab frames in a structure with earthquake resistant ductile walls (tests A); secondly to study the performance of the system beyond the design displacements (tests B). The first aim corresponds to verifying the requirement that the structure should bear gravity loads in correspondence of the maximum lateral displacement reached for the design action. The latter provides understanding of the deformation capacity of the system.

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Project #3 – EUCENTRE BTS – Dynamic testing of variable friction seismic isolation devices and isolated systems

Seismic isolation is the prominent seismic protection technology for buildings, bridges and generally different kind of structures. It aims to significantly, or in many cases totally, reducing structural/non-structural seismic vulnerability under severe earthquake ground motions. Seismic isolation is implemented with isolation devices of two basic types: rubber bearings with lead core, and friction pendulum devices. Steel-based friction pendulum devices are gaining increasing popularity over rubber isolators and are being widely used in several applications worldwide. This is mainly due to the versatility in design and production, and their easier implementation in practice. The variability of the seismic demand is much less in friction pendulum devices. Moreover, torsional eccentricity imposed by the distribution of friction pendulum devices along the isolation interface is less significant compared to the rubber devices, hence their re-centring capacity is higher.

The main focus of the proposed project is to improve friction pendulum isolation devices by imposing variable friction properties along the sliding surfaces. Although there are several theoretical studies in literature on the theory and analysis of variable friction devices, there is no developed technology yet. The variable friction devices that will be developed within the scope of the proposed project will be designed and produced by the industrial partner TIS. The validation of the proposed concept will be performed through characterization tests following an EN15129-like type testing protocol, then moving to seismic tests once satisfactory preliminary results are obtained. The dynamic response of the isolated system under uniaxial seismic excitation will be observed. An improved definition of ground motion intensity measures (IMs) will be developed, particularly in near-fault conditions, as well as the corresponding hazard-compatible record selection procedures for friction based isolation devices. Finally, non-linear numerical models will be implemented and calibrated through the experimental data for predicting the isolator and system response accurately, and then, based on a larger analytical study (i.e., simulation-based) propose design procedures for structures isolated with variable friction devices.

Project #4 – CEA ST - SE.RE.ME. – Seismic Resilience of Museum contEnts

Earthquake actions pose an immense threat to museums and their contents. For example, during the recent earthquakes on 21 July 2017 and 24 March 2020, in the island of Kos (Greece) and in Zagreb (Croatia), respectively, severe and widespread damage were reported in the archaeological museums of the cities. The earthquakes extensively damaged the sculpture exhibition, where many artefacts were dislocated, leaned against the walls, or overturned. In the case of heavy and slender sculptures, the overturning mechanism, apart from damaging the sculptures themselves, poses a serious threat to other standing exhibits in the gallery and the visitors. It is, therefore, of paramount importance to rely on methods and tools for characterizing the seismic risk of museum artefacts and, where necessary, proposing cost-efficient protective measures.

The study of the seismic behaviour of museum assets and the investigation of novel and cost-effective risk mitigation schemes for improving the seismic resilience of European museums has received little attention in the past. The H2020-SERA project Seismic Resilience of Museum contEnts (SEREME) aims to fill this gap through extensive shake table tests on real-scale busts and statues. The aim of this large experimental campaign is to understand the seismic response of statues and busts and then develop novel and cost-effective risk mitigation schemes for improving the seismic resilience of museum valuable contents. The study focuses on the investigation of the seismic response of two real-scale marble roman statues and three busts of roman emperors standing on pedestals of different types and size. Both isolated and non-isolated artefacts are considered, while two new and highly efficient base isolation systems, tailored to art objects, are tested dynamically under seismic scenarios. The tested isolators include a pendulum-based system and devices with Shape Memory Alloy (SMA) wires. Furthermore, the importance of the hosting building is examined. Specifically tailored, numerical models of varying complexity, for single and two-block rocking systems, will developed for the needs of this study and will be assessed with the aid of the experimental results of the SEREME campaign.

The study of the seismic vulnerability of museum artefacts, especially of slender, human-formed statues, is related to the research on the dynamic response of rocking rigid blocks. The dynamic characteristics of the hosting structures are also important. This is evident from the fact that, on many occasions, damage to the structure was reported leaving the exhibits intact and vice-versa. Although the problem is coupled, it can be studied looking separately at the structure and its contents, provided that the contents are not attached to the building. The seismic response of building contents is a topic of growing interest, since it is directly related to seismic loss assessment and earthquake community resilience. Building contents can be either attached to the structure, or may consist of objects that are simply standing. Museum exhibits belong generally to the latter category, while free-standing components are often studied as rocking objects. The response of the latter components is sensitive to acceleration and velocity-based quantities and also their geometry. Today, there is lack of standards, while the existing approaches in the literature are general in concept and do not sufficiently address the mechanisms of the variety of rocking objects. The reliability of such analytical approaches has also been scarcely validated with extensive testing, such as shake experiments.

Common structural analysis and design methods require the assessment of stress resultants and displacement-based quantities. Additionally, the three-dimensional rocking response has not received the interest it deserves. On the other hand, building contents, in most cases, consist of objects that are freestanding. There are recent works in which the seismic response of freestanding contents is investigated, e.g. Berto et al. (2013), Chiozzi et al. (2015) and Di Sarno et al. (2017), among others. Museum exhibits belong to the latter category and the free-standing components are often studied as rocking objects, hence their response is sensitive to acceleration and velocity-based quantities. Geometrical properties of the artefacts also have significant effects on the dynamics and earthquake response of the components. Additionally, when free-standing components are placed on a pedestal, made either from marble or steel, their dynamic response is more difficult to be predicted with simplified methods.

The seminal analytical work carried out on the seismic response of rocking objects in the 60's by Housner (1963) stimulated several quantitative studies that have focused primarily on numerical solutions, e.g. Zhang and Makris (2001), Voyagaki et al. (2013), Dimitrakopoulos and Fung (2016), Diamantopoulos and Fragiadakis (2019). Recently, however, Purvance et al. (2008) carried out extensive experimental and numerical studies in order to investigate the overturning response of symmetric and asymmetric blocks with both simple and complex basal contact conditions and also proposed block overturning fragilities. Similarly, ready-to-use fragility curves were proposed by

Konstantinidis and Makris (2009) through a comprehensive experimental program on full-scale freestanding laboratory equipment located on several floor levels. The latter studies, however, focused primarily on the behaviour of single blocks. Dual block systems were first studied numerically by Psycharis (1990), while the recent experimental work of Wittich and Hutchinson (2017) studied asymmetric free-standing component configurations. It is worth noting that, for rocking rigid objects, such as artefacts, the response, at least in terms of overturning motion, is size-dependent, thus the scaling of the specimens is not possible and the experimental tests should be based on full-scale specimens.

Nowadays, considering the huge earthquake losses registered in the recent earthquakes, especially in the Mediterranean region, it is also deemed imperative to propose viable and cost-effective seismic protection measures for free-standing statues and busts. Podany (2015) discussed a range of retrofitting measures based on the best practice followed by the J. Paul Getty Museum in Los Angeles, in California, where a newly developed base isolation device has been employed. However, the effectiveness of the use of seismic isolators for light weight components should be further investigated to characterize thresholds for accelerations and horizontal displacements for an adequate seismic protection of the artefacts.

The H2020-SERA SEREME project aims to fill the experimental gaps highlighted above and to include comprehensive shake-table tests of several configurations of free-standing and base isolated statues and busts. The freestanding artefacts are installed either directly on the marble floor, or on a pedestal. The objective of the campaign was to give insight on the seismic behaviour of statues and busts as well as to evaluate the effectiveness of two different seismic risk mitigation systems. A total of 5 pairs of real scale marble artefacts were tested, 3 busts installed on marble pedestals and 2 statues. Seven different testing arrangements (also termed “Configurations”) were considered during this experimental campaign and more than 400 seismic tests were performed. Two innovative base isolation devices were utilized as retrofitting remedies. The first system is a combination of friction pendulum isolators (Castellano et al. 2016), a system designed for light components. The second system is a newly developed device utilizing shape memory alloy wires in the horizontal plane. The isolation devices tested are patented systems, namely ISOLART® PENDULUM &ISOLART® SMA, which are manufactured by the Italian company FIP Mec, a member of the User Team. In order to obtain a direct evaluation of the isolator effectiveness, for each test configuration, pairs of two similar artefacts were tested together in an isolated and a non-isolated arrangement. The shake-table tests were carried out considering uniaxial, biaxial and triaxial earthquake loadings at increasing amplitudes. In order to evaluate the influence of the frequency content and the directionality of the seismic excitation, 13 different waveforms were applied to the shake table (8 uni-directional motions, 3 bi-directional motions and 2 tri-directional motions). Regarding the instrumentation, the artefacts motions were recorded using accelerometers, gyroscopic and displacement sensors.

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Project #5 – CEA ST – Full-scale experimental validation of steel moment frame with EU qualified joints and energy efficient claddings under near fault seismic scenarios

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 behavior of MRFs is largely influenced by the behavior of the joints; (ii) the loading protocol adopted to qualify/test beam-to-column joints are representative of cumulative and maximum rotation demands imposed by far-field seismic ground motions 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 focused mainly on the testing of sub-assemblage, 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. Furthermore, there is a lack of knowledge of the behavior of steel joints when subjected to NF seismic demand. Additionally, earthquake reconnaissance studies have shown that the ratio of vertical-to-horizontal peak ground acceleration can be larger in NF than in far-fault seismic events. Near-fault strong motions tend to increase the inelastic demand on structural steel members and joints. On the other hand, 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 use of material, constructional costs and encouraging the adoption of more sustainable solutions. The use of such ductile non-structural components will also lower the earthquake-induced losses arising from claddings.

The experimental project FUTURE aims to qualify the behavior of steel moment frames equipped with three different types of detachable beam-to-column Joints. The project investigates also the influence of energy efficient ductile non-structural claddings under NF seismic scenarios. Therefore, a two-story 50-ton scale 2/3 model was then designed and manufactured.

The main findings expected from the tests are as follows:

1. Provide design rules for steel frames under combined effects of horizontal and vertical components NF, which are yet not considered in the design standards for new and existing structures;
2. 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. 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 beams;
4. Demonstrate the efficiency of fully detachable dissipative beam-to-column joints, which allow easy replacement once the seismic damage is occurred;
5. Contribute with new background data for 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;
6. 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. 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 interstory height.
8. Develop experimentally-based fragility relationships for such ductile non-structural components, which tend to minimize the earthquake losses due to claddings.

Project #6 – LNEC ST – (Towards the) Ultimate Earthquake proof Building System: development and testing of integrated low-damage technologies for structural and non-structural elements

The seismic design of modern buildings follows a performance-based approach targeting Life-Safety criteria. Structures are conceived as ductile systems where inelasticity is concentrated within discrete plastic hinge regions as per capacity-design principles and this primary structure is designed for allowing buildings to sway and stand during earthquakes and people to evacuate. As continuously highlighted after past seismic events, notwithstanding these buildings performed as expected depending on the seismic intensity level they were subjected to, the Life-safety design philosophy is no longer acceptable due to the significant damage to both structural and non-structural components which can result

(Figure 14, left). Repairing traditional structures may be uneconomical when compared with the cost of demolition and re-construction of the entire building system, in terms of money and time.

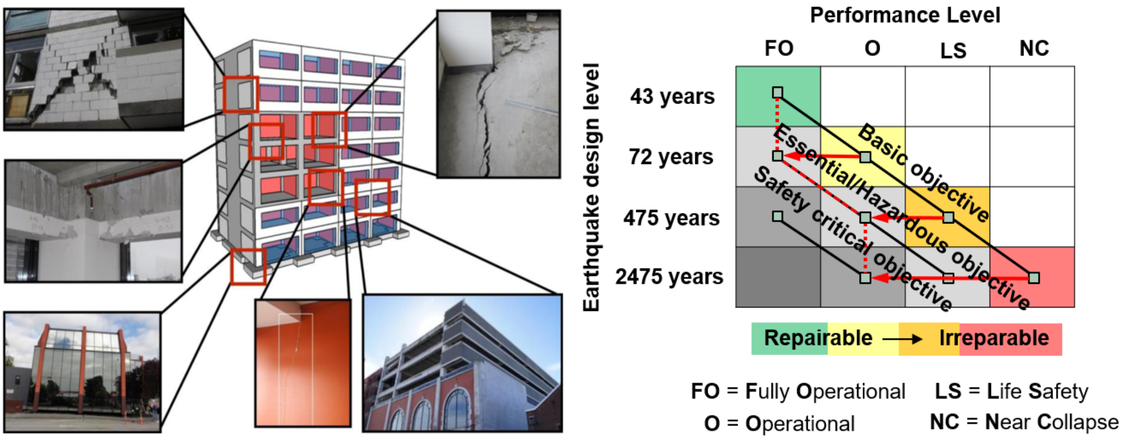

Figure 14: Left – typical damage occurring in modern RC buildings (Johnston et al., 2014); Right – seismic performance design objective matrix of SEAOC Vision 2000 (1995) modified to achieve a damage-control design philosophy (Pampanin, 2012, 2015)

The high socio-economic impact of moderate-to-strong earthquakes and the increased public awareness of seismic risk have facilitated the acceptance and implementation of damage-control technologies, whose development is nowadays demanded. Performance-based design criteria and objectives need a shift towards a low-damage design approach (Figure 14, right) and technical solutions for engineers and stakeholders to control the performance/damage of the entire building system, including superstructure, foundation systems and non-structural elements. Moreover, this new design philosophy should be considered to define an ultimate "earthquake-proof" building system (Pampanin, 2012, 2015).

Apart from well-known innovative techniques such as base isolation and supplemental dissipative braces, more recently developed "low-damage" systems are receiving attention by the engineering community. These solutions are based on a combination of self-centering and dissipative capabilities and are called as PRESSS (PREcast Seismic Structural System) technology for concrete (Priestley et al., 1999; Pampanin, 2005; Pampanin et al., 2010) and Pres-Lam (Prestressed Laminated) for timber (Palermo et al., 2005; Pampanin et al., 2006, 2013). Nevertheless, protecting the primary structure from extensive damage is not enough for the actual society expectation, whilst the structural skeleton should be "dressed" using low-damage non-structural components, i.e. exterior enclosures, partitions, ceilings, services and contents. Therefore, innovative technological solutions have been recently developed and studied with the aim of mitigating the damage to either vertical or horizontal elements (Baird et al., 2013; Tasligedik et al., 2014; Tasligedik and Pampanin, 2016; Pourali et al., 2017).

The integrated structural/non-structural system comprising all these low-damage solutions should represent the next generation of modern structures. However, notwithstanding initial studies on such type of integrated system (Johnston et al., 2014), more comprehensive investigations are required for demonstrating the high seismic capability of this building solution and refining the construction detailing. With this aim, as part of the H2020 SERA project, 3D shaking-table testing of a half-scale integrated low-damage system were carried out at the National Laboratory for Civil Engineering (LNEC) in Lisbon, Portugal. The project was proposed and developed with the aim of promoting a research effort within the European industry/community for the wider uptake of an integrated low damage building system, including skeleton and non-structural components for the next generation of buildings. An overview of the entire research programme is provided within this report, focusing on the description of the test specimen, on its construction/assembly phases as well as on the experimental setup and test and initial research outcomes.

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Project #7 – LNEC ST – Seismic Response of Masonry Cross Vaults: shaking table tests and numerical validations

The observation of damage caused by past seismic events demonstrates the high vulnerability of historic masonry buildings. Several types of mechanisms can be activated during an earthquake. The mechanisms that involve the horizontal structural elements are dangerous and fundamental for the seismic performance of buildings. Thus, these types of mechanisms should be better investigated (Rossi, 2015).

Widely spread among monumental masonry buildings (mainly in churches and palaces), masonry cross vaults are some of the most vulnerable horizontal structural elements. Acting as both a ceiling and a structural horizontal diaphragm with significant mass, vaults' mechanical behaviour affects the overall seismic response of buildings, in terms of strength, stiffness, and ductility. Moreover, their local damage and collapse may produce significant losses in terms of cultural assets and casualties.

Because of these reasons, the seismic assessment and the seismic vulnerability reduction of masonry vaults are interesting topics, which deserve attention and care by the research community. The need of care is associated to several open issues that researchers and practitioners have to face when dealing with masonry cross vaults. In fact, many authors highlighted the difficulties on analysing the complex 3D behaviour of existing masonry cross vaults. These structures may be damaged due to the interaction with adjacent structural elements or with the counteraction system (such as flying buttresses or foundations). Moreover, in general, there is not the possibility of knowing their thickness and the different sizes of cross vaults may lead to difficult comparisons from the structural point of view (Bertolesi et al., 2019). In the last twenty years, giant steps were certainly made in the safety assessment of masonry structures and the design of interventions in heritage buildings. However, there is still a lot to be done.

Most of the studies, in the past, were oriented to the description of the structural response of vertical masonry structures, disregarding the role of horizontal diaphragms. These were neglected in the analyses (since considered very deformable, such as the case of timber floors), or considered infinitely stiff (since substituted by, or reinforced with, RC elements). Conservation and safety issues pushed towards a different approach: on the one hand, the substitution of timber floors with RC floors, as well as the reinforcement of masonry vault with concrete "jackets" is not acceptable anymore; on the other hand, recent earthquakes showed that the introduction of excessively rigid diaphragms may compromise the structural response of the masonry building. Today, improved structural analyses and assessment procedures requires improved models for diaphragms. This is one of the most crucial issues in structural masonry modelling and analysis.

Another large quantity of past studies was oriented to the description of the behaviour of masonry arched structures (arches and vaults). These studies were mainly focused on the analysis of special buildings, such as churches and monumental structures, and were mainly based on the study of the equilibrium of rigid blocks, disregarding the deformability of such structures in the elastic and inelastic field and the limited strength of the material in compression. Moreover, as already stated, they considered the 2D behaviour of the arch/vault only, disregarding their 3D behaviour involving shear/sliding mechanisms. Today, such approaches should be improved, in particular for complex 3D vaults such as the ones considered in this research project.

Two PhD studies which have been recently developed, namely the work carried out by Gaetani (2016, 2017) and Rossi (2015, 2017), represent the starting point of this investigation work.

Gaetani's work, performed at the University of Sapienza and University of Minho, corresponds to a phased study based on a wide literature review, numerical analyses and experimental activities with the aim of an expedite assessment of the seismic capacity and the failure mechanism for groin vaults. Moreover, a standard limit analysis code was implemented. Rossi's research, performed at the University of Genoa, presents the experimental investigation of groin vaults, subjected to static actions, with the use of a small-scale mock-up.

Previous investigations, from the state-of-art until the experimental campaigns and the theory of scaled tests design lead up to the definition of the shaking table tests, performed at the National Laboratory for Civil Engineering (LNEC) in Lisbon, Portugal, in the framework of the transnational activities of the H2020 SERA project. The preparation and operation of the shaking table follows standard protocols to achieve the target motions, as proposed by Candeias et al. (2017).

In particular, three sets of shaking table tests were planned:

1. Tests on a 1:5 scale cross vault made of 3D-printed blocks assembled with dry joints (Rossi, 2015): to validate the efficacy of static tests on reduced scale mock-ups, performed in earlier studies, and to describe the seismic dynamic response of masonry vaults;
2. Tests on a 1:1 scale model of a brick unreinforced masonry cross vault: investigating the behaviour of brick masonry cross vaults under different seismic inputs, in terms of damage, displacement capacity and peak acceleration;
3. Tests on a 1:1 scale model of a brick reinforced masonry cross vault: to evaluate the effectiveness of reinforcing techniques to repair the vaults tested in b).

The originality and innovation of the proposed research lies in several aspects:

- Despite both the structural and architectural relevance of masonry cross vaults, only a few experimental tests were carried out and can be found in the literature;
- The test setup was designed in order to reproduce the diaphragm shear response of cross vault (which is very difficult to model dynamically). Moreover, since the setup considers the vault only, it allows to disregard the "filter effect" produced by its supporting structures (piers or columns) on the dynamic action applied;
- The innovativeness of the proposed strengthening technique, since based on highly efficient and compatible materials. The efficiency of the technique was never tested on masonry cross vaults in the dynamic field.

The theoretical interpretation of the results, aims not only to calibrate advanced non-linear numerical models but also to validate/propose safety assessment procedures to be implemented in European codes.

The broader impacts of the research regard the safety and preservation of historical masonry buildings in the European earthquake prone areas. It is well known that policies for the preservation of cultural heritage, in the structural field, are based on two main lines of development: the improvement of safety assessment procedures and the improvement of strengthening techniques. The idea is that, for heritage buildings, the safety should be guaranteed with "minimum intervention", which is one of the pillars of conservation theory. In this framework, the more reliable the safety assessment procedures are, the less interventions are needed; the more efficient the strengthening interventions are, the less interventions are required.

In conclusion, by improving the knowledge and the modelling/analyses approaches of vaulted masonry structures, this research contributes to a better safety assessment of heritage buildings and to a better design of strengthening interventions, thus contributing to an improvement of the safety and preservation policies of heritage buildings in the EU.

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Project #8 – STRULAB RW – ARISTA – Seismic Assessment of ReInforced Concrete frames with SmooTh bArs – Proposals for EC8-Part 3

Smooth (plain) bars are not used anymore as primary reinforcement of new concrete structures. The codes of most countries have banned them from such a use long since. Nonetheless, being common in old structures which are assessed for retrofitting, they enjoy the renewed interest of the structural engineering community. However, still little is known about the performance of structures with smooth bars in strong earthquakes. Lack of knowledge is not only due to the rarity of such extreme events. In the heyday of smooth bars, systematic research of the modern type and scale was unknown to structural engineering. Early works (1909-1912) seem today trivial demonstrations of the effectiveness of hooked smooth bars, while later studies were motivated by the emergence of ribbed (deformed) bars as a more advanced alternative; smooth bars were studied just to show that they were inferior to ribbed bars.

The gap in knowledge is to a good extent being filled nowadays, thanks to the renewed interest in smooth bars brought about by the recent emphasis on rehabilitation and re-use of old structures. Although numerous, the tests which are of interest to earthquake engineering have, so far, essentially been limited to quasi-static cyclic loading of single members – normally columns. However, the single or double cantilever specimens or the columns fixed at top and bottom against rotation listed in these two references do not represent well the columns of real multistorey buildings, in which vertical bars are continuous through joints and typically lap-spliced at floor levels. The three-storey, two-by-two-bay, asymmetric building, pseudodynamically tested at the ELSA lab in Ispra, IT for EU-funded project SPEAR ("Seismic Performance Assessment and Rehabilitation", 2005), was one of the very few seismic tests performed in the past on a (nearly) full-scale structure with smooth bars. However, it focused on aspects other than the type of bars: the torsional response to bi-directional earthquake, the effects of poor detailing or of column jackets consisting of Fibre-Reinforced-Polymer (FRP) or of concrete reinforced with ribbed bars, etc. Cyclic lateral load tests (2002) carried out at the University of Pavia on a three-storey, three-bay 2:3 scale plane frame without floor slabs focused on the vulnerability of exterior unreinforced beam/column joints, which failed at interstorey drifts as low as 1.6%, by diagonal compression in those joints and “push-out” action of the 180-deg hook of the beam’s compression bars. So, models developed for single members still await validation testing of near-full-scale specimens with layout and detailing representative of real-life structures with smooth bars.

A prime feature of old concrete buildings is the – typically short – lap-splicing of columns' vertical bars at floor levels, i.e., where plastic hinges form in strong earthquakes. In countries influenced in the past by British codes, lap-spliced column bars even had straight ends, without hooks; such detailing may be sufficient for gravity loads, but not for earthquake resistance. Because of these features and of the rapid loss of bond along smooth bars during cyclic loading, the structural engineering profession has doubts concerning the performance of old columns with smooth bars in earthquakes.

In order to put to test the conventional wisdom that structures with smooth bars are inherently vulnerable to earthquakes, to further our understanding of the seismic behaviour of RC frame structures with smooth bars and to support the development or validation of models, cyclic lateral load tests were conducted on a 2:3-scale three-storey one-by-two-bay RC frame structure with smooth bars in the columns. The detailing of bars, the testing program and the instrumentation focused on the behaviour of smooth bars during the test and its effect on local and global structural performance:

- the instrumentation captured the distribution of deformation along columns;
- strains in vertical bars were measured at column end sections and at the ends of lap-splices, in order to see whether they remained tensile after the cyclic decay of bond along bars;
- although most columns had their vertical bars lap-spliced at floor levels and at the connection to the foundation, for comparison, two diagonally opposite corner columns in building plan had continuous bars, from the footing to the roof;

after three half-cycles of inelastic deformation, the frame had both ends of three ground storey columns wrapped in FRP, before been subjected to larger amplitude cycles; the comparison of the FRP-wrapped columns to the unretrofitted ones extended to the middle storey, where columns were exposed to similar deformation demands as in the ground storey.

Project #9 – STRULAB RW – ARCO – Effect of Axial Restraint on the Seismic Behaviour of Shear-Dominated Coupling Beams

Reinforced concrete coupled walls are an efficient structural system for medium to tall buildings that provides large stiffness and strength against wind and seismic loads. The coupling of the individual wall units is typically provided by short and stiff coupling beams which deflect in double curvature with high shear stresses, and therefore are susceptible to brittle shear failures. At the same time, in regions of high seismicity, the coupling beams are required to possess large ductility and energy dissipation capacity. However, while a number of experimental programs have been performed to evaluate the ductility and complete cyclic response of coupling beams, the boundary conditions used in the tests deviate in an important detail regarding the boundary conditions encountered in real structures. Specifically, in coupled wall systems, the stiff walls and floor diaphragms restrain the elongation of the beams due to cracking under seismic loading, and this generates compression in the coupling members influencing their behaviour. Therefore, this type of beams is characterised by a shear-dominated response, being susceptible to brittle shear failures.

This research project intends to study the effect of axial restraint on the seismic behaviour of short coupling beams. To address the research goal, the experimental approach proposed focuses on testing to failure of four conventionally reinforced coupling beams with longitudinal reinforcement and stirrups. Such beams are common in pre-1970s coupled-wall structures and are particularly vulnerable to brittle shear failures as evidenced by past earthquakes. First, three large-scale nominally identical specimens RB1, RB2 and RB3 with variable level of axial restraint were studied under monotonic loading up to the post-peak regime. Furthermore, an unrestrained fourth beam (RB4) is tested under a large inelastic pulse in one direction followed by a push to failure in the opposite direction. This unconventional cyclic loading scenario can be associated with a near-fault pulse-type ground motion.

Project #10 – University of Bristol ST – SERENA – Seismic Response of Novel Integral Abutment-Bridges

In the last few years the Integral Abutment Bridge (IAB) concept has generated considerable interest among bridge engineers, not only for the newly built bridges but also in the retrofit of existing ones (Briseghella and Zordan, 2006) because of the benefits associated with the elimination of expansion joints and reduced installation and maintenance costs. Although not a new concept, its formulation dating back at least to the 1930s, it has been successfully employed to address long-standing structural problems frequently occurring in conventional bridge designs (Horvath 2005). Regarding number of applications, United States has the widest experience on IABs (Burke 1993) and it is reported that more than 13,000 such bridges (Maruri and Petro 2005) were built by the mid 2000’s. Nevertheless, a meaningful number of bridges within this family can be found in central Europe, mainly in Germany, Switzerland, UK, Austria, Luxembourg and France.

In view of the large number of realizations worldwide, one would expect that a consolidated design practice and guidelines would be available. On the contrary, indications are missing even in modern codes, in particular for the specific aspect of seismic design, e.g., Caltrans 1999; ATC 1996a, 1996b; Eurocode 8/2. This can be attributed, to a good extent, to the fact that from an analysis and design view point the structural continuity existing between deck, abutment wall and supporting piles makes essential a full consideration of soil–structure interaction (SSI) phenomena, an area which still requires specialized expertise. Moreover, the consideration of SSI is important also for service loads such as thermal loads. In fact, very high earth pressures can be generated on the abutment wall, which can further increase at the occurrence of the seismic action (England et al. 2000).

Regarding experimental studies, laboratory tests were performed on thermal load effects; Frosch et al. (2009) performed cyclic tests to investigate abutment-pile connections; Muttoni et al. (2013) executed push-pull tests on the transition slabs; Qian et al. (2016) studied the SSI for micropiles of a semi-integral bridge through shaking table tests. The experimental investigations of soil-structure interaction and the role of abutments in the case of seismic excitations are rare. Recently, a comprehensive joint research of several US universities (UNR, UCSD, UCB) devoted to seismic response of bridges with seat type abutments was completed. Saiidi et al. (2013) ran shaking table tests on large scale models of two-span and four-span bridges at the University of Nevada, Reno; Wilson and Elgamal (2009) ran shaking table tests to investigate the abutment contribution in the response.

SERENA project had the aim of developing a basic understanding of IABs under seismic loads through shaking table testing on: (a) the earthquake response of such systems, and (b) ways of minimizing associated demands using pertinent design solutions such as disconnecting (i) the pile heads from the cap, and (ii) the abutments from the backfill through a compressible foam inclusion, (c) settlement due to dynamic compaction effects in the backfill. To the best of the authors' knowledge, research on the above has been very limited. Findings from the proposed research may lead to the development of more robust provisions on IABs allowing the amendments on some limitation imposed on the use of such structural system.

The objectives of SERENA were:

1. to explore earthquake response of IAB's (mainly driven by Soil-Structure Interaction (SSI) between backfill, abutment, foundation and bridge structure) on a shaking table;
2. to assess different connection schemes between: (i) abutment and piles, (ii) abutment and backfill, using a variety of materials such as foams;
3. to explore the influence of vertical motion on earthquake response.

The above experimental results will allow firstly the development of simplified analysis methods and preliminary design criteria for IAB's that could be used in engineering provisions such as the Eurocodes, secondly the validation of numerical methods and constitutive soil models for simulating such systems, and thirdly the reduction of epistemic uncertainty in IABs design leading to lower safety factors and reduction in cost.

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Project #11 – University of Bristol ST – Statistical verification and validation of 3D seismic rocking motion models

In 1963, Housner (1963) published his seminal paper where he explained the remarkable properties of rocking structures: (i) the larger of two geometrically similar blocks can survive the excitation that will topple the smaller block, and (ii) out of two acceleration pulses with the same acceleration amplitude, the one with longer duration is more capable of inducing overturning.

Since then, the behavior of a simple, free-standing rigid rocking block has been systematically studied (Yim et al., 1980; Makris and Vassiliou, 2012). The dynamic behavior of assemblies or rocking bodies, such as multi-drum ancient columns (Konstantinidis and Makris, 2005) or rocking frames or walls (Papaloizou and Komodromos, 2009; Dimitrakopoulos and Giouvanidis, 2015), has also been studied. It was concluded that these assemblies are also remarkably stable when excited by earthquakes. Experiments show that the deterministic models of rocking motion are not easy to validate (Ma, 2010; Bachmann et al., 2016), thus necessitating a probabilistic treatment (Psycharis et al., 2013; Bakhtiary and Gardoni, 2016).

Rocking is treated as a 2D, in-plane, problem in most of the literature. Published research on the dynamic response of 3D rocking of rigid bodies is much more limited. In Koh (1990; 1991) the motion of a rigid cylinder under seismic excitation is studied. Other researchers studied the 3D response of ancient conical or cylindrical columns numerically (Ambraseys and Psycharis, 2011; Stefanou et al., 2011) or experimentally (Krstevska et al., 1996; Drosos, and Anastasopoulos, 2014). Makris et al. (2015) experimentally tested scaled models of uplifting bridges. These studies conclude that 3D motion (so-called wobbling) is present even under in-plane initial conditions and/or under uniaxial horizontal component ground excitation. Stefanou et al. (2011) proved this observation theoretically.

The 3D behavior of non-cylindrical bodies has also recently received attention. Konstantinidis and Makris (2007), Zulli et al. (2012), Chatzis and Smyth (2012) studied the motion of a 3D prism. Mathey et al. (2016) studied the influence of geometric defects on the 3D response of small-sized blocks. They concluded that blocks with imperfections are less stable than the theoretically perfect ones. Pappas et al. (2016) numerically explored the behavior of an ancient cylindrical column with a height of 6 m and a diameter of 0.66 m with the intension of defining proper ground motion intensity measures to characterize the rocking response of such structures.

Dynamic models used in the research discussed earlier are multi-degree-of-freedom (MDOF) models and assume unbounded 3D motion. They involve stepping or rolling rigid rocking bodies out of their initial position. This results to residual deformations. Thus, these models are suitable for equipment but not for structural components designed to uplift, because rolling out of the initial position would be prohibited for such structural components from the standpoint of seismic performance of the structures, they are a part off. Theretofore, Vassiliou et al. (2017) developed a simpler model in which a cylinder rocks and wobbles (rolls unsteadily) exclusively above the initial position of its base, without sliding or rolling out (i.e., a 3D inverted pendulum) (Figure 15, left). In this sense, the investigated model is a direct extension of Housner's model, which also constrains the rocking body to restore to its original position. Subsequently, the model was extended to include a slab, supported by four wobbling columns (Vassiliou, 2018) (Figure 15, right).

One of the main research gaps in the study of rocking motion (from the engineering point of view) is the lack of model validation. This has led the earthquake engineering community not to trust the existing rocking models. A series of papers has been published characterizing the rocking motion as “chaotic” (Yim and Lin, 1991; Jeong et al., 2003; among others) and employing non-linear dynamics concepts to study it. However, this work is based on idealized excitations that do not correspond to real earthquakes. Given that there is uncertainty in the ground motion itself, the engineering question is not whether the structural models can predict the response to a specific ground motion, but whether they can predict the statistics of the response to an ensemble of ground motions used for design. Based on the early work of Yim et al. (1980), Bachmann et al. (2018; 2017) validated the Housner rocking model and concluded that it is able to predict well the response of a block rocking in-plane. They compared the numerical and experimental empirical Cumulative Distribution Functions (CDF) of the maximum rotation angle when 100 ground motion with the same statistical properties were used as excitation. They concluded that the CDFs matched well. By performing a Kolmogorov-Smirnov test, they found that the rocking motion of a rigid structure is predictable in a statistical sense, and that the 1963 Housner numerical model can be used to predict it. However, this work is limited to planar rocking motion of specimens that were engineered to concentrate the impact forces on at the impacting corner. No sliding was observed, as the specimens were relatively slender.

The research gap that this project aimed to bridge is the statistical validation of 3D rocking models. This is necessary: first, to trust and calibrate the models that are used for the study of precious equipment, and second, to use rocking as an earthquake response modification technique.

More specifically, the objectives of the 3DRock project were:

a) To generate a dataset and to statistically validate numerical models of seismic response of unconstrained rocking objects (referred to as “Free Rocking” in this report)
b) To generate a dataset and to statistically validate numerical models of seismic response of rocking structures comprising columns supporting a rigid plate and constrained to wobble about their original position without being able to twist and without restraining tendons (referred to as “Wobbling Frame” in this report)

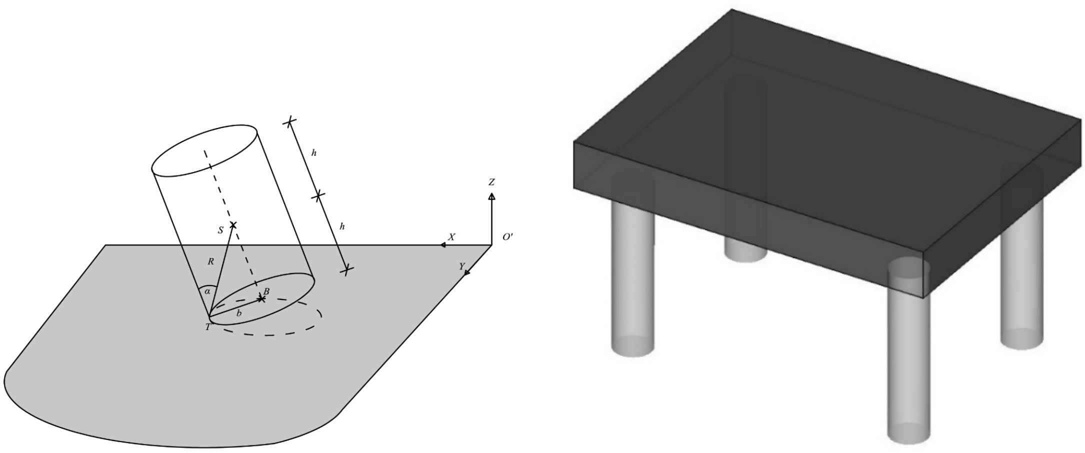

Figure 15: Left: Free rocking cylinder. Right: Wobbling frame

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Project #12 – University of Bristol ST – RE-BOND – REsponse of as-Built and strengthened three-leaf masONry walls by Dynamic tests

Three-leaf masonry walls are found throughout Mediterranean seismic-prone regions, especially for the area of L'Aquila, Italy. They are made of two external relatively slender stone leaves, typically un-connected through the wall thickness, and an inner core made of loose aggregates kept together by poor quality lime mortar. Past earthquakes, and more specifically the L'Aquila earthquake of April 6 2009, have shown the intrinsic vulnerability of this masonry typology, widespread in historical centres.

The problem is more evident in the presence of repeated cyclical actions over time, with unbundling of the entire wall before the mechanical resistance is achieved. Although delamination appears to be the most significant source of fragility, three-leaf walls show weak in-plane behaviour as well, depending on the weakest component material (mortar) as showed by Silva B. et al (2014). The in-plane behaviour becomes fundamental in walls strengthened by grout injections and by introducing connections between the outer leaves, as evidenced by Vintzileou et al (1995). Furthermore, the response of both as built and strengthened walls need to be fully investigated in order to understand to which extent their strength can be increased. The presence of a strong Vertical Ground Motion (VGM) could be relevant in Near Field (NF) earthquakes, which repeatedly decompress and compress the masonry wall, reducing the shear strength of the pier, as highlighted by A. Borri in "Costruzioni storiche e qualità muraria: problematiche e possibili interventi di consolidamento". Studies of the past on the evaluation of the masonry quality by A. Borri et al. (2010), S. Brusaporci et al. (2007), and L. Fanale et al. (2017), have shown the presence of three macrogroups of external leaf wall's types placed in the area of L'Aquila: a) stone masonry of small dimensions, mixed with natural or split pebbles and stones; b) stone masonry with lime mortar and sand mixed with stone flakes; c) block masonry made of squared stone. Figure 16 shows a typical aquilano apparatus for external leaf, using regular limestone (similar to the Poggio Picenze stone) and weak hydraulic mortar. The Filling Material (FM) is used to fill the wall between the two external leaves and is made of mortar and pebbles/waste materials. The exact composition of FM is not clear in the literature since it's always prepared randomly. The VGM could be significant in this kind of construction as FM tends to thrust with the presence of VGM.

The purpose of this project is to investigate the effects of earthquakes on three-leaf masonry walls with dynamic tests. More specifically, tests were thought to investigate: the influence of VGM on the behaviour of the as-built rectangular walls; the in-plane strength of rectangular and T-shaped as-built walls; the effectiveness of strengthening techniques.

The experimental campaign is part of Seismology and Earthquake Engineering Research Alliance (SERA) project. The project proposal is under the name REBOND (REsponse of as-Built and strengthened three-leaf masONry walls by Dynamic test).

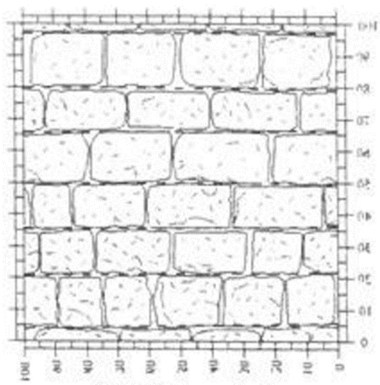

Figure 16: Aquilano apparatus for external leaves, by S. Brusaporci (2007)

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Project #13 – IZIIS ST – Influence of the floor to piers interaction on the seismic response of coupled wall systems

Buildings with RC walls have been one of the most frequently and successfully used structural systems to resist seismic action. Nevertheless, in several cases (in particular during the recent earthquakes in Christchurch and Chile) some walls were heavily damaged, requiring high cost of repair or even demolition.

In many such structures the damage was due to poor understanding of the complex interaction between the floor system and wall piers. This problem was therefore recognized as one of the priority research goals within the Virtual International Institute for Performance Assessment of Wall Systems (NSF SAVI Wall Institute) joining together most of the leading researchers in the field from all over the world.

However, the experimental studies of RC coupled walls, which could significantly contribute to the clarification of these response mechanisms, are very rare. Due to the specific geometry and high resistance of walls, experiments have required large and costly experimental facilities. This problem becomes particularly relevant when floor to walls system interaction is studied.

The shape and the reinforcement of the piers provided a realistic representation of the floor-pier interaction as well as realistic boundary conditions for the floor system.

Two 1:2 scale 3-story coupled walls were tested within the project. The first test was performed on 13th -14th February 2019, and the second one on 23rd -24th August 2019. Description of the tests with brief results will be provided in this report.

The improved numerical models and the findings of the experiments will be used to propose adequate design procedure, which might be included into the future versions of seismic codes, in particular, Eurocodes. The proposed research is compatible with the work of the project partner UCLA, particularly in the frame of NSF SAVI Wall Institute, which has been established with the main goal to improve the design practice for RC walls and wall systems, and to develop the appropriate tools to achieve this goal. Through the partners of the Institute, the results of the project will be efficiently disseminated.

Project #14 – University of Cambridge C – Seismic behaviour of anchored Steel Sheet-Piling (SSP) retaining walls: experimental investigation, theoretical interpretation and guidelines for design

Steel Sheet-Piling (SSP) walls are frequently adopted as retaining structures in quays and wharves, as they may be more economical with respect to concrete caissons or other types of retaining structures.

In current design practice, SSP retaining walls are usually designed using simple calculation tools, based on Sub Grade Reaction Models (SGRM) or Limit Equilibrium Methods (LEM). If the seismic action is introduced following a pseudo-static approach, then the same methods can be used, at least in principle, for the seismic design of SSP walls. However, depending on wall flexibility, contact properties at the soil-wall interface, strength properties of the system, and assumptions on both the seismic action (amplification/phase shift of accelerations within the soil) and the stress distribution into the soil, these methods can lead to highly over-conservative or un-conservative predictions. Numerical Finite Difference (FD) and Finite Element (FE) methods often provide more economical solutions than SGRM or LEM methods. However, numerical modelling of geotechnical systems under dynamic conditions is quite complex, requiring careful consideration of many factors (e.g.: the definition of the input motion and of suitable boundary conditions and, most of all, the choice of an adequate constitutive model for the soil), and not always readily accessible for the practicing engineer.

Following the Performance-Based Design methodology, in recent years a new design concept has started to be explored for the seismic design of retaining structures. This is based on the idea that the structure can experience permanent displacements during the design earthquake, provided that the related damage does not exceed some allowable threshold, defined on the basis of a given required performance level. Within this context, the attention has progressively moved from the computation of the maximum internal forces in the retaining structure under an equivalent system of pseudostatic forces, to the prediction of the permanent displacements experienced by the structure under a given acceleration time history (earthquake). To this end, the Newmark's sliding block procedure has been successfully applied to the evaluation of permanent displacements of both gravity and cantilevered walls, and the critical acceleration has been proved to control both the maximum internal forces in the structural members and the final permanent displacement.

A possible extension of these procedures to the seismic design of anchored SSP walls requires a better understanding of the dynamic behaviour of these systems to identify the main factors affecting their response under seismic actions. In this respect, centrifuge tests carried out on reduced-scale physical models provide a powerful tool to investigate the seismic response of geotechnical systems in idealised situations, in which the initial state of the soil, the hydraulic and kinematic boundary conditions and the dynamic input motion are controlled and well defined.

This project aimed to provide a better insight into the seismic behaviour of anchored SSP walls, focusing on the main physical mechanisms affecting the distribution of earth pressures on the wall during the earthquake, the possible increase of internal forces in the structural members and the progressive accumulation of permanent displacements. To this end, four centrifuge tests were carried out at the University of Cambridge, considering different layouts and input earthquakes. The experimental results allowed to understand how the critical acceleration of the soil-wall system governs the behaviour of SSP walls, both in terms of maximum internal forces and permanent displacements, and how the activation of different plastic mechanisms can affect the overall observed behaviour. Moreover, based on the experimental outcome, new theoretical methods have been explored for the seismic design of anchored SSP walls.

Project #15 – University of Cambridge C – STILUS – Structure-Tunnel Interaction in Liquefiable Sand

Relatively shallow and light underground structures, such as urban tunnels, may cross liquefiable sand deposits and liquefaction has induced floatation and large uplift to sewer pipes or open-cut tunnels in some recent strong earthquakes. It is worth noticing that in urban area shallow tunnels are likely close to the foundations of buildings and easily interact with them during earthquakes (i.e. Soil-Structure-Underground Structure-Interaction, SSUSI). Nevertheless, the reciprocal influence of a tunnel and an adjacent building in presence of soil liquefaction has not been investigated in the literature yet. This problem appears rather important considering the rapid extension of the built environment, both above- and underground, to areas that may be subjected to seismic-induced soil liquefaction.

The research investigates the problem of the dynamic interaction of an underground structure and a building founded in liquefiable sand. To this aim a series of centrifuge tests are carried out on a reduced scale model of a rectangular tunnel embedded in a liquefiable layer of sand, with and without a model building founded in proximity, as a typical case of a cut-and-cover tunnel in urban environment. Furthermore, tests will be carried out on models where the liquefiable ground is improved by adding nanomaterials (laponite) to increase locally the fine content. The position of the improved ground is varied in the models: either a layer of sand beneath the tunnel or a layer of sand beneath the building is improved.

The mechanism of the uplift behaviour of underground structures, focusing on the influence of the degree of liquefaction, the external forces acting on the underground structure and the deformation of the liquefied ground, has been investigated in past studies with reference to free ground surface conditions. Recent centrifuge testing on the behaviour of buildings founded in liquefiable ground layers have, however, shown that smaller net excess pore pressures are generated within the liquefiable layer under a structure by increasing the contact pressure and height/width ratio of the building. Other studies have shown the reciprocal influence of adjacent buildings, affecting non-uniform settlement during liquefaction.

How the uplift mechanism of an adjacent underground facility is influenced by the presence of the building and how the development of a mechanism beside the building due to the floating of the underground structure can affect the tilt and settlement of the building are both aspects that have not been investigated in the literature.

This problem appears rather important for the earthquake engineering community considering the rapid extension of the built environment, both above- and underground, to areas that may be subjected to risk of liquefaction. Hence the study intends to contribute to the wider topic of the resilience of urban environment to natural hazards.

The models are created at reduced scale and tested accordingly at N-times increased g-level in the Turner Beam Centrifuge at the Schofield Centre of the University of Cambridge.

The ground layer consists of homogenous Hostun sand at a relative density of about 45%-50%. This is dry pluviated in thin layers through an automatic hopper system. During the model preparation, arrays of miniature pore pressure transducers (PPTs), piezoelectric and MEMS accelerometers are deployed at the desired locations. Displacement transducers (LVDTs) are used to measure the settlements at different locations.

During model preparation a model tunnel is embedded in the sand layer (see the list of tests later on). The rectangular model tunnel is made using an extruded section of aluminium alloy. Rough dimensions are provided in the sketches of figure 1. The rectangular tunnel represents a section of a metro station tunnel that can accommodate two separate platforms. The soil cover above the tunnel corresponds to an embedment ratio C/HT = 1.

A linear-elastic sway frame (SDOF) made of aluminium is founded in the sand layer in most tests (see the list of tests later on). Rough dimensions are provided in the sketch in Figure 17. The figure shows the centrifuge models including the sway frame (i.e. the building), that is located beside the tunnel. The sway frame is fitted with accelerometers to capture its horizontal sway as well as rocking behaviour. Two vertical accelerometers are positioned on the base of the structure to enable measurement of rocking angles. A displacement transducer is located at the base of the frame to measure vertical settlement.

The sand layer needs to be saturated before testing. To avoid the incompatibility between the dynamic and diffusion time scaling laws, a high viscosity aqueous solution of hydroxypropyl methylcellulose (HPMC) is used to saturate the sand layer, with a viscosity N times larger than water.

Considering the need to study the displacement field around the tunnel, high speed photogrammetry is used in the tests. Hence stems the choice to use a transparent side container. A rigid container with a Perspex window is used. It is known that this type of model container may cause boundary effects affecting the response, particularly when liquefaction is reached. Therefore, a soft material called Duxseal® is used on the walls, to minimize the boundary effects: it has been showed that it can reduce the stress wave reflections by about two-thirds.

In total 4 centrifuge models were tested (Figure 17), according to the following sequence:

1. Tunnel only, in window box;
2. Tunnel and adjacent building;
3. Tunnel and adjacent building, ground treatment below the tunnel floor;
4. Tunnel and adjacent building, ground treatment below the building.

A servo-hydraulic earthquake actuator is used to apply near-sinusoidal earthquake motions to the centrifuge model. The amplitude of the signal will be increased during the test, until soil liquefaction is achieved.

Time histories of acceleration and pore pressure in the ground are recorded during shaking, along vertical and horizontal arrays. Similarly, displacement time histories at a few points at ground surface (settlement) and on the sway frame (settlement, horizontal displacement and tilt) are monitored.

PIV Photogrammetry enables a deep insight on the triggering of uplift and the evolution of the mechanism. This is very useful for the calibration of a numerical model to simulate the centrifuge tests and to reliably extend later the study to different geometrical conditions.

Comparing the time histories measured in model #1 and #2 will enable to highlight the influence of tunnel-building interaction on the displacements field induced by soil liquefaction.

In model #3 a volume of sand below the tunnel is improved by pouring the sand in a laponite/water suspension during model making. An amount of laponite corresponding to 1% of the dry weight of sand is mixed to water in concentration equal to 5%.

In model #4 a similar improved volume is located beneath the foundation level of the sway frame. A comparison among results of tests #2, #3 and #4 enables to discuss the effectiveness of laponite injection in the ground to reduce the effects of sand liquefaction on both the underground structure and the building.

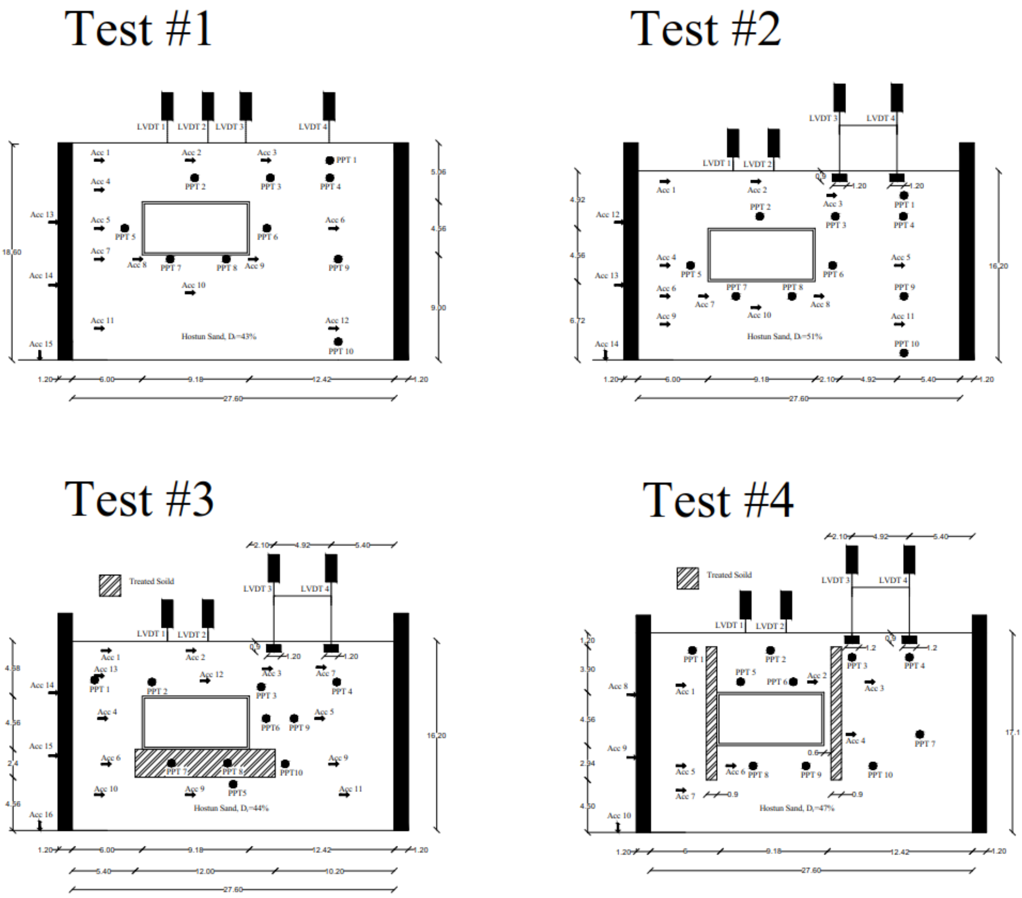

Figure 17: Schematic drawings of the four centrifuge models

Project # 16 – EUROSEISTEST – IMPEC – On the broadband synthetic signals enhancement for 3D Physic based numerical analysis, the EUROSEISTEST Case study

In the past two decades, the seismic hazard analysis and vulnerability assessment took progressively advantage of the ever-increasing computational power available (Paolucci et al., 2014). This outstanding technological and numerical progress seemingly broke through the evergreen and most stringent bottleneck in computational seismology: the impossibility to solve the complete source-to-site seismic wave propagation problem in a single-step analysis. All the ingredients (i.e. source, path and site effects) can nowadays naturally be convolved in one-step all-embracing analysis, capable of predicting a realistic seismic wave-field and to explain the observed time-histories in sedimentary deposits (local scale, i.e. approximatively 1-10 km of characteristic length) and/or at the continental scale (i.e. 100 km or greater, De Martin, 2011). Once shattered these computational barriers, a new holistic philosophy took place, driven by the deterministic modelling of the physics underlying each aspect of the earthquake phenomenon, for more accurate sensitivity analyses and uncertainty quantification of models and related parameters. In spite of the inherent complexity and the huge dimensions of those computational models, their power is essentially embodied by the higher broad-band accuracy they provide (i.e. up to 4-5 Hz, De Martin, 2011), gradually bridging the gap between low-frequency source models obtained via wave-form inversion techniques and the structural modal frequencies (i.e. up to 20 Hz). This achievement is paving the way to fully couple the large-scale seismological models for the region of interest, with local engineering models for geotechnical, site-effect and structural analyses, in the next few years.

A major challenge related to the high-fidelity earthquake numerical simulation is represented by the accuracy of the predicted wave-motion at the frequency of interest. Unfortunately, due to the well-known spatial aliasing of the computational grid, major computational efforts are required to enlarge the wave-field frequency bandwidth propagated with accuracy, since finer meshes are required. Moreover, the simulation of realistic ground shaking scenarios in a broad-band frequency range (BB2S2S) requires a reliable estimation of several different parameters, related to the source mechanism, to the geological configuration and to the mechanical property of the soil layers and crustal rocks. The great impedance contrast between soft sedimentary layers and crustal bedrock entail the need for smaller time steps, i.e. increasing the overall CPU-time required to simulate realistic time-histories (e.g. of approximately 30 s), containing the P- and S-wave strong phases, as long as the coda-waves. Finally, due to the enormous extension of those regional scale scenarios, the degree of uncertainty associated to the whole earthquake process (from fault to site) is extremely high. At this point, it appears necessary to build up a multi-tool HPC-platform (High Performance Computing) capable to tackle the following issues:

1. to mesh the domain of interest, its geological conformation (bedrock to sediment geological surfaces), the surface topography and the bathymetry (if present)
2. to represent the material rheology (i.e., elastic, viscous-elastic, non-linear hysteretic)
3. to describe the natural heterogeneity of the Earth's crust and soil properties, at different scales (i.e., regional geology, local basin-type structures and heterogeneity of granular materials).

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Project # 17 – NORSAR SA – Blind beamforming in array processing

Contrary to the conventional model-based beamforming, blind beamforming operates directly on the available signals, without making any assumptions regarding the mechanism(s) that generated them. In other words, blind beamforming stands for data-driven instead of model-driven beamforming apart from its superior enhancement capabilities, the direct estimation of the time delays enables a more natural formulation of the signal detection and parameter estimation problems that truly captures the advantage of seismic arrays over conventional networks.

The visit had two main objectives. The first one was to offer the visiting researcher the opportunity to familiarize himself with state-of-the-art array processing techniques as well as gain insight on modern array applications, through the collaboration with the experienced researchers at the hosting institute. The second objective of the visit was the realization of a preliminary investigation concerning the use of blind beamforming techniques, based on Semi-Definite Programming (SDP-BB), for the solution of the signal detection and parameter estimation problems in seismic arrays. Regarding signal detection, the main idea was to formulate the detection problem as a hypothesis testing problem, discriminating between the hypotheses of structured vs random time delays. With this goal in mind, one of the objectives of the visit was the examination of time-delay sets from real array data, with the purpose of determining the statistical properties of the obtained delays under the scenarios of “pure noise” and “signal”. On the other hand, regarding the parameter estimation problem, the goal was to formulate an inverse problem based on the obtained delay-estimates, for the estimation of the back-azimuth and apparent velocity parameters of the incoming wave. For this purpose, the objective was to analyse several cases of seismic phases with known wave parameters, recorded at the hosting institute.

Project #18 – EUCENTRE ST – SEismic Response of Actual steel SILOS (SERA-SILOS)

The structural design of steel 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 and, 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 and structural failures still occur in the filling and, especially, the discharge phases as well as during strong ground motions. Both metal and concrete silos are known for their relatively high failure rate, a state of affairs due partly to the complexity of the structural response but also to the significant uncertainty inherent in the loading assessment. In particular, silos are known to frequently fail or be seriously damaged during large earthquakes, such as during the 1974 Lima (Peru), the 1987 Edgecumbe (New Zealand), the 1999 Chi-Chi (Taiwan) and the 2003 Zemmouri (Algeria) earthquakes (Dogangun et al., 2009).

The seismic assessment of such silos focuses on the estimation of the quasi-static horizontal forces generated on the silo wall by the ensiled mass. In this respect, the seismic design of silos is usually performed on the basis of the identification of an "effective mass", which interacts with the silo wall under seismic excitation, that is, the fraction of the total ensiled mass supported horizontally by the silo wall.

For flat-bottom circular silos, the EN 1998-4 (2006) considers an effective mass equalling roughly 80% of the total ensiled mass, according to the research works by Rotter and Hull (1989) and the analytical studies by Younan and Veletsos (1998), balanced by the horizontal actions provided by the silo wall. However, there is strong evidence that this formulation is too conservative (Dvornik and Lazarevic, 1999; Wagner et al., 2002). By means of extensive numerical simulations, Holler and Meskouris (2006) showed that, while for slender silos the Eurocode 8 provisions provide a reasonable performance indicator, for squat silos a more appropriate (with respect to that of EC8) effective mass should be considered.

Starting from the widely adopted classical approach of Janssen (Janssen, 1895; Sperl, 1895), Silvestri et al. (Silvestri et al., 2012; Pieraccini et al., 2015) studied analytically the load imparted by an incompressible ensiled content under constant horizontal acceleration confined in a flat-bottom cylindrical container. The theory was developed by simulating the earthquake ground motion with time-constant vertical and horizontal accelerations and was carried out by means of simple dynamic equilibrium equations that take into consideration the specific mutual actions developing in the ensiled granular solid (in particular, horizontal and vertical shear forces). The findings indicated that in case of squat silos characterized by low but typical height to diameter aspect ratios, the portion of the granular solid mass that interacts with the silo walls turns out to be noticeably smaller than the total mass of the granular solid in the silo and the effective mass adopted by Eurocode 8.

The theory has so far been validated only on shaking-table tests (Silvestri et al., 2016) performed in the Bristol EQUALS lab on a small-scale Plexigass cylindrical specimen with different heights of the ensiled material (about 0.5 mm diameter Ballotini glass) and different values of the particle–wall friction. The results indicate that for squat flat-bottom silos, the effective mass is indeed lower than the Eurocode specification, suggesting that the specification is overly conservative and that the particle-wall friction coefficient strongly affects the overturning moment at the silo base (Silvestri et al., 2016). These findings are also consistent with the numerical results obtained by Holler and Meskouris (2006) with reference to FEM models of real silos under earthquake excitation. Experimental verification on a full-scale actual silo specimen is thus desirable.

In this respect, a wide shaking-table experimental campaign was carried out at the EUCENTRE lab in Pavia (Italy) between February and March 2019 on a full-scale flat-bottom manufactured steel silo filled with soft wheat, considering both fixed-based and seismically isolated-base conditions.

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Project #19 – LNEC ST – Seismic Testing of Adjacent Interacting Masonry Structures (AIMS)

Historical city centres throughout Europe have developed and densified during long periods. The densification caused the historical centres to be characterized by masonry building aggregates. In building aggregates, façades of adjacent buildings often share a structural wall. Connection between older and newer unit is often done through weakly interlocking stones or by a dry joint. Furthermore, since the densification was often a process spanning throughout long time periods, it is not uncommon for adjacent units to be constructed of different materials, to have different distributions of openings and different floor and roof heights. However, advances in the development of analysis methods for such aggregates have been impeded by the lack of experimental data.

One large scale campaign was performed at EUCENTRE in Pavia, Italy (Guerrini et al., 2017, 2019; Senaldi et al., 2019). The specimen was a half-scale stone masonry aggregate of a similar typology. A unidirectional shaking table test was performed with increasing PGA stages. After reaching the significant damage, the specimen was retrofitted and the test continued. No full separation of the units was detected, most likely because of the existing interlocking of the stones between the units at their interface.

Although modelling guidelines and experimental data to calibrate the models is missing, various authors have performed numerical analyses of masonry aggregates. The macro-element approach using the Tremuri software (Lagomarsino et al., 2013) and the macro-element developed by Penna et al. (2014) are used in Senaldi et al. (2010) to study the behaviour of single units within an aggregate. Numerical modelling and experimental results from the abovementioned EUCENTRE campaign are compared in Senaldi et al. (2019). A simplified non-linear methodology is proposed in Formisano et al. (2013), while a simplified large-scale assessment procedure for seismic vulnerability of masonry aggregates is proposed in Formisano et al. (2015), by adding five additional aggregate parameters to the well-known vulnerability form for masonry buildings. Theoretical and numerical approaches were used for case studies in Maio et al. (2015) and Formisano (2017), whereas non-linear boundary connections were modelled and compared in the response of an aggregate as a whole in Formisano and Massimilla (2018).

In order to benefit the most from this H2020 SERA project transnational access experimental research and aiming to fulfil the gaps in knowledge, the following set of objectives was defined through numerical modelling of the test unit during its design phase (
Figure 18):

- Increase the opening phenomena of the interface between Unit 1 and Unit 2;
- Have a global behaviour sensitive to the behaviour of the interface (meaning that the numerical results are sensitive to the modelling assumptions of the interface model);
- Different modal properties of the isolated units with respect to the units as a conglomerate;
- Favour shear rather than flexural failure in the piers;
- Avoid early out-of-plane behaviour;
- Respect the shaking-table limits.

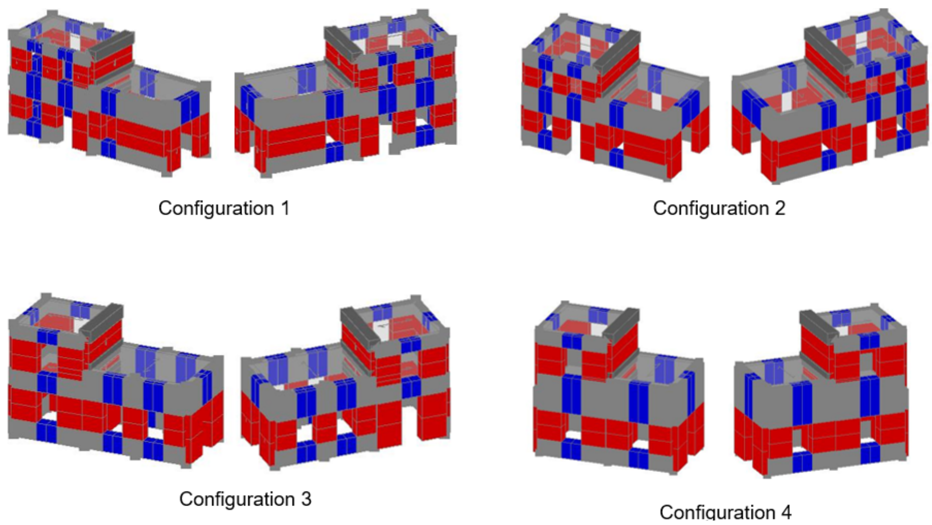

Figure 18: Evolution of specimen geometry

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Project #20 – STRULAB RW – hybrid Testing of an Existing Steel FRAme with Infills under Multiple EarthquakeS (HITFRAMES)

Existing steel residential framed buildings were often designed primarily for gravity loads, as a result they exhibit low energy absorption and inadequate dissipation capacity under seismic loadings, which has been demonstrated by recent earthquakes occurred in the Mediterranean regions. Damages such as significant lateral residual drifts, buckling and facture of structural steel members, and partial collapse of masonry infills were frequently observed on existing steel framed building during post-quake investigations. A critical point in this regard is the effects of slender masonry infill walls on the seismic behaviour of existing steel frames with low lateral stiffness and strength. However, the current provisions in Europe for the seismic performance assessment of existing steel structures are scarce and they do not account for the presence of masonry infills. It is therefore necessary to provide effective methods for the seismic assessment and retrofitting of existing non-compliant steel frames. To this end, the HITFRAMES project aims at four major purposes:

- Develop reliable methods for the seismic assessment of existing steel frames, especially under earthquake sequences;
- Develop design procedures for buckling restrained braces (BRBs) considering contribution of masonry infills to the lateral load resisting system;
- Evaluate the effectiveness of BRBs as seismic retrofitting measure;
- Derive fragility curves for existing steel frames with infills and systems retrofitted with BRBs and infills, considering also the effects of earthquake sequences.

The recent 2016-2017 Central Italy earthquakes have caused widespread damage on low-to-medium rise steel buildings that do not incorporate ductile seismic detailing and highlighted the significance of an advanced assessment framework of existing steel buildings. The insufficient lateral stiffness of existing steel frames led to significant lateral drifts and buckling in the steel components, especially in the columns. Local damage (buckling) has also been observed at the beam-column connections due to the strut-action induced by the masonry infills. However, seismic performance assessment of existing steel frames still faces many issues due to the complex behaviour and the interactions between beam-to-column connections, composite steel and concrete slabs and masonry infills among many others). Additionally, the current European code for assessing existing buildings do not provide specific indications on the modelling and safety checks for steel frames with masonry infills.

Currently, most of the advanced modelling strategies of masonry infills were developed for reinforced concrete (RC) structures, among which the single-strut model is a popular approach, as it achieves a good balance between simplicity and accuracy. This model consists of a single strut in each diagonal direction to simulate the infill wall panels, which is easy to implement in finite element software and is capable of concentrating the infill wall-frame contact area to the corners. However, currently the property of such model was all calibrated based on RC frames rather than steel frames, which are usually more flexible. Therefore, the reliability of those models for estimating the performance of steel frames remains unclear and requires further justification.

Apart from the effects of masonry infills, earthquake sequence is another critical issue that needs to be addressed in the assessment of existing structures. During seismic events, the mainshocks are often accompanied by several foreshocks and aftershocks with comparable magnitude. This can lead to large cumulative seismic demand on existing structures, especially non-ductile systems. Premature fracture and local buckling may occur in plastic hinges especially of steel columns, thus leading to stiffness reduction and strength deterioration. The response of the masonry infills used for claddings of steel residential buildings is also significantly affected by the earthquake sequences. Although researchers have yet to agree on the fundamental differences in characteristics between a mainshock and major foreshocks and aftershocks, it is of great interest in assessing the effects of seismic sequences especially on the structural response of existing buildings. Extensive inelastic analyses have been recently carried out on a large ensemble of as-recorded main and aftershocks to investigate the effects of repeated earthquakes on inelastic displacement demands. Note that the above findings refer primarily to comprehensive numerical simulations carried out with advanced hysteretic models with stiffness and strength degradation.

Project #21 – University of Bristol ST – NSFuse: Ductile steel fuses for the protection of critical non-structural components

Recent seismic events have showcased the vulnerability of non-structural components to even low- or moderate-intensity earthquakes that occur far more frequently than design-basis ones. Thus, community-critical buildings, such as hospitals, telecommunication facilities or fire stations, often face lengthy functionality disruptions despite having suffered little structural damage during an earthquake. Notable examples of the aforementioned seismic performance are the Sylmar County Hospital in the aftermath of the 1994 Northridge earthquake (Naeim, 2004) and the Santiago and Concepcion airports during the 2010 Maule earthquake in Chile, which sustained very little structural damage but massive non-structural damage (Fierro et al. 2011; Miranda et al. 2012).

To this end, the engineering community has shifted its attention, for countries with modern seismic codes, on the development of robust methodologies for the evaluation of the acceleration demands that are imposed to the non-structural components located at any one floor level during an earthquake. A more accurate absolute acceleration demand assessment could lead to an effective design strategy of non-structural components. Relatively recent, Kazantzi et al (2020a), on the basis of an analytical study that involved floor motions that were recorded during earthquakes on instrumented buildings in the United States (US), have showcased two important attributes with reference to the performance of the non-structural components, these being:

1. The acceleration demands imposed to the non-structural components could be amplified by several orders of magnitude compared to those specified in the current seismic design code provisions (i.e. ASCE 7-16 and EN1998-1-1) if the component has its fundamental period at or close to the supporting building' predominant modal period (fundamental or any other higher mode). This is illustrated in Figure 19, adapted from Kazantzi et al. (2020a), where apparently the a_p factor, which provides a measure of how much the peak component acceleration (PCA) is amplified relatively to the peak floor acceleration (PFA), hence the ratio PCA/PFA, could reach a peak which, for the particular case of tuning with the fundamental period of the supporting structure (i.e. $\tau_m=T_{component}/T_{building}=1$) and a component damping ratio, β_{comp} equal to 2%, approaches a value of 8 on average.
2. Allowing for some inelasticity to occur either in the support or the bracing of the non-structural component could substantially reduce the peak component acceleration demands. Allowing for inelasticity to reduce the seismic demands is a well-known strategy in earthquake engineering that is reflected in modern seismic codes in the capacity design approach. The extension of such a strategy to the non-structural components was initially introduced by Miranda et al (2018) and further expanded in Kazantzi et al (2020a) via computing inelastic floor spectra for single-degree-of-freedom (SDOF) secondary systems assumed to have a bilinear, non-degrading hysteretic behaviour that was characterized by a post-yield stiffness of 3% of the elastic stiffness. This is shown in Figure 20, adapted from Kazantzi et al. (2020a) illustrating two inelastic floor spectra for two component ductility levels μ_p, 1.5 and 3.0. The study concluded that allowing for nonlinearity in the non-structural component has a significant effect on limiting the peak component acceleration demands. Furthermore, the component ductility utilization results in acceleration demands less conditioned to the τ_m ratio, since the computed inelastic floor spectra were substantially flatter compared to their elastic counterparts, with the latter having pure narrow-band characteristics.

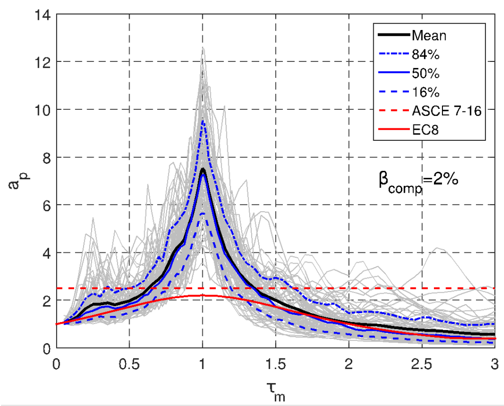
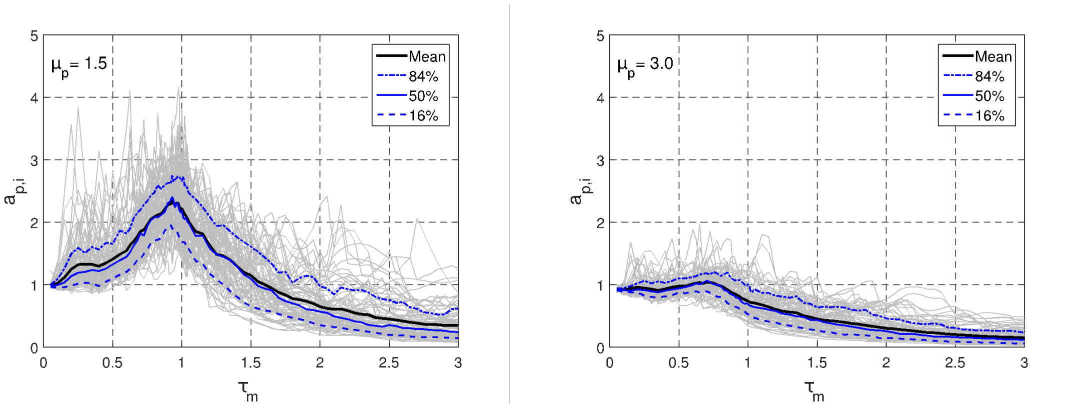


Figure 19: Mean and 16, 50, 84% percentiles for a_p as evaluated for records tuned to the fundamental period of the supporting buildings and a component damping level, β_{comp}=2%. Also shown are the a_p

spectra of individual records (light grey), ASCE7-16 and EN1998-1-1 (adapted from Kazantzi et al., 2020a)



(a) β_{comp}=2%, μ_p=1.5 (b) β_{comp}=2%, μ_p=3.0

Figure 20: Inelastic floor spectra for a component damping ratio, β_{comp}=2%, and two component ductility levels, μ_p (adapted from Kazantzi et al, 2020a)

This report summarises the findings of the NSFUSE experimental study that was undertaken at the shake table facility of the University of Bristol during the SERA Project, to investigate the conceptual validity of using ductile steel fuses for protecting acceleration-sensitive critical non-structural components during earthquakes. The objective was to offer a reliable and inexpensive solution, via replaceable sacrificial elements, for the protection of critical non-structural elements.

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Project #22 – University of Bristol ST – SEeismic BEhavior of Scaled MOdels of groin VAults made by 3D printers (SEBESMOVA3D)

Damages on existing masonry churches after the earthquakes occurred recently in Italy and Spain revealed that the collapse of such structures could be ascribed to the local failure of singular structural elements. Furthermore, it was shown that vaults are among the most vulnerable structural elements and it is their central portions that collapse rather than their supports, as they are embedded into the latter, while they counteract the outward thrust of the roof system (Croci 1998, Piermarini 2013, Cancino 2009).

The aim of the SEBESMOVA3D project (SEeismic BEhavior of Scaled MOdels of groin VAults made by 3D printers) is to focus the attention on the dynamic and earthquake response of the groin vault, that is one of the weakest structures found in historical constructions when not sufficiently confined. This model vault considers dry joints between the voussoirs (like many monumental structures in South Mediterranean) and was built in an innovative way to allow study of its dynamic behaviour and repetition of tests carried out until collapse.

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The physical model was realised with dry-joint blocks made of a 3D-printed plastic skin filled with mortar, which provided sufficient stiffness and strength to sustain impact without damage and allow for a quick and reliable re-assembly. This technique was used in similar tests previously performed on a small barrel vault at the “Laboratorio Salvati”, Technical University of Bari, Italy (Foti et al. 2018): the arches and vaults tested were made with modular blocks of wood and stone, respectively, and assembled with dry joints (Foti et al. 2019, Diaferio et al. 2019).

The main objectives of SEBESMOVA3D project were to evaluate the crack pattern and the collapse mechanism of groin vaults with two different support conditions:

- Configuration 1: on four fixed supports;
- Configuration 2: on two fixed springings combined with two one-directional moving supports characterized by very low lateral stiffness.

The rationale behind this choice lies in the observation that a vault under an earthquake excitation is mainly subjected to two different phenomena (Carfagnini et al. 2018):

- dynamic response of the vault itself to acceleration imposed at its springings, reproduced by Configuration 1;
- response of the vault to differential horizontal shear displacement imposed at its springings by the excitation of the underlying structures (walls and piers, characterised by different lateral stiffness), reproduced by Configuration 2.

Also, four boundary conditions along the four lateral arches (wooden panels, Plexiglass panels, Cut Plexiglass panels and no panels) were considered to account for different confinement levels.

The information to be gained from the effect of the supporting structures is fundamental to correctly plan seismic strengthening interventions in vaults and may be useful to professional engineers.

The experimental campaign was carried out in two separate sessions: August 2019 and January/February 2020.

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Project #23 – IZIIS ST – Investigation of Seismic Deformation Demand, Capacity and Control in a Novel Self-Centring Steel Braced Frame (SC-CBF)

Diagonal bracing members in CBFs are critical elements and during strong seismic loading experience repeated cycles involving yielding in tension and member buckling in compression. The performance of these members depends on various factors, including global slenderness, local slenderness, material strengths and end restraint/connections (Elghazouli AY., 2003). Due to the difficulty of accurately modelling this complex response, experimental studies have been employed to study the cyclic inelastic behaviour of bracing members. Early studies examined the load-displacement hysteretic response which was shown to be most strongly influenced by global slenderness (Popov EP, Black RG., 1857). Slender members lost compressive resistance more rapidly than stocky members, resulting in fewer inelastic response cycles and less energy dissipation. Later research examined the factors influencing the fracture life of bracing members. Through experimental testing, both global and local slenderness were found to influence fracture life (Tremblay R., 2002). The structural efficiency of thin-walled hollow section members has led to their widespread use as bracing members in CBFs. However, in the post-buckling phase, local buckling occurs in the plastic hinges which form at mid-length of these members. The high strain demands in these local buckles cause crack initiation, leading to complete fracture in subsequent load cycles, with a number of empirical expressions for fracture life and ductility capacity being proposed (Nip K.H. et al., 2009).

Gusset-plate connections employed in CBFs in which out-of-plane brace buckling is envisaged must be designed to accommodate the large end-rotations experienced by buckled compression braces at large storey drifts. This requires the formation of a stable ductile plastic hinge within the gusset plate, while the connection design details must also prevent gusset plate buckling in compression or yielding in tension (AISC/ANSI Standard 341-05, 2005). Current design guidance and practice on these issues can lead to the use of over-sized plates which can reduce the seismic performance of the brace members themselves. More recently, improved gusset plate detailing rules have been recommended that result in more efficient connection designs, while improving the seismic performance of the CBF overall (Yoo J.H. et al., 2008).

To support the development and validation of design rules for CBFs in Eurocode 8, members of the user team completed shake table tests to investigate the influence of brace slenderness and overstrength on hysteretic behaviour (Elghazouli A.Y. et al, 2005). Further tests examined the response of brace members with realistic brace connection details subjected to low, medium and high levels of seismic excitation, including ultimate response and fracture (Figure 21) (Salawdeh S. et al, 2017; Goggins J. et al., 2018).

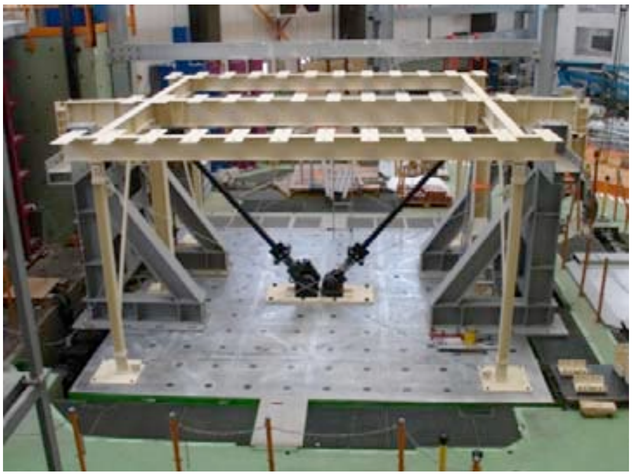

Figure 21: Test frame on Azalee shake table (CEA Saclay) without added masses showing pair of brace-gusset plate specimens (Goggins J. et al., 2018)

These shake table experiments were supported by complementary cyclic testing of brace members with a wide range of member slenderness and connection details at Trinity College Dublin and NUI Galway (Goggins J.M. et al., 2005; Hassan M.S. et al., 2018). Additional testing at Imperial College London characterised cyclic material behaviour in hot-rolled and cold-formed tubular members through cyclic axial and cyclic bending tests on coupon specimens (Nip K.H. et al., 2009), providing a strain-based damage criterion for modelling low cycle fatigue failure, validated through quasi-static cyclic axial loading tests on tubular bracing members with a wide range of member and cross-section slendernesses (Nip K.H. et al., 2009). Complementary 3D continuum model analysis using ABAQUS was employed in sensitivity and parametric investigations at NUI Galway (Hassan M.S. et al., 2018), and in an extensive numerical study on the cyclic behaviour of concentric bracings with different cross-sections (angles, U, RHS) at the University of Ljubljana. Optimum procedures for accurately modelling the global response of CBFs in OpenSees have also been developed and validated through comparison with experimental results (Ryan T. et al., 2017).

The CBFs in the above shake table tests suffered large residual drifts after high level seismic excitations that were associated with asymmetric hysteretic brace response and deteriorations in strength and stiffness. Peak and residual drifts were observed to be greater when the brace gusset plates were connected to a beam only (which is common practice in European construction) rather than both a beam and a column (which is typical practice in other regions including the USA). For a more resilient CBF with minimum residual drifts, several innovative damage control procedures have been suggested such as buckling-restrained braces (BRB) (Watanabe A. et al, 1988; Tremblay R. et al., 2004; Fahnestock L.A. et al., 2007) and self-centring systems (Christopoulos C. et al., 2002; Ricles J.M. et al., 2001; O'Reilly G.J. et al., 2013). In self-centring systems, post-tensioning arrangements are used to return the structure to its original position following inelastic deformation demands. A novel self-centring CBF system has been developed at NUI Galway and validated through push-over physical laboratory tests and nonlinear time-history analysis of numerical models (O'Reilly G.J. et al., 2012). Hence, these shake table tests are required to fully validate this novel system under representative dynamic response conditions.

Generally, the necessity of the shake table tests for this project can be summarized through the following objectives:

- Experimentally investigate the variation of seismic deformation demands in CBFs with ground motion characteristics and CBF design parameters;

- Advance the development of a novel self-centring method for damage control in CBFs (SC-CBF);
- Obtain experimental data for the validation of numerical models.

A unique set of data is obtained on the seismic deformation demand and capacity of SC-CBFs with realistic brace members and connections subjected to a variety of ground motions. The processed results include residual frame and brace deformations, brace ductility demand and capacity; the influence of connection detailing on maximum and residual deformations; and measurements of effective stiffness and equivalent viscous damping in SC-CBFs.

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Project #24 – University of Cambridge C – Seismic Behaviour of Rigid Pile Inclusions

Vertical rigid pile inclusions are frequently used as supports for the foundations built on soft soils. They act as load transferring elements onto more resistant and less compressible soils. Although the rigid pile inclusions are envisaged as a form of ground improvement method in current design practice, their performance in transferring loads on the structure under dynamic conditions are not well studied. Some of the recent examples, where rigid pile inclusions not connected to the structure are used as foundation support, include the New Mexico City Airport (NAICM), Rion – Antirion and Izmit Bay Bridges.

There is increasing interest in assessing whether such foundation systems offer an advantage in terms of seismic demand on the structures over traditional pile foundations where the piles are connected to the structure through a raft or pile cap. Moreover, the performance criteria set out for such foundation systems may also require some measure of pile structural assessment. Apart from detailed numerical Dynamic Soil-Structure Interaction (DSSI) models, there is no widely-accepted method for the assessment of this type of foundation systems. In this context, centrifuge testing can provide useful insight in terms of the underlying physical mechanisms for the load transfer.

The main objective of this research is to study the seismic behaviour of rigid pile inclusion systems. The focus of the study will be the dynamic soil-structure interaction mechanisms involved in these systems. Three small-scale dynamic centrifuge experiments using the beam centrifuge at the University of Cambridge are proposed that will supply information about the inertial and kinematic interaction between the rigid pile inclusions and the structure. Numerical models calibrated based on the experimental results will also complement the study. The study will be used as a basis for further study through the dissemination of the research outcome.

Project #25 – University of Cambridge C – COSMO: Change Of Seismic MOtion due to pile-soil kinematic interaction

Seismic analysis of structures supported on piles is conventionally performed by considering the free-field motion as the base excitation. In this regard, possible piles-induced modification of the seismic motion due to the interplay between soil and piles, which is referred to as 'kinematic soil-pile interaction', is neglected. However, piles, depending on their stiffness, are not always able to follow motions with short wavelengths induced by the surrounding soil. As a result, piles may filter the high-frequency components of the free-field motion and, thus, modify the input motion of a pile-supported structure. The above physical phenomenon which is referred to as 'filtering effect' may be particularly relevant for soft soils, where piles represent the most common design option. Experimental evidence on this filtering action of piles is still limited to some instrumented pile-supported buildings in Japan. These experimental data clearly indicate that piles filter out the high frequency component of the free-field motion. However, the above acceleration recordings at the foundation of these buildings include inherently the effect of the superstructure oscillation. Thus, there is a lack of experimental evidence on the alteration of seismic motion that can be attributed exclusively to piles.

COSMO research project aims to advance the present state-of-the-art on the above critical issue of piles-induced filtering effect. For this reason, a series of centrifuge tests are proposed on models of aluminium piles embedded in soft soils. The proposed model tests include both single piles and groups of three piles rigidly connected by a cap under harmonic excitations. The influence of diameter, soil-cap contact and cap-embedment on the alteration of seismic motion will be also investigated.

Objectives

The main objective of this experimental program is to provide well-documented experimental evidence on the critical issue of the change of seismic motion induced by pile-soil kinematic interaction. Moreover, the testing campaign within COSMO project will be complementary to a relevant series of centrifuge test already performed at the Schofield Centre of the University of Cambridge on models of aluminium piles rigidly connected by a cap (clear to the soil) and embedded in kaolin with variable pile spacing (under Reluis 2017 research project granted by the Italian Emergency Management Agency). The additional tests planned within COSMO project will investigate for the first time a set of critical parameters that are involved in the kinematic response of a piled foundation such as the cap-soil contact and the cap embedment. The proposed model tests will be also examined numerically by the use of a hysteretic non-linear model based on Ramberg-Osgood formulation, so as to reproduce in a realistic manner the degradation of the shear stiffness of soil, the increase of soil damping ratio generated by the passage of seismic waves and the occurrence of earthquake induced excess pore pressures. The experimental evidence supplied by the above projects will serve as a benchmark to assess the validity of the simplified methods of analysis aimed at the evaluation of the base excitation for pile-supported structures. The experimental assessment of the transfer functions for both pile groups and the isolated piles, will have a remarkable scientific, technical and economic impact. First, the results of this testing campaign will have a direct positive impact on the understanding of the physical problem under examination. Second, the experimental evidence supplied by this work will enhance the ability to predict the seismic input motion of pile-supported structures, thus allowing for a more rational allocation of resources in seismic risk mitigation strategies. Third, the investigation of the basic aspects of the mechanism governing the change of seismic motion by pile-soil kinematic interaction will provide guidance for the selection of physical model of pile groups to be tested in the future.

The originality and innovation of the proposed project lie within the following research advancements:

Development of a new well-documented database of recordings for piles filtering effect

As outlined before, the available experimental evidence on the filtering effect exerted by piles is limited to published works that go back to the early 70s (Kawamura et al. 1977) and 80s (Otha et al. 1980, Gazetas 1984). The experimental data that will be acquired from the COSMO project will advance the database which is already available from project ReLUIS 2017, to provide a well-documented database on the alteration of seismic motion due to pile-soil kinematic interaction.

Validation of theoretical/numerical models and analysis tools: The Users Team of COSMO proposal has established a strong theoretical background on the issue of the filtering action of piles by means of pertinent analysis methods, as reflected in several publications of the research group Part of the above research has resulted in simple analytical expressions of pile-to-soil kinematic response ratios in the frequency domain. The above analytical expressions were obtained under the assumption of raft clear to the soil. Within COSMO project, predictions of the above models will be compared with the centrifuge tests results in order to check the applicability of the published formulae under circumstances where the raft is in contact with the soil or embedded and, eventually, develop ad hoc design oriented formulae for quantifying the filtering effect in the presence of a piled raft.

Contribution towards seismic design practice of piles.

Di Laora & de Sanctis (2013) observed that, in case of large diameter pile in soft soils, the filtering action may result in a reduction of the seismic demand up to 50% - 70% (for low-period structures). The reduction of spectral accelerations between pile-head and free-field may be even higher when piles are embedded in inhomogeneous soil (Rovithis et al. 2015, 2017). The above considerations will be validated accordingly by means of the experimental dataset produced by the COSMO project and may have a direct impact in future revisions of seismic codes with reference to the design of structures on piles. Under this perspective, piles in the future may be also viewed as 'seismic demand reducers' in the design of a structure.

In view of the fact that European researchers, practitioners and companies will be the beneficiaries of the outcome of this research, the following benefits are expected:

- Improvement of the accuracy of existing methods for seismic vulnerability assessment of buildings and infrastructures;
- Improvement of public safety, as current design practice will surely benefit from the results obtained;

Improvement of European competitiveness, as the experimental evidence supplied by this research can be used by European companies and exported abroad to support innovative solutions for seismic risk mitigation strategies.

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Project # 26 – EUROSEISTEST – Dynamic Soil Structure Interaction: Three-dimensional Time-domain Analysis of Field Model Scale Experiments

Dynamic soil-structure interaction (SSI) is a complex phenomenon that takes place as a result of seismic loading or other types of dynamic excitation. Dynamic SSI phenomena are typically distinguished in inertial and kinematic interaction effects. The kinematic interaction, which is more important for embedded structures, stems from the inability of a structure to comply with the free-field deformation pattern induced by a particular ground-motion. This can be the case for foundations of structures which are much stiffer than the surrounding soil and therefore cannot follow free-field deformations. The inertial interaction results from the development of inertial forces in the vibrating structure associated with the compliance of the foundation, which would not occur in a fixed-base structure. If the surrounding soil is compliant, the imposed inertial stresses can cause the foundation to displace and rotate.

Many studies have shown that structural response affects the foundation soil and vice versa. When a structure is founded in soft soil, SSI effects play a significant role due to founding soil compliance. It is known that SSI effects increase the natural period and damping of a soil-structure system and can decrease the seismic intensity at the foundation level. Due to these facts, it is conventionally believed that SSI effects are beneficial. Therefore, these effects are neglected conservatively in practice or they are considered by using simplified approaches that take into account their beneficial effects only. However, Mylonakis and Gazetas (2000) have shown that under certain circumstances, such as in soft soil sites, SSI effects could be detrimental. These circumstances are not captured by design provisions. It is clear that more research is needed to explain better SSI effects.

In engineering practise, there are two methods that are used to account for SSI effects; the substructure and the direct methods. The substructure method involves two independent analyses that consider kinematic and inertial interaction effects separately. This method facilitates the physical interpretation of SSI effects and can be easily employed with existing numerical tools. Kinematic interaction is considered by reducing the free-field motion at the foundation levels by employing analytical solutions (e.g. Veletsos and Prasad 1989, FEMA 2015). As far as inertial interaction effects are considered, the simplest application of the substructure method is the use of SDOF fixed-base models that have an increased structural natural period and damping of the first mode of oscillation. Another way to apply the substructure method is to employ flexible-based structures where the soil compliance is modelled using frequency dependent springs and dashpots at the foundation positions (e.g. Gazetas 1983; 1991). The spring and dashpots properties were derived based on a number of assumptions, using analytical, semi-analytical formulations and finite element models. The analytical formulations assume that frictional shear tractions cannot develop during vertical and rocking vibrations, while for horizontal vibrations the normal tractions at the interface are assumed to be zero. The analytical, semi-analytical formulations and finite element models that are employed for the calculation of the dynamic stiffness and dashpot properties are typically based on the assumptions of massless, rigid foundations that are subjected to machine-type loading. Foundations rest on a homogeneous half-space, or on a soil stratum underlaying bedrock or a half-space. These assumptions limit the reliability of the substructure method as they are unrealistic for most engineering structures. Additional limitation of models that consist of SDOF structures that are either fixed or flexible at their base, is that they applicable only for structures whose response is dominated mainly by the first mode. Few substructure approaches involve frequency domain analyses. For example, in modal analysis the response is estimated as the superposition of uncoupled vibration modes that are computed independently. An important limitation of this method is its inability to reproduce wave propagation and therefore soil material and radiation damping. An equivalent-linear substructure approximation method in the frequency domain was developed to overcome the latter limitation and approach soil nonlinearity. It employs Fourier transforms to approximate loading time series and it calculates the total response by adding the solution of each harmonic. However, neither modal analyses nor equivalent linear analyses are applicable for non-linear systems, as they use superposition and they do not account for soil nonlinearity that is resulted from structural response.

The most rigorous approach for SSI systems is the direct method. This method simulates soil-structure interaction in a single step in the time domain and overcomes the limitations of the frequency domain methods. Limitations of this method are the large number of degrees of freedom and the computational time needed for analyses to run. Thus, sophisticated 3D analyses are very scarce in the literature. More importantly literature lacks 3D finite element methodologies that are validated against field real-scale SSI experiments and account for nonlinear soil behaviour realistically. This is one of the motivations for this research programme.

The first objective of the research programme run by Imperial College London is to investigate key parameters of SSI by using data from the real-scale experiments conducted in collaboration with Aristotle University of Thessaloniki (AUTH). The advantage of these experiments over other similar studies which can be found in the literature (e.g. Barros and Luco 1995; Tileylioglu 2008), is the large number of instruments (e.g. seismometers, accelerometers) that were installed on both the structure and soil. These instruments allow the detailed examination of the structural response, as well as the thorough investigation of the soil response. Appreciating the complexity of SSI effects, sets of real-scale experiments were carefully designed to identify and characterise the main factors that affect SSI phenomena. The experiments involve forced and free vibrations, involving inertial interaction effects of structures founded on shallow foundations. In comparison with other experiments, which involve both inertial and kinematic effects, for example structures subjected to seismic excitations, the present set of experiments allows to focus on inertial effects. The structural design of the current research programme allows the reconfiguration of the structure's dynamic properties, stiffness and mass. The examined structure was exposed to free and forced vibration tests, and during the latter tests, sinusoidal forces of different frequencies and magnitudes were applied. Therefore, the design of the experiments allows the separate investigation of factors that, as generally accepted, influence the severity of SSI effects. These factors are structural mass, structural stiffness, motion frequency content and motion intensity.

The second aspect of this research programme is related to the numerical modelling of dynamic soil-structure interaction effects. The objective is to simulate the carefully designed set of real-scale experiments, with a rigorous modelling of both the soil behaviour and structural aspects. The developed numerical model is validated against the SSI experimental data, while the model calibration will be based on previous site investigation campaigns (Pitilakis et al. 1999, Raptakis et al. 2000, Pitilakis et al. 2014). The numerical analyses are carried out by using the bespoke software, Imperial College Finite Element Program (ICFEP) (Potts and Zdravković 1999) which includes state-of-the-art features for the modelling of geotechnical problems. In order to capture the soil-structure interaction effects, a 3D numerical model will be developed, consisting both the structure and the soil and accounting for soil nonlinearity. Such simulations involve many challenges such as the exact spatial discretization of both the structure and the soil, the use of boundary conditions which will ensure a realistic wave propagation over a wide range of frequencies. Another challenging aspect is the investigation of the effect of soil nonlinearity on the response of the SSI system. Finally, comparisons will be made between results of 2D and 3D models and between numerical analyses, analytical and simplified approaches that are used in practice. The comparisons will allow the examination of the extent to which the use of those approaches which are currently used in engineering practice is acceptable.

In summary, the aim of the project is to provide results supported by both experiments and numerical analyses to enrich the current knowledge in the field of Soil-Structure-Interaction. The main ambition of this research is to establish newly validated advanced 3D FE modelling procedures that will guide numerical studies of SSI problems. The validation procedure will also provide guidance on the performance of different constitutive models and the use of boundary conditions for direct SSI simulations. In addition, the project will improve the general understanding of the inertial interaction mechanism and give an insight on the impact of structural rocking. Finally, it will provide guidance on the adequacy of 2D plane strain approximation and the range of applicability of simplified approaches used in practice to study dynamic SSI problems.

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Project # 27 – EUROSEISTEST – SISIFO – Seismic Impedance for Soil-structure Interaction From On-site tests

SIt is well known since several decades that the seismic response of structures is affected by the dynamic interaction with the underlying soil (Gazetas 1983, Mylonakis and Gazetas 2000, Kausel 2010). If the foundation depth is significant, the 'kinematic interaction' due to the relative soil-foundation stiffness may introduce a 'filtering effect' on the seismic motion transmitted to the superstructure with respect to the free-field condition (Elsabee and Morray 1977). For structures founded on shallow foundations, the filtering effect is often negligible, and the soil-foundation-structure (SFS) interaction reduces to the so called 'inertial interaction', determined by the compliance of the soil to the structural motion. As a result, with respect to a fixed-base structure, the fundamental period of the system increases and additional energy is dissipated by downward wave radiation and soil hysteresis (Richart et al. 1970).

Simplified approaches based on the uncoupled 'substructure method', as well as refined complete SFS models, have been proposed in the literature to catch the effects of the inertial interaction. Finite elements or finite difference complete models are generally justified only for high-value buildings (e.g., Pitilakis and Karatzetzou 2015, de Silva et al. 2017, de Silva et al. 2018) due to the computational effort required for the analysis. In the most widespread simplified approach, also suggested by some international guidelines (e.g. BSSC 2004), the structural model is placed on translational and rotational springs and dashpots (Veletsos and Meek 1974). The stiffness of springs and the dashpot coefficients are computed on the basis of the real and imaginary parts of the frequency-dependent 'impedance functions', usually with reference to the fundamental frequency of the SFS system.

Numerous analytical formulations of impedance functions are available in literature for rigid shallow foundations resting on the surface of a homogeneous half-space or finite thickness layer, with linear visco-elastic behaviour. Modifications of the classical solutions were proposed by Gazetas (1991), Pitilakis and Karatzetzou (2015) and Iguchi and Luco (1982) to take into account the embedment and the deformability of the foundation, respectively. The main issue related to the use of such analytical formulations remains the choice of equivalent values for the stiffness and the damping coefficient of the linear homogeneous soil, since the actual foundation is generally embedded in a layered subsoil with non-linear behaviour, in which the above properties vary with depth and strain level. Some authors (Gazetas 1991, Mylonakis et al. 2006, Stewart et al. 2003) suggested assuming an equivalent stiffness as the mean shear wave velocity, V_S, throughout the depth of the soil volume involved in the foundation motion, which is typically related to the foundation width. With respect to the value measured in free-field geophysical tests, the mean V_S should be in principle corrected to account for the overburden pressure induced by the structural weight and for soil non-linearity.

In the analysis of existing buildings, the introduction of equivalent properties often represents a difficult issue, since the geometry of the foundation is usually unknown and the properties of the underlying soil are, on the average, not fully documented.

Laboratory-scale investigations on the SFS interaction are usually performed by shaking table and centrifuge tests (Richart and Whitman 1967, Dobry et al. 1986, Knappett et al. 2015). These model tests provide precious insights on the effects of the non-linear soil behavior, but they show limits in the reproduction of the radiation damping, due to the small size of the test container.

Full-scale field tests on instrumented facilities were performed to evaluate the impedance associated to horizontal translation (swaying) and rotation (rocking) in the vertical plane. The on-site investigations available in the literature provide results over a limited range of frequency (Lin and Jennings 1984, Luco et al. 1988, Wong et al. 1988) or for specific structures, such as an accelerograph station Crouse et al. 1984) and a nuclear reactor (de Barros and Luco 1995). In all cases 1) the limited resolution of the data acquisition system introduced significant noise, leading to spurious results; 2) the shear wave velocity profile was measured in free-field conditions, neglecting the stress increment exerted by the structural weight.

More recently, forced-vibration tests were executed on a steel frame prototype in California (Tileylioglu et al. 2011). The tests were executed monitoring the structural response only, without any instrument recording the soil motion. Since a very low amplitude excitation was applied, the structural motion was disturbed by the noise; the experimental data were successfully compared to analytical impedance functions in a frequency range limited to 5-15Hz.

Summarizing, the available inventory of both model and prototype tests is still limited to validate the analytical solutions on impedance functions in the range of frequency of interest for earthquake engineering. Moreover, the few and heterogeneous past experiences do not allow for individuating the most appropriate experimental layout to facilitate the computation of the impedance functions from the recorded data.

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Project # 28 – EUROSEISTEST – Ambient and forced vibration techniques for improving design and performance assessment of structures with consideration of soil-structure interaction

Excessively simplified design of new buildings or performance assessment of existing buildings, without eliminating major sources of epistemic uncertainties, can lead to incorrect decision-making. Ongoing research is thus focused on the improvement of design and assessment procedures of structures without increasing their complexity. The objective of the proposed project is to support such research by investigating the usability of detailed measurement of soil-structure interaction (SSI) based on ambient and forced vibrations of a simple structure. Two series of experiments were performed at EuroProteas site:

a) Ambient-vibration measurements;

b) Free- and forced-vibration measurements.

The results of the first series of experiments can be used to validate different methods for system identification, and to study how these results can be used to reduce epistemic uncertainties involved in seismic assessment of existing buildings. The results of the second series of experiments can supplement the results of the first series of experiments and can be used to validate nonlinear models which can then be used in parametric studies in order to develop a simplified method for definition of design spectrum with consideration of soil-structure interaction.

The proposed experimental campaign at EuroProteas is in line with ongoing research at University of Ljubljana, which addresses the development of design response spectrum with approximate consideration of soil-structure interaction and the usability of the non-destructive dynamic system identification techniques for the risk assessment of existing structures. The interest of the user group is also to acquire the knowledge to design and perform such experiments.

Project # 29 – EUROSEISTEST – Seismic SITE effects in sedimentary basins from 3D physics-based numerical modeling (SITE3D)

It is widely recognized that local geologic irregularities may affect significantly strong ground motion, modifying its amplitude, duration and frequency content characteristics. Therefore, an accurate evaluation of local site effects is crucial for the definition of site-specific ground motions for the earthquake-resistant design of structures.

EUROSEISTEST is one of the best-documented sites worldwide from both an instrumental and geological-geophysical-geotechnical point of view, making it an excellent case study for testing and validating numerical methods for earthquake ground motion prediction in complex geological configurations. The main purpose of the SITE3D project is to evaluate seismic site effects in the Mygdonian basin (EUROSEISTEST site), located about 30 km northeast of the city of Thessaloniki (Northern Greece), based on 3D physics-based numerical simulations of seismic wave propagation from the seismic fault rupture up to the site. Specifically, the main objectives of the project are: (1) set-up of a 3D numerical model of the Mygdonian basin area, including both the 3D basin structure and the active faults located in proximity of the investigated area; (2) physics-based numerical simulation of different earthquake scenarios; (3) evaluation of 3D site amplification effects within the Mygdonian basin.

In the framework of this project, the 3D numerical modelling of the Mygdonian basin is carried out through the high-performance open-source spectral element code SPEED - Spectral Elements in Elastodynamics with Discontinuous Galerkin, see http://speed.mox.polimi.it/ (Mazzieri et al. 2013). The SPEED code is the result of a ten-year research activity involving the Department of Civil and Environmental Engineering and the Department of Mathematics at Politecnico di Milano, and its development has been supported by several international research projects funded by both public and private institutions.

After the set-up of a large-scale "source-to-site" 3D spectral element model of the broader EUROSEISTEST area, 3D physics-based numerical simulations of ground motion in the Mygdonian basin by SPEED are prompted to account for a representative set of earthquake scenarios along the seismogenic fault sources. Then results are processed to get ground motion time histories at selected soft sites, maps of different ground motion intensity measures, and to estimate 3D site amplification functions with respect to ideal outcropping bedrock.

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Project # 30 – EUROSEISTEST – Comparison of rocking on rigid and compliant base using the EUROPROTEAS real-scale facility

Inspired by the remarkable behavior of tall and slender structures such as water tanks and tombstones during the 1960 Chilean Earthquake, Housner (1963) published his seminal paper where he explained the dynamic stability of rocking structures. During the same earthquake, other seemingly more stable structures, such as buildings and bridges, collapsed. Since then, the rocking motion has been extensively studied using conceptual models (e.g. Yim et al., 1980; Psycharis and Jennings, 1983; Zhang and Makris, 2001; Dimitrakopoulos and DeJong, 2012) to conclude that large slender structures present remarkable stability against earthquakes.

A salient conclusion of such models is that the stability of rocking objects is controlled by both the frequency of the excitation and the size of the rocking structure: ground motions whose spectra are dominated by high frequency content have less overturning potential, while out of two rectangular rigid blocks with the same aspect ratio, the largest one is more stable. The latter can be easily understood through displacement-based design concepts: a larger block has a larger “displacement capacity” up until it reaches the point of unstable equilibrium. This superior performance of rocking structures has led researchers to propose rocking as an earthquake hazard mitigation technique, using the term “rocking isolation” (e.g. Meek 1975; Huckelbridge and Clough, 1978; Mergos and Kawashima, 2005; Chen et al., 2006; Anastasopoulos et al., 2010).

According to the concept of rocking isolation, instead of fixing the structure firmly to the ground, uplifting and rocking is allowed. Uplifting acts as a mechanical fuse, limiting the forces transmitted to the structure. Rocking isolation aims to increase the safety of a structure against collapse, while simultaneously decreasing its residual displacements. Thus, it can be used for the design of resilient structures while it also often emerges as a cost-effective approach for seismic upgrading.

Two main rocking isolation concepts are of interest for this project. The first refers to rocking of a structure onto a rigid base while the second promotes rocking of the structure along with its foundation on the underlying soil.

The first concept has been studied, with the use of a restraining tendon (Mander and Cheng, 1997; Palermo et al., 2004; Chen et al., 2006; Cheng, 2008; Makris and Vassiliou, 2014; Vassiliou and Makris, 2015), or without. Most studies use rigid body models (e.g. Housner, 1963; Hogan, 1989; Makris and Roussos, 2000; Zhang and Makris, 2001). However, research has also been conducted taking into account the flexibility of the structure (Acikgoz and DeJong, 2012; Vassiliou et al., 2014, 2015, 2017). Despite the wealth of work on this topic, real-scale experimental results are scarce, despite the great significant such results could have for the validation of analytical or numerical tools.

The second concept introduces the deliberate under-sizing of the foundation to promote full mobilization of its moment capacity during strong seismic shaking. This way, the soil experiences inelastic behavior and the footing is allowed to uplift (e.g. Mergos and Kawashima, 2005; Gajan and Kutter, 2008; Anastasopoulos et al., 2010; Gelagoti et al., 2012; Antonellis et al., 2015). Depending on the safety factor against static (vertical) loading, the mode of intentional foundation failure is either uplifting (for large FS_v) or soil yielding (for small FS_v) (Anastasopoulos et al., 2012). Despite its proven beneficial seismic performance, such reversal of capacity design (from the superstructure to the soil) is still not allowed by current seismic codes, which only allow limited uplifting of the foundation, prohibiting full mobilization of soil bearing capacity. However, there are a few exceptions of structures that have been designed and constructed employing the concept of rocking footings, such as the Rio-Antirrio bridge in Greece and the Vasco de Gama bridge in Portugal (Pecker, 2003). The comparative advantage of such a design concept lies in its simplicity and compatibility with the current state of practice. There is no need for special connections, and methods compatible to elastic design spectra have been developed (Gelagoti et al., 2012). Once again, real-scale experimental results are particularly limited (e.g. Antonellis et al., 2015) despite the great potential for validation of numerical predictions.

Conventional foundation capacity design aims to guide failure to structural members (i.e., the base of a column or pier) by "over-designing" the foundation. The collapse of the Hanshin Expressway Fukae bridge during the 1995 Kobe earthquake dramatically demonstrated that such design principles do not guarantee avoidance of collapse. Rocking isolation is an alternative design concept, which aims to limit the inertia loading of a structure by allowing foundation uplifting and full mobilization of its bearing capacity, at the expense of increased settlement and rotation.

Overall, rocking isolation concepts have been shown to be beneficial in the event of an earthquake, protecting a structure against collapse, limiting structural failure and potentially limiting residual displacements. As part of this project, both rocking concepts discussed above were examined by experimenting on the real-scale structure of EUROPROTEAS in order to assess their performance, compare their effectiveness and produce data for the validation of analytical and numerical tools.

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Project # 31 – NORSAR SA – Seismic tremor detection in Greece using small aperture arrays

The main objective of this research proposal is to detect tremors of tectonic origin in Greece using seismic arrays and array data processing techniques. This type of signal is usually associated with slow-slip events, which have been mostly observed in several subduction zones worldwide. In Greece no such tremor recordings have ever been documented. There are, however, two candidate zones where they could possibly occur: the Hellenic Arc subduction zone, where the observed strain is mostly aseismically accommodated, and the western Corinth Rift. In the latter case, a strain transient associated with a slow-slip event was observed in December 2002, while there is evidence of creeping that occurs on a developing detachment within the brittle-ductile transition zone.

In the proposed research, an array that consists of 7 broadband seismometers, installed near the town of Magoula, at the western margin of the Corinth Rift, will be employed to detect tremors that may have occurred in the region using beamforming techniques. Candidate signals will be evaluated using a conventional method, such as envelope cross-correlation, at the stations of the local Corinth Rift Laboratory (CRL) network. The developed methodology will be also applied to another seismic array, composed of 9 stations, that is installed in Pylos, South Peloponnese, in collaboration with the National Observatory of Athens. This could target the SW portion of the Hellenic Arc, where tectonic tremors are more likely to be observed, but may be more difficult to evaluate due to the sparse distribution of stations of the regional Hellenic Unified Seismological Network (HUSN). The detection of tectonic tremors in Greece could reveal sites where slow-slip occurs, explaining part of the aseismically accommodated strain and could have implications on the seismic hazard assessment.

The main objective of the SERA-TA visit was the development of array processing tools for the detection and location of tectonic tremors in the region of Greece. Prior to the visit at NORSAR, data had been collected from two arrays in Greece; one located in Pylos, S. Peloponnese, close to the interface between overriding and subducting plates of the Hellenic Arc, which is considered as a possible zone where tectonic tremors might occur; the other array is located in Magoula, in the W. Corinth Gulf, a region characterized by intense microseismic activity, where at least one slow slip event has been recorded as a strain transient signal by a dilatometer in December 2002. A data-sample of about one month was to be processed during the TA-visit at NORSAR. A “training dataset” of recorded tremors in Cascadia was also available to test the various array-processing techniques for their tremor-detecting capability. The latter appear as emergent, noise-like, coherent signals, mainly within the 2-8 Hz band, which may persist for several minutes to hours, days or even weeks. Their source is expected to be sustained for a long time in the same fault patch or gradually migrate over time. The source location can be determined using back-projection techniques, preferably using observations from multiple arrays, or other constraints such as a fixed depth. The detection and location of such events may provide information on aseismic slip that could possibly accelerate the occurrence of significant earthquakes in the area of study.

Project # 32 – NORSAR SA – A new velocity model up to 300 km deep based on receiver function data from the NORES array (Baltic Shield)

The main goal of the proposed research is to construct a P- and S-wave seismic velocity of the crust and uppermost mantle of the southern part of Norway (Fennoscandian shield) by combining P-wave receiver-function data and S-wave receiver-function data of the NORSAR/NORES seismic arrays. For this purpose, we are going to use well known method of the receiver-function analysis, developed by the Institute of Physics of the Earth of Russian Academy of Sciences, along with classical array techniques. The model will include:

a) P-wave velocity model;

b) S-wave velocity model;

c) position of the major seismic interfaces in the crust and upper mantle.

In particular, we will investigate the basic mantle boundaries such as Lithosphere-Asthenosphere-Boundary (LAB) and Lehmann discontinuity along with the mantle transition zone in 410 – 660 km depth. The model will be combined with the P- and S-wave velocity models of the crust and upper mantle obtained by the NORSAR local event studies.

To investigate the velocity structure of the crust and uppermost mantle of the southern part of Norway using NORSAR data along with all the broadband seismic data for the region that could be obtained. Another goal of our attempts is to look for the mantle transition zone in 410 – 660 km to see whether any topography of this boundaries exists in southern Fennoscandia. The final goal is to get an accurate velocity model of the investigated area. To successfully obtain these goals the receiver function method has been chosen.

Project # 33 – NORSAR SA – Joint processing of seismo-acoustic array data as tool to discriminate between man-made explosions and earthquakes

Recently, a constant increasing of interest in analysing the infrasound data to include them in interdisciplinary domains as physics and geoscience have been observed at the global scale. The worldwide infrasound monitoring stations have proven capable to detect and locate atmospheric explosions as well as other natural phenomena generating infrasound signals. The proposed research is aimed to monitoring geophysical man-made hazard, i.e., controlled explosions, by jointly using data well-recorded with the Romanian seismic and infrasonic arrays, focusing on the Plostina seismo-acoustic site (PLOR and IPLOR stations).

During the project, infrasound and seismic array data recorded by Romanian stations will be processed and analysed in order to discriminate between tectonic sources (earthquakes) and artificial events (quarry blasts and mine explosions). The examination of the infrasound propagation changes over time and distance is essential to understand the differences between real propagation through atmospheric layers and a hypothetical propagation along the earth's surface. The capability of the Romanian dense seismic network to detect and locate small events led to an undesirable side-effect as including of many man-made blasts and explosions in the Romanian earthquake catalogue ROMPLUS (Oncescu et al., 1999).

To monitor man-made hazards by jointly using data well-recorded with the Romanian seismic and infrasonic arrays, focusing on the Plostina seismo-acoustic site (PLOR and IPLOR stations) by building an efficient tool to discriminate between man-made explosions and earthquakes, followed by seismic catalogue decontamination

Activities to follow:

- selection of natural and artificial reference events for the seismo-acoustic analysis and the stations (seismic and infrasound) where they were detected
- analysis of the infrasound data using standard processing methods to extract the waveform characteristics (direction of arrival - backazimuth, phase apparent velocity, frequency, amplitude, SNR)
- analysis of IPLOR infrasound station detection capacity to observe the diurnal and seasonal variations and identification of the causes which produce these variations

- analysis of seismic data from reference events in order to extract the characteristics of their seismic signature, such as waveform, frequency, amplitude, particle motion for determining the direction of arrival of the energy at the measuring sensor
- association of the infrasound detections obtained (backazimuth and arrival time measured with the IPLOR array) with the seismic events in the analysed set (theoretical backazimuth and arrival time), considering the effect of the dynamics of atmospheric propagation
- inspection of the recorded seismic waveforms for events identified as acoustic sources based on their association with infrasonic detections (aspect, frequency content, radiated energy) for their validation as quarry bursts

creation of templates of seismo-acoustic signals generated by man-made explosions in order to compare them with the other recorded waveforms.

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Project #34 – EUCENTRE ST – Seismic performance of multi-component systems in special risk industrial facilities

Past earthquakes demonstrated the high vulnerability of industrial facilities equipped with complex process technologies leading to serious damage of the process equipment and multiple and simultaneous release of hazardous substances in industrial facilities. The Tang-Shan earthquake (Beijing, China) in 1976 seriously damaged the highly industrialized zones and coal mines in its vicinity. The 1989 Loma Prieta and the 1994 Northridge earthquakes damaged factories and energy supply facilities. The Kocaeli (Turkey) and Chi-Chi (Taiwan) earthquakes in 1999 damaged petroleum complexes and thermal power stations. The 2011 Daiichi earthquake lead to the Fukushima nuclear disaster, and more recently Emilia-Romagna (2012) damaging approximately 500 small scale factories.

The seismic behaviour of industrial facilities was intensively studied (Klinkel et al., 2016) with numerical models and several component-based fragility curves were developed. In general, floor response spectra of the primary structure are used to determine the response of installed components (Hoffmeister et al., 2011; Medina et al., 2006). However, this approach does not consider dynamic interaction between the structure and the installations and thus the effect of seismic response of the installations on the response of the structure and vice versa. Most experimental studies described in the literature deal with specific components tests (Retamales et al., 2006; Astroza et al., 2015), for instance tests of pipe joints (Ju, B. S., & Gupta, A., 2015; Goodwin et al., 2004), fire sprinkler piping systems (Guzman J. & Ryan K. L., 2015; Rahmanishamsi et al., 2014) or investigation of floor response spectra (Nims D. K. & Kelly J. M., 1990). Only a limited number of full-scale tests (Mosqueda et al., 2006) have been conducted so far.

A variety of construction measures and techniques have been developed in order to improve the behaviour of industrial structures and their installed components. One option is to install seismic isolation measures (Guzman et al., 2015; Cazadieu et al., 2014) to the overall structure or specific components. Furthermore, the isolation of single components is an effective and well-accepted solution to decouple substructure and components (Nawrotzki P. & Siepe D., 2014). Increased effort to develop powerful monitoring systems that quickly recognize dangerous patterns and consequences in case of seismic events are developed and coupled with automatic shutdown devices (Stiegler et al., 2014; Hollender et al., 2014). Their use, mainly focused on NPP so far, will continue to increase with the introduction of digital building models.

The current code-based approach for the seismic design of industrial facilities is considered not enough for ensure proper safety conditions against exceptional event entailing loss of content and related consequences. Accordingly, SPIF project (Seismic Performance of Multi-Component Systems in Special Risk Industrial Facilities) was proposed within the framework of the European H2020 - SERA funding scheme (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe).

The proposed project aims to investigate the seismic behaviour of multi-component systems in nuclear and special risk industrial facilities by means of shaking table tests paying special attention on the interactions between the primary structure and components as well as between the components themselves. Due to high cost of the process engineering components and due to the risk of operational interruptions and the release of harmful substances into air, water and ground in case of damage occur, the planned investigations are of utmost importance.

The test structure is a three-story moment resisting steel frame with vertical and horizontal vessels and cabinets, arranged on the three levels and connected by pipes. The dynamic behaviour of the test structure and installations is investigated with and without base isolation.

The achieved results on the seismic behaviour of the multi-component test structure with mutual interactions can be used for probabilistic safety analyses in power plants as well as in industrial plants. In addition, important findings can be derived for the definition of performance limits, the isolation of structural systems in plants and the use of sensor systems for rapid damage assessment.

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Project #35 – University of Bristol ST – SHAking Table TEsting for Near Fault Effect Evaluation (SHATTENFEE)

Recent surveys conducted after destructive earthquakes demonstrated that, in near-fault conditions, combined vertical and horizontal motions caused unusual damage to geotechnical and structural systems. The investigation of vertical ground motion, mono-dimensional propagation, and the ensuing soil-structure interaction is still scarce; therefore, this project aimed at investigating the soil response for near-fault response. To do so, the vertical dynamic behaviour of a typical soil deposit, with and without the presence of a foundation pile, has been explored experimentally on the 6-Degree-of-Freedom shaking table at the University of Bristol. A newly designed soil container has been utilized to analyse experimentally the vertical wave propagation.

The SHATTENFEE project was carried out to investigate experimentally the following learning outcomes (LOs):

1. Vertical response analysis of a typical soil column, e.g., estimation of natural frequency and amplification, vertical frequency variation due to densification induced by prolonged shaking;

2. Validation of numerical and theoretical models based on a reliable experimental database;

3. Potential nonlinear effects due to increased amplitude of input;

4. Assessment of the effects of the response of a piled foundation – SSI response.

The main objective of the above LOs includes the vertical dynamic identification/response of the soil model. Hence the experimental investigation mainly focused on the vertical dynamic behaviour in free-field conditions considering the following fundamental response quantities:

- fundamental vertical period of vibration (Tv);
- compression wave velocity (Vp);
- verification of the theoretical formulations correlating Tv, Vp and soil height H;
- vertical amplification amount (A_V).

Particular attention is paid to the definition of the test phases. Focal points have been the input signal type (i.e. white noise, harmonic input, and natural earthquake records), the input characteristics (i.e. duration, frequency and intensity), the identification of the dynamic response of the model, taking into account the soil-container interaction. Additionally, tests were also carried out on the empty cylindrical container.

The characterization of the vertical dynamic response was developed both experimentally and numerically. An extensive preliminary analytical study was carried out. The advanced experimental activity, the large dataset collected during the numerous shake table tests, and the analysis results provide insights for the understanding of the soil response. Such results can guide further research to improve the study of the seismic near-fault effects and may lead to guidelines and pre-code documents.

Project #36 – University of Bristol ST – SSI-STEEL: Soil-Structures Interaction effects for STEEL structures

Although modern Codes and Provisions concerning steel structures have been refined more and more in the last decades, however, several issues have not been solved yet. Among these, the one related to the fact that, in the current design practice, steel structures are modelled rigidly restrained at the base, neglecting the Soil-Structure Interaction (SSI) effects, is of paramount interest.

The dynamic response of structures founded on soft deposits may be different with respect to the one of the same structures on a rigid subsoil. In general, higher the structure-to-soil relative stiffness, higher the SSI effects (Veletsos and Meek, 1974). This relative stiffness, thus the SSI effects can be quantified by the so-called "Wave Parameter" (1/σ), defined according to *eq.* (1) (NEHRP Consultants Joint Venture, 2012):

$$\frac{1}{\sigma} = \frac{h}{V_s \cdot T} \qquad (1)$$

Where, referred to an equivalent SDOF system, V_s is the shear velocity of the soil deposit, T is the main structural period of the structure in the fixed-base condition, h is the height of the mass.

On the one hand, the period elongation, due to the additional deformability, and the added damping, due to the dissipation of a part of the vibrational energy through the ground, could lead to reduced seismic actions/effects on the structural system. Thus, SSI is commonly neglected, since it is assumed that its omission leads to conservative seismic response results.

On the other hand, tests and analyses demonstrate that, for some period ranges, SSI could provoke an undesired detriment of the structural response, in terms of unexpected demands of strength and ductility.

Several numerical studies proved that the inclusion of SSI in practical seismic analyses can be performed approximately by employing spring-dashpot-mass discrete linear models, as those developed by (Mulliken and Karabalis, 1998) and (Wolf, 1994). Nevertheless, these models cannot capture non-linear phenomena near the soil-structure region, e.g. the foundation uplift/sliding and the plasticity of the soil, which, conversely, can be taken into account only by using macro-elements (Millen *et al.*, 2018), beam-on-non-linear-Winkler foundations (Harden and Hutchinson, 2009) or other contact models (Gajan and Kutter, 2009).

In literature, so far, few researchers have studied SSI effects on the seismic response of steel structures. Among these, the numerical works of (Raychowdhury, 2011), (Farhadi, Saffari and Torkzadeh, 2018), (Minasidis, Hatzigeorgiou and Beskos, 2014) are surely worth of being mentioned. Also, some efforts have been undertaken in order to investigate the SSI effects on structures with dampers: (Flogeras and Papagiannopoulos, 2017) carried out some analyses on buckling restrained braces, whereas (Zhou, Guo and Yong, 2012) investigated structures with velocity-dependent dampers, proving that SSI significantly modifies frequencies, damping and mode shapes. Nevertheless, several issues remain unexplored, such as the influence of SSI on structures with dampers that use materials with significant strain-rate dependency (e.g. shape memory allows).

As far as the experimental studies are concerned, one of the most interesting campaign concerning SSI effects was carried out at the BLADE laboratory of the University of Bristol as part of the European project SERIES (Durante *et al.*, 2015), (Durante *et al.*, 2016). Shake table tests were carried out on a group of five piles crossing two different layers of soil. The superstructure was a simple oscillator formed by an aluminium or steel column with an added mass on the top that was varied in order to get different dynamic responses. The obtained results allowed to appraise the influence of SSI in terms of change of natural frequencies due to the SSI, also depending on the piles head conditions. Furthermore, experimental tests in order to study the response of two physical models characterized by a partially embedded shallow foundation were carried out at the same laboratory (Massimino and Maugeri, 2013). All the results of these tests were used to calibrate SSI nonlinear models.

In this frame of research, the SSI-STEEL project (Soil-Structures Interaction effects for STEEL structures) deals with an experimental campaign, through shake-table tests, to be carried out on different steel structural systems in order to achieve a better knowledge on the SSI effects on their dynamic linear and non-linear responses. In particular, three structural types are investigated, those are: *i)* a Concentrically Braced Frame (*CBF*), *ii)* a Moment Resisting Frame (*MRF*) -also considering the presence of a beam reduced end sections- and *iii*) dual steel frame (*DSF*) with a new brace-type damper made of a shape memory alloy material.

Few similar experimental researches concerning SSI effects on steel frames are currently present in literature. They are often focused on SDOF systems made of a column with a mass atop -as the study of Durante et al. (2015)- or, when more complex structures are considered, just investigate specific aspects influencing the structural response of steel structures. For example (Tabatabaiefar, Fatahi and Samali, 2014) performed shake table tests on a 15-story properly scaled steel frames under four different earthquakes: the experimental and numerical outcomes obtained by validated numerical models allowed to evidence the detrimental effects due to the SSI in terms of elastic displacements.

On the other hand, there are not experimental studies that compares the SSI influence on the responses of different structural types designed according the same criteria, as well as that consider also nonlinear phenomena such as buckling and yielding. These are the aspects that the project aims to investigate. The goal is to lead the current knowledge to a larger extent and to propose modification factors, to be expressed as a function of the soil-to-structure relative stiffness, to be included in the current design formulations that are of interest for technicians. Therefore, the proposed research represents a significant breakthrough in the field of structural / geotechnical engineering, with evident returns in terms of Code/Provisions updates and meaningful design tools that will be used by engineers in the future.

The whole research activity is articulated into five steps:

Step 1. Design of the frames to be tested
Step 2. Set up of preliminary numerical models
Step 3. Shake Table Tests
Step 4. Validation of the Numerical Simulation Procedure
Step 5. Execution of Numerical Parametric Analyses.

Steps 1-2-3 are the core of the project presented in the current report. Steps 4-5 are activities that will be carried out after the project, according to a refinement/validation of the model developed in Step 2 based on the tests developed in Step 3.

It must be pointed out that, so far, the shaking table tests, which have been designed and for which all the specimens been manufactured, have not been carried out yet. In fact they were scheduled for the second decade of March (starting from the 16^{th}), but, because of the national/international restrictions due to the SARS-CoV-2 all the involved researchers have had limitations to mobility, this making impossible to do the tests, which, anyway, will be carried out in a later phase, immediately after the end of the ongoing Coronavirus pandemic.

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Project #37 – IZIIS ST – INfills and MASonry structures protected by deformable POLyurethanes in seismic areas (INMASPOL)

The behaviour of RC frames with masonry wall infills is influenced a lot by the stiffness and yield displacement difference between the frame and the infill. The flexible frame is unable to carry high loads at low displacements and this can cause the infill to damage already at moderate seismic intensity. In case of aftershocks, the damaged infills can fail out-of-plane. On the other hand, if the stiff infill is too strong relative to the column, it may cause undesirable behaviour of the frame or even shear failure in the column. The response of structural system can be improved by using a flexible interface between the frame and the infill. This project consisted of testing RC frames with a flexible joint made of polyurethane (PUFJ) with the masonry wall infills. The application of around 2 cm thick PUFJ reduces the stress concentrations at the contact and thereby reduces damage to infills and RC frames and improves the displacement capacity of the structural system. Furthermore, it offers additional amount of damping. Despite the flexibility of the polyurethane (PU), the bond between the PU and the other materials can transfer significant loads during in-plane and out-of-plane excitations. The PUFJ is versatile because different types of PU with very different stiffness, damping and strength characteristics can be used to manipulate the system dynamic behaviour. In case of premature out-of-plane flexural or in-plane diagonal tension infill failure, PUs can be used for bonding of various composite fibres to the weak masonry substrate to form Fiber Reinforced PU (FRPU) as well as for repair of damaged RC frames. The PU can cover emergency situations as it cures within hours and is easy to apply. The proposed project assessed the efficiency of the method through testing of full-scale infilled RC building on shake table. The seismic tests validated in-plane and out-of-plane infill performance when modified, repaired or strengthened with PUFJ and FRPU systems.

Project #38 – EUROSEISTEST – Resonant metamaterial-based earthquake risk mitigation of large-scale structures and infrastructure systems: assessment of an innovative proof-of-concept via medium-size scale testing

Periodic and resonant foundations and buried anti-vibration barriers designed to attenuate the propagation of seismic waves can represent a breakthrough for the safety and the preservation of historical and strategic infrastructures, including hospitals and power plants (Bao et al, 2011; Basone et al., 2019; Krodel et al., 2015; Miniaci et al., 2016; Palermo et al., 2016; Shi et al., 2014; Smith and Smith, 2015; Sun et al., 2019; Yan et al., 2014). These isolation systems commonly referred to as ”seismic metamaterials” (Brule et al., 2014; Colombi et al., 2016), base their capabilities on physical concepts recently developed in material science and solid-state physics, where novel materials dubbed “phononic crystals” and “resonant metamaterials” have been introduced to control the propagation of elastic waves (Deymier, 2013).

Phononic crystals are periodic materials that can exhibit large band gaps, i.e., frequency regions where the propagation of waves with wavelengths in the order of material periodicity is hindered. For seismic scale applications, meter size phononic crystals made of cylindrical holes in sedimentary soil have proved the possibility of reflecting seismic elastic energy, achieving attenuation of ground accelerations at a frequency range around 50 Hz (Brule et al., 2014). Although revolutionary in their conception, implementation of these systems at the low frequencies characteristic of seismic events (<30 Hz) requires very large structures, since the wavelengths of typical seismic waves can be of several decameters.

Unlike phononic crystals, resonant metamaterials exploit an array of sub-wavelength units to attenuate the propagating waves without relying on material periodicity. Therefore, for seismic waves characterized by long wavelengths, resonant metamaterials allow for the construction of more viable devices, i.e., of smaller and feasible dimensions. Based on this paradigm, meter-size buried structures, in the form of resonant metafoundations (Cheng and Shi, 2013) or resonant metabarriers (Palermo et al., 2016), have been proposed in recent years to isolate buildings and infrastructures from incoming seismic longitudinal and shear waves or to shield them from surface Rayleigh waves, respectively. The idea of a resonant metabarrier is motivated by the fact that far from the epicenter surface waves can carry a significant portion of the earthquake energy (Graff, 1975) and that existing structures may be hard to be retrofitted with innovative foundation systems.

The resonant metabarrier exploits purposely designed resonant units able to interact with surface waves in the low-frequency regime (<10 Hz). The resonant units are passive devices (mass-stiffness resonators), placed atop of the soil or buried below the surface, and excited by the vertical component of the Rayleigh wave motion. Once activated, their dynamic interaction with the soil redirects part of the surface elastic Rayleigh wave energy into the soil deposit as vertically polarized shear waves. The dynamics of these resonant systems has been predicted analytically and verified numerically at different wave scales, or in other words, at different frequencies. Conversely, experimental proofs of their working mechanism and attenuation capabilities are up to now limited to few table-top experimental tests (Palermo et al., 2016). Nonetheless, measurements at the geophysical scale have shown a reduction of the surface motion due to the resonance of forest trees (Colombi et al., 2016), encouraging the realization of an experimental proof of a metabarrier working in the Hz range. Indeed, full-scale realizations and tests of a resonant barrier are still missing, probably due to its cost of realization as well as due to the significant resonating mass needed to activate the wave conversion.

Therefore, the REWARD project has been designed to make a further step towards the realization of this isolation system for seismic waves by testing the effectiveness of a resonant metabarrier at a medium-size scale, within a 50−100 Hz frequency range, taking into account the variability in stiffness and strength of the soil profile. Here we report the results of the experimental campaign, developed at the Euroseistest TA facility (Pitilakis et al., 2008), where a metabarrier has been designed according to the in-situ soil properties and the available operative frequency range of the measuring equipment and tested.

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Project #39 – EUROSEISTEST – "DYMOBRIS" Dynamic identification and Monitoring of scoured BRIdgeS under earthquake hazard

Bridge scour, the removal of sediments surrounding underwater foundations due to water flow and turbulence (Melville and Coleman, 2000; Pizarro et al., 2020) is the leading cause of bridge failure worldwide. Exacerbated by climate change effects (Imam, 2019; Fioklou and Alipour, 2017), this phenomenon induces considerable fatalities, traffic disruption, and significant economic and societal losses. Notable examples of recent failures in Europe are the Margarola bridge in Spain (two casualties) and the Hintze Ribeiro bridge in Portugal, that collapsed in 2001 due to general degradation of the riverbed, causing 60 casualties (Innovation & Research Focus Issue 93, 2013).

Foundation scour has two main effects on bridges: loss of foundation carrying capacity, and increased flexibility of the soil-foundation-structure (SFS) system. Many types of bridges, such as masonry-arch or multi-span bridges, have shallow foundations and are very vulnerable to scour (Tubaldi et al, 2018), which often worsens with time due to accumulation of the effects, i.e. scour, under multiple floods (Tubaldi et al., 2017). New bridges usually have deep foundations, making them less vulnerable to scour. However, even for these bridges, the scouring of their foundations may result in changing of the boundary conditions, which may modify and eventually decrease their capability to withstand loadings.

It is well known that the overall response of bridges to dynamic loads such as those induced by earthquakes is dependent on SFS interaction effects (Gazetas, 1991). Thus, scour has also a significant potential to alter this response, by affecting both the kinematic and inertial soil-structure interaction (Guo, 2014) and increasing modal periods. Since many bridges spanning waterways are located in seismically active regions, the occurrence of earthquakes in the presence of flood-induced scour is a very likely, and hence critical design scenario (Yilmaz et al., 2016).Thus, understanding the complex interaction between the continuously evolving scour process and the dynamic behaviour of the affected bridges is of paramount importance for quantifying the risk and resilience of our infrastructure under multiple hazards (Argyroudis et al., 2020). This also calls for the development and deployment of innovative sensors and monitoring strategies for assessing scour and its effects on bridges (Prendergast and Gavin,2014), without having to resort to potentially costly and inaccurate visual underwater inspections. In this context, monitoring the change of dynamic features of bridge superstructure, without recourse to underwater instrumentation, appears to be a very promising technique to detect scour (Foti and Sabia, 2011). For example, Briaud et al. (2011) focused on the use of accelerometers and tiltmeters to monitor scour, and for this purpose, they carried out two large scale laboratory models of a column and a column on piles. Subsequently, two individual monitoring systems were designed and installed on two real bridges. The results of the experimental campaigns showed that the instruments could be successfully employed to provide warnings of potential bridge failure. However, there were shortcomings with regard to the accelerometers, which are related to lack of sufficient excitation from traffic and the high-power consumption required for the transmission of accelerometer data, for which typical solar panel and battery are not sufficient. Another study (Prendergast et al., 2013) focused on single cantilever piles with the bottom part embedded in the soil, excited by a top impulse force, and on the development of a finite element model for capturing the effects of scour. The study showed that the effect of water on the measured natural frequencies of the cantilevers is negligible. Bao et al. (2017) conducted similar experiments for vibration-based monitoring of scour and also investigated the effect of the scour hole shape. This is usually assumed as symmetric in experiments, whereas in reality it has a non-symmetric shape (Tubaldi et al., 2018). Unsymmetrical scour hole scenarios were tested, shedding light on the importance of this factor for vibration-based scour detection.

Even though many studies have investigated experimentally and numerically the dynamic behaviour of bridges with deep foundations subjected to scour (Zhang et al., 2017), it is surprising that researches on bridges with shallow foundations are quite scarce. To our best knowledge, only the works of Guo (2014) and Yuan et al. (2019) have investigated numerically the impact of scour on bridges with shallow foundations. Guo (2014) analysed the changes of foundation impedances due to foundation scour, highlighting the reduction of foundation stiffness and radiation damping, and evaluating the effects on the seismic performance. Based on the study results, it was found that scour may be beneficial for mitigating seismic force demands, though it may induce excessive displacement demands in case of severe foundation scour profiles. Yuan et al. (2019) investigated the effect of scour on the seismic vulnerability of a two-dimensional bridge model, showing how the various bridge components may be differently affected by scour. Thus, further research on shallow foundations is urgently needed, given the importance of the problem, the high number of bridges with shallow foundations, and the higher impact of scour on this type of foundations compared to deep ones.

The DYMOBRIS project was conceived with the objective of contributing to fill this knowledge gap. For this purpose, full-scale tests, from ambient vibrations to forced-vibrations, were carried out on the EuroProteas SFS system at Euroseistest to evaluate the effects of foundation scour on the dynamic properties, i.e. frequency and damping, of a Soil- Foundation-Structure (SFS) system. The experimental tests were complemented by numerical analyses, aimed to identify the extent of the scour hole to be excavated in the tests, and to evaluate the suitability of various modelling strategies for simulating the effects of scour.

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Project #40 – EUROSEISTEST – SOil Frame-Interaction Analysis through large-scale tests and advanced numerical finite element modeling (SOFIA)

The Project SOFIA was devoted to studying full-coupled large-scale soil-structure systems including new isolating materials (GRM mixtures), investigated by full-scale experimental tests on the existing EUROPROTEAS structure in the EUROSEISTEST site, to be subsequently modelled by advanced numerical FEM codes. The main goals have been: investigating the material and radiation damping of the wavefield emanating from the foundation; studying the wave propagation away from the structure; investigating the influence of rubberized foundation soil on the response of the structure; validating advanced FEM modelling of DSSI (dynamic soil-structure interaction).

As for field and laboratory studies, DSSI phenomena are commonly studied in small-scale by 1-g or N-g shaking-table tests (Pitilakis et al., 2010; Abate et al., 2010; Abate & Massimino, 2016; Massimino et al., 2019a). Laboratory studies are particularly precious for the known initial and boundary conditions, and a large number of applied instrumentations. However, very often they show some disadvantages, such as certain limitations in reproducing actual field conditions (unbounded subsoil medium, radiation condition to infinity and realistic stress fields in the soil). On the other hand, large-scale field experiments account for realistic boundary conditions and fulfil the radiation condition to infinity; but up to now, very few large-scale experiments have been performed, such as that at EUROSEISTEST (Pitilakis et al., 1999; 2013; 2014; Abate et al., 2017).

Among numerical approaches, finite element (FE) modelling is nowadays widely performed. FE modelling allows a realistic evaluation of coupled soil-foundation-superstructure system, in terms of initial and boundary conditions, soil profile, geometry, nonlinearity of soil and/or soil-foundation interface, even if, nowadays, fully-coupled analyses are still very rare, above all concerning the interface modelling (De Barros & Luco, 1995; Massimino et al, 2018; Massimino et al., 2019b).

However, FEM modelling, combined with field and laboratory tests, is the most useful tools for investigating the complexity of DSSI (Combescure & Chaudat, 2000; Paolucci et al., 2000; Massimino & Maugeri, 2013; Biondi et al., 2003; 2015; Ueng et al., 2006; Abate et al., 2007; 2008a, 2008b; 2017; Ugalde et al., 2007; Anastasopoulos et al., 2013; Pitilakis et al., 2015).

The pressing environmental need for recycling waste automobile tires led to reuse these materials. In the last two decades, many geotechnical projects have been devoted to recycling rubber poor or mixed with granular soils (SRM = sand-rubber mixtures; GRM = gravel-rubber mixtures) in an innovative manner. The mixtures of granular soils with granulated rubber display satisfactory natural and mechanical properties (low specific weight, high strength, high flexibility and high level of permeability). Primary geotechnical field applications include backfilling in embankments, road constructions and retaining walls structures (Zhang et al., 2018; Khatami et al., 2020). Feasibility studies on the capability of rubberized soils for vibration isolation against earthquake have also been carried out (Tsang et al., 2009; Senetakis et al., 2015; Argyroudis et al., 2016). Vibration is isolated mainly by the high damping ratio and energy-absorbing attributes of the rubber inclusions. For these reasons, these mixtures can represent a very useful isolation systems for buildings.

So, the impact of the results of the SOFIA Project, dealing with new large-scale tests on fully-coupled systems with different GRM, can be remarkable both on current and future research and on practice.

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Project #41 – NORSAR SA – Earthquake Spectral Provisions and Urban Fragility Evaluation - ESPUFE

Seismic prevention and mitigation of historical towns/centers have gained a central position within earthquake engineering topics, particularly in such areas having a high seismic risk. They have been modelled in terms of structural safety with a comprehensive strategy for seismic prevention and mitigation. In this project, two complex cases of Italian historical town have been selected for development of risk reduction programmes. The carried-out approach was based on two main parts:

- the first was urban risk assessment

- the second was a prioritization of retrofitting interventions to optimally increase urban safety.

Seismic input has been assumed as a function of the earthquake intensity expressed in terms of Mercalli-Cancani-Sieberg (MCS) intensity scale and fragility functions was defined in order to evaluate the probability of failure of each class of buildings or infrastructures. The MCS intensity scale is linked to the detected damage (post-earthquake damage). The detected damage is depending both on damage evaluation procedure and on social “pressure” on infrastructure under evaluation.

Due to the uncertainties involved in the analysis, a probabilistic approach had to be applied. Generally, the proposed methodology involves the following steps:

(i) identification of the Urban Minimum System (UMS);

(ii) selection of the target safety level, which is dependent on the component type;

(iii) definition for each component of the fragility curve, which gives the probability of a structure to exceed a certain limit state;

(iv) evaluation of the fragility behaviour of the whole system by applying structural reliability methods;

(v) identification of an optimal retrofitting strategy.

With respect to performance levels Significant Damage (SD) and Damage Limitation (DL) have been considered. The obtained fragility functions define the probability of failure of each class of buildings as a function of the earthquake intensity expressed in terms of Mercalli-Cancani-Sieberg (MCS) intensity scale.

The implemented procedure concerns exclusively the urban configuration and it shows a weak aspect in the earthquake intensity definition in terms of Mercalli-Cancani-Sieberg (MCS) intensity scale. The logical steps within the improved project are the followings:

(i) definition of a site catalogue of historical seismicity at different sites involved in recent earthquakes;

(ii) seismic hazard definition by means of deterministic or probabilistic approach including site effects (using NORSAR’s Liquefact Software and collected pre-earthquake data);

(iii) earthquake input definition for the UMS probabilistic approach (i.e., PGA maps, MCS maps, ...) to the selected urban area;

(iv) fragility curves fitting to this selected earthquake input (using NORSAR’s Liquefact Software and proposed new fragility curves calibrated on post-earthquake data).

Project #42 – NORSAR SA – Beamforming of aftershock strong-motion time-histories recorded on the ICEARRAY for earthquake source studies

Using a unique dataset of over 1700 ml 0.4-4.8 aftershocks of the Mw 6.3 Ölfus earthquake in the South Iceland Seismic Zone on 29 May 2008, recorded at hypocentral distances between 3 to 18 km by the ICEARRAY accelerometric array of 11 stations with inter station distances between 54 and 1900 m, we have applied conventional array data analysis at first and intend to apply a beamforming algorithm to produce clear waveforms that allow a detailed earthquake source analysis using a suite of theoretical crack rupture source models. A relocation of the aftershocks based on the array data will be done to decide whether a specific array response calibration can yield higher array-derived direction of arrival accuracy. Additionally, the near-source array data may allow tracking of the mainshock's rupture front propagation across its two faults, which can be a valuable addition to training datasets of array-based Earthquake Early Warning applications. Created code will be made available to increase the capabilities of the community.

Phase detection and identification using frequency wavenumber analysis and cross-correlations are to be carried out, improved location of all recorded aftershocks using a circular wavefront assumption due to proximity, and determination of magnitude are to be done as well. Since many strong and shallow earthquakes have been recorded, attempts at analysing larger events through full waveform simulations will be made to study near-source effects. The earthquake spectra will be analysed to derive physical source parameters through Bayesian inference. These studies will give indications as to how well earthquake parameters can be resolved with a near-source array and physical modelling. The rupture propagation of the main shock (2008-05-29 M6.3) shall be illuminated using the array data. Besides posters, presentations and papers about the findings to be published, created computer code (mostly Python) useful to the community will be published online. The gained insight, training and new code will be useful in routine and advanced analysis of real-time data from the new array HEKSISZ of the Icelandic Meteorological Office, which will monitor the seismicity under the volcano Hekla and in the surrounding active region.

Project #43 – NORSAR SA – Investigation of (micro-)seismicity of the Laptev Sea using a small-aperture array

So far, the local (micro-)seismicity of the Laptev Sea region is poorly described, due to a lack of local seismological stations and data sets. To investigate the regional seismicity of the Laptev Sea, 13 stations were temporarily installed as a seismological small-aperture array of 2 km width close to Tiksi. Over a period of nine months, these instruments continuously recorded seismic data under the extremely harsh environmental conditions. The data of the Tiksi-Array shows a large number of small events and the array azimuth determination points to the nearby coastline of the Buor Khaya Bay. The results from array-processing will help to investigate the geodynamic processes of the Laptev Sea Rift and to better describe this amagmatic rifting and its consequences in an Arctic and global context.

The project is aimed to investigate the seismicity of the continental Laptev Sea Rift using new data from a small-aperture array. Located north to the Laptev Sea, the ultraslow spreading Gakkel Ridge is propagating into a continental rift system – the Laptev Sea Rift. This rift system separates the North American plate from the Eurasian plate and presents a rare opportunity to investigate mechanisms of recent continental breakups. In general, divergent plate boundaries are accompanied by magmatic and earthquake activities. The earthquake activity at the Gakkel Ridge shows a sharp image of seismicity, confined to the rift valley that extends to the continental shelf of the Laptev Sea. In contrast, the Laptev Sea region indicates less and more diffuse seismicity and an absence of magmatic activity. However, new data from a local array close to Tiksi show a large number of small events. With array processing techniques the main objective will be to detect these events and analyse their spatio-temporal distribution.

Project #44 – NORSAR SA – Design, location and processing of a regional array in SW Portugal - Europe

A permanent seismic array will be installed in Portugal to study its seismicity and that of adjacent zones, and to support the national Earthquake Early Warning System (EEWS). Nevertheless, Portugal does not have own experience in this field of seismic research. To install a seismic array, several subjects must be addressed before the installation such as location, seismic instrumentation, and aperture and geometry of the array.

Visiting NORSAR is paramount to acquire skills in the seismic array design and processing. Concerning data processing, there are several processing methods available like beamforming, f-k analysis, VESPA process, slant stacks. The access to NORSAR is advantageous to gather knowledge and experience from a leading institution in seismic arrays.

With the research visit, we will define the design and siting of the seismic array that fulfil the following goals: monitoring in detail the seismicity, refine velocity models, detection of small-scale heterogeneities, forensic seismology.

The main goals proposed were attained with the design of the seismic array and data processing.

The implementation of a seismic array in Portugal will allow to study in detail the micro-seismicity and seismicity on the offshore of SW Iberia and the Iberia itself. The array is a paramount infrastructure on the study of the seismogenic sources of the 1755 Lisbon earthquake (M 8.5-9.0) and the one of 1969 (Mw 8.0).

Improving the knowledge of the seismogenic sources on the offshore is essential to assess and review the seismic hazard models and develop scenarios.

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