EUROPEAN LABORATORY FOR STRUCTURAL ASSESSMENT: 30 YEARS OF COLLABORATIVE RESEARCH

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Abstract: *The European Commission's Joint Research Centre (JRC) inaugurated the European Laboratory for Structural Assessment (ELSA) in 1992. The ELSA Reaction Wall facility has unique dimensions and testing capabilities in Europe and worldwide. ELSA has become a world-renowned reference for experimental research in earthquake engineering, fostering collaboration across laboratories, research centres, academia and industry, and providing transnational access to the Reaction Wall facility within the European Union framework programmes for research and innovation. This paper revisits selected large-scale experimental tests that were performed at the ELSA Reaction Wall in the framework of collaborative research projects and summarises the key developments of the continuous pseudodynamic testing method, which allowed more efficient seismic testing of large-scale specimens. The impact of collaborative research at the ELSA Reaction Wall has been manifold: i) advancement of the knowledge on the structural and seismic safety of structures, ii) development of conventional and innovative techniques for the design, assessment and retrofit of buildings and bridges for earthquake resistance, iii) transfer of state-of-the-art knowledge to European and international standards and codes of practice, and iv) training of young researchers.*

1. Introduction

The European Commission's Joint Research Centre (JRC) inaugurated the European Laboratory for Structural Assessment (ELSA) in 1992. The construction and operation of the ELSA Reaction Wall filled the gap of a European research infrastructure with the physical and technological capacity to test real-scale structures with high quality, independence and in collaboration with the European and international scientific community. Over the last 30 years, the ELSA scientific and technical staff has implemented and continuously refined the pseudodynamic (PsD) testing method and performed numerous large-scale reference tests.

ELSA operates a 16 m-tall, 21 m-long Reaction Wall, with two reaction platforms of total surface 760 m^2 that allow testing real-scale specimens on both sides of the wall. The laboratory is equipped with 28 actuators with capacities between 0.2 and 3.0 MN and strokes between ±0.125 and ±0.5 m. The actuators control system is designed in-house to perform tests with the step and continuous PsD methods with substructuring, that permits testing elements of large structures, bidirectional testing of multi-storey buildings, and testing of strain-rate dependent devices.

The experimental tests that are conducted at ELSA are of such scale and complexity, that no other infrastructure in Europe can match. Eventually, an experimental campaign at ELSA starts with the internal or external calibration of the instruments to be used –while the specimen is constructed outside of the lab–, transportation of the specimen into the lab and clamping it to the strong floor. Then it continues with the installation of instrumentation, actuators and controller, execution of preliminary small tests for the controller tuning and execution of nominal tests –with data treatment and test quality checks in parallel. Finally, the specimen is transported outside of the lab for its demolition. 'Built-in safety' design has been introduced since 2018. Occupational health and safety issues are managed from the design of the experimental campaign, improving the safety management of research projects without affecting delivery times and budgets.

Since its opening, ELSA developed a tradition of collaboration with research and industrial partners from all over Europe, thus contributing to the establishment of the European Research Area through supporting mobility of researchers and offering transnational access within the European Union framework programmes for research and innovation, and the programme for opening access to JRC research infrastructures.

This paper revisits selected large-scale experimental tests that were performed at the ELSA Reaction Wall in the framework of collaborative research projects. It also summarises the key developments of the continuous pseudodynamic testing method, which allowed more efficient seismic testing of large-scale specimens. In particular, the paper highlights the challenges and accomplishments of test campaigns on various types of structures, such as reinforced concrete (RC) buildings representative of existing vulnerable structures, precast concrete buildings for industrial and commercial use, and full-scale bridges including irregular configurations, isolation and asynchronous input motion. Because of limited space, several older tests on RC frame buildings with and without infills, steel structures and soil-structure interaction are not included.

2. The pseudodynamic method

From the studies in the 1980s (Shing and Mahin 1987), it was made clear that pseudodynamic tests could be much more sensitive to experimental errors than simple quasi-static tests, due to cumulative effects that appear in closed loop systems in which the measurements are fed back for the determination of the targets.

From the early 1990s, a main objective for ELSA was the implementation of the PsD method with modern digital controllers and reliable time-step integration algorithms and the verification of the accuracy (Donea et al., 1996, Magonette and Negro, 1998). The digital controller, associated to the encoder displacement transducers, made possible a significant reduction of the errors and allowed the execution of PsD tests in a reliable manner on multi-storey real-size buildings (Negro et al. 1996), even with bidirectional action (Molina et al. 1999), and substructured bridges with physical piers of realistic size (Pinto et al. 2004). A typical time step of 1 to 5 ms in the prototype ground acceleration time history was performed in a real-time lapse in the order of one to several seconds, consequently with a time-scale factor in the order of 100 or 1000. The real-time step comprised a ramp for the increment of the target and subsequent phases for stabilisation, measurement and computation. The choice of the duration of those phases affects the error magnitude because the move-and-stop nature of this 'classic' or 'step' PsD method is the origin of real-time mechanical oscillations that ideally should not enter in the prototype response.

Those oscillations were drastically cancelled with the introduction in the 2000s of the 'continuous' PsD method which meant another improvement in accuracy. Using the continuous method, every sampling time of the digital controller (of 2 ms of real time in those years) was used for performing a sub-step in the equation of motion with all the ramp, stabilisation, measurement and computation phases included in it (Magonette et al. 1998). This required dividing the accelerogram step in sub-steps of just a few microseconds when a time-scale factor in the order of 100 was applied. This method also allowed performing the tests with a shorter real-time duration, which was an advantage for reducing the stress-relaxation effect in the behaviour of the materials. For example, for the PRECAST-EC8 experiments described in section 4, typically an accelerogram of 30s was reproduced in the lab in less than one hour.

The adaptation of the substructuring methods to the continuous technique was a challenge when the model of the numerical substructure was non-linear since this could not be solved within 2 ms, or even less, of real time. The problem was solved at ELSA by developing a partitioned method that combines an explicit algorithm for small sub-steps at the physical substructure with an implicit algorithm for larger steps at the numerical substructure (Pegon et al. 2008). Thanks to this method, the accuracy improvement of the continuous technique was also observed in the substructured tests. For example, the accuracy of the RETRO substructured experiments described in section 6 regarding the effects of the control errors is reported by Molina et al. (2017).

Even though the developed methods and the hardware improvements, such as faster controllers, more accurate transducers and dramatic reduction of the length of the cables for analogue signals in recent years (Peroni et al. 2021), have allowed for further performance of the PsD technique, limits always exist and compromises need to be done in order to have reliable results within a reasonable duration of the tests. In order to assess the response distortion that is introduced by the control errors in PsD tests, ELSA has developed a special analysis technique that uses the tests measurements without needing a previous theoretical model for the tested specimen. This technique directly identifies a spatial model in the time domain and uses it for estimating frequency and damping distortions at every mode of the structure helping to assess the validity of the performed experiment (Molina et al. 2011, Molina et al. 2017).

3. Reinforced concrete buildings

One of the first PsD tests conducted at ELSA was aimed at providing the necessary experimental data for the commissioning of the first draft of Eurocode 8. The research involved a large number of European experts in earthquake engineering who were serving in the relevant CEN committee. The mock-up was a four-storey two-bay by two-bay full scale specimen (Negro et al. 1996). The PsD tests represented a primer for the implementation of the PsD method at ELSA, and were conducted for different values of peak ground acceleration up to 1.5 times the design acceleration. They yielded a wealth of experimental results, which assisted in the calibration of the numerical models developed by the participants in the research project, which in turn were used in the assessment of the code provisions. In particular, light was thrown onto the effects of the adoption of the B500 Tempcore steel, which was becoming dominant at those times, and the possible consequences in terms of cyclic damage (Negro 1997).

The same mock-up was reused to investigate the effects of non-structural masonry claddings. PsD tests were repeated with both a uniform pattern of infills and a soft-storey configuration, confirming the importance of those effects, which were not considered in design at those times (Negro and Verzeletti 1996). This evidence justified the conduct of a new research project on a new three-storey RC frame, which was specifically designed to account for the presence of irregular infills (Fardis et al. 1999) through rules that subsequently found their way in the Eurocodes.

It later became evident that the frontier of earthquake engineering was the assessment and rehabilitation of the existing under-performing reinforced concrete buildings, an issue that recurrently emerges in reconnaissance reports, e.g. (Pinto et al. 2003), for which dedicated clauses were badly needed in the Eurocodes. This motivated the project Seismic Performance and Assessment and Rehabilitation of existing buildings (SPEAR), funded by the Competitive and Sustainable Growth Programme (Fardis & Negro 2005).

The core of the activity involved the testing of a three-storey RC building which was designed as representative of the constructions of the 60's and 70's in Southern Europe. The mock-up adopted mild steel in smooth rebars, the detailing included bent rebars for shear resistance and was affected by the systematic lack of strength hierarchy (or capacity design) criteria and from insufficient confinement. More importantly, to adequately represent the existing stock of buildings lacking seismic design provisions, it was decided to introduce some sources of in-plan irregularities in the mock-up. The specimen (Figure 1) had columns of different sizes and the frames were not planar, thus resulting into an in-plan irregularity of 13 %.

To account for the torsional irregularity, bidirectional PsD tests had to be conducted, by defining two components of the seismic input and by controlling the two horizontal degrees of freedom as well as the rotation of each storey, a primer in the PsD testing of full-scale structures. Tests were conducted on the original under-performing structure, thus yielding precious information about the behaviour of non-ductile structures as well as about the effects of in-plane irregularity. The tests were then repeated for two conceptually different rehabilitation strategies: the first one was based on the use of carbon fibre laminates to increase the ductility of all potential plastic hinge locations (Di Ludovico et al. 2008), the other aimed at reducing the strength eccentricity by strengthening some of the columns by means of traditional steel and concrete jacketing. The first approach turned out to be much more effective (Negro & Mola 2015), demonstrating that stiffness eccentricity and available ductility govern the seismic response rather than strength. The test results, along with those obtained by the other partners in the project on smaller specimens, much assisted in defining the Eurocode 8 clauses for the redesign of existing buildings.

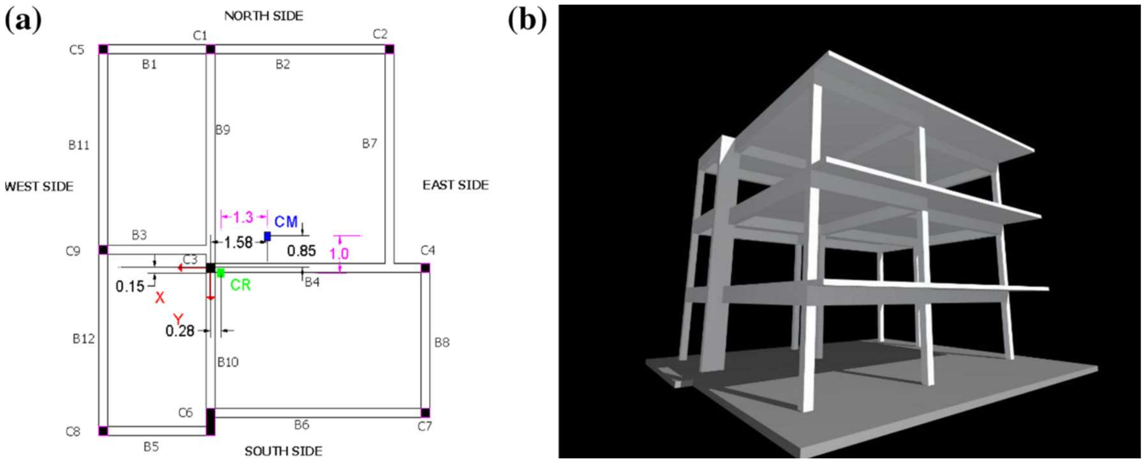

Figure 1. Plan configuration (left) and rendering (right) of the SPEAR structure

New walls are an effective and economic method for retrofitting multi-storey reinforced concrete buildings, especially those with soft storeys. However, Eurocode 8 (CEN 2005) does not cover this technique, contrary to jacketing with concrete, steel and fibre reinforced polymers. Previous experimental research addressed squat walls of small thickness that are not representative of the flexure-dominated response and the effect of higher modes on multi-storey buildings with slender walls. The SERFIN project, proposed by a research group from the Cyprus University of Technology, University of Cyprus, École Centrale de Nantes and DENCO design & engineering consultants, within the transnational access activities of the SERA project, studied a four-storey frame structure with the central bay infilled with an RC wall (Chrysostomou et al. 2013). Different connection details and reinforcement percentages for the two infilled bays were used.

The real-scale specimen was 12.0 m high, 6.0 m wide and 8.5 m long (

Figure 2). The frames were designed and detailed for gravity loads only and were typical of frame buildings constructed in Cyprus in the 1970's. The material properties used in the specimen were constrained by the availability of materials in the Italian and European market. Two PsD tests were performed for input motion with 0.10g and 0.25g maximum peak ground acceleration. The high stiffness of the specimen with infill walls resulted in difficulties in the displacement control typically used for PsD tests. In order to guarantee stable behaviour, the control parameters were tuned and the test was conducted 800 times slower than the real duration of the input acceleration time history. A cyclic test was run next to explore the final capacity of the specimen.

Figure 2. The four-storey SERFIN specimen with infill walls in the central bay.

The tests demonstrated that adding infill walls is a viable method to increase the strength and ductility of existing frame buildings. Indeed, the structure sustained an earthquake of 0.25g without significant damage and showed five times higher resistance, compared to a typical 1970's building in Cyprus. The two connection arrangements performed satisfactorily, but no solid conclusions could be drawn on the advantages of the one over the other. Finally, the tests confirmed the flexural response slender walls and the effect of higher modes on multi-storey buildings.

The SlabSTRESS project aimed to fill the standardisation gap for the use of flat slab RC structures in seismic zones. The European standard EN 1998-1 for the seismic design of buildings (CEN 2004) does not provide specific guidance on flat slab design, while several European countries in seismic zones have already adopted this solution for low-rise buildings (Coronelli 2020).

The test structure was a real-scale two-storey flat slab frame with three by two bays, as shown in Figure 3. The floors were standard 0.2 m thick reinforced concrete slabs. The spans were 4.5 m and 5 m in the longitudinal direction and 4.5 m in the transverse direction. The storey height was 3.2 m. Columns cross-sections were square with dimensions 0.4, 0.35 and 0.3 m for internal, edge and corner columns respectively. Numerical substructures in the pseudodynamic tests simulated shear walls.

Figure 3. The two-storey SLABSTRESS specimen.

The ultimate drift capacity of the connections resulted comparable or higher than in tests reported in literature, which were performed on isolated joints and/or reduced-scale specimens. The results obtained on a real structure extend the knowledge in the literature (Coronelli 2021). The tests showed the importance of the damage and failure in edge and corner connections, the feasibility of repairing earthquake-damaged connections (Ramos 2023) and allowed the development of a novel deformation-capacity model for seismic design of flat slabs (Muttoni 2022).

With the increasing demand for sustainability in the construction sector, the ELSA laboratory is also working towards this goal. The ongoing project RecycleSLAB will test a full-scale building similar to SLABSTRESS, but using drop-panels that allow a 20 % reduction in concrete for the same performance. The concrete used in the specimen will contain at least 50 % of recycled aggregates.

4. Precast concrete buildings

ELSA has a long tradition in testing for the needs of the standardisation for precast concrete structures. The first activity, conducted in collaboration with the Italian association of precast producers, Politecnico di Milano and the National Technical University of Athens (Saisi and Toniolo 1998), focused on the seismic behaviour of single elements. The aim was the investigation of the ductility capacity of precast cantilever columns with pocket foundation. Twenty columns, characterised by different reinforcement arrangements and axial load, were subjected to cyclic loads of increasing amplitude. The results demonstrated that precast columns are able to dissipate a large amount of energy up to significant ductility (>> 5) with stable loops, and that the connection between the precast column and the plinth is at least as rigid as a cast in situ foundation.

A research programme aimed at demonstrating the equivalence between the available behaviour factor of precast and cast-in-situ single-storey industrial buildings was then activated. The research project 'Seismic behaviour of precast R/C industrial buildings', partially financed within the European 'Ecoleader' research programme, was performed at the ELSA Laboratory. Three associations of producers (ASSOBETON from

Italy, ANDECE from Spain and ANIPB from Portugal) were involved together with Politecnico of Milan, the University of Ljubljana and two industrial precast manufacturers. PsD tests were conducted on two planar frames, one cast-in-situ the other precast, subjected to earthquakes corresponding to identical demands. The results of the tests demonstrated the excellent capacity of precast buildings to withstand earthquakes without suffering important damage (Ferrara et al. 2004) and also the fundamental importance of the quality of construction in the global safety of structures (Dimova and Negro 2005).

The data obtained within the two mentioned research projects provided the starting point for the PRECAST EC8 project. A number of European and overseas partners were involved: Politecnico of Milan, University of Ljubljana, National Technical University of Athens, National Laboratory for Civil Engineering of Lisbon, Tongji University of Shanghai, and the precast elements manufacturers Gecofin and Magnetti Buildings from Italy, Civibral from Portugal and Proet from Greece. PsD tests were conducted at ELSA on two different arrangements of single-bay by two-bay of precast elements to represent typical industrial buildings. The research pointed out the very good behaviour of precast structures under earthquake conditions and their substantial equality to traditional cast-in-situ ones as for the safety under earthquake excitation, even without monolithic joints (Ferrara et al. 2006).

The only, but crucial, missing link in the modelling of such precast structures was the adequate knowledge about the behaviour of connections. This was the objective of the SAFECAST project, undertaken by national associations of precast concrete producers, along with universities and research centres. The testing activity at ELSA was performed on a three-storey full-scale precast residential building, measuring 15 × 16 m in plan and 10.9 m in height. The size of this specimen (Figure 4), possibly the largest specimen building ever tested in a laboratory, was motivated by the aim of simulating the behaviour of the structure for a wide range of structural schemes and types of connections. The final deliverable of the project was a set of guidelines, which were finally adopted as an ISO standard (ISO 2019).

Figure 4. The SAFECAST specimen measuring 15 × 16 m in plan and 10.9 m in height.

Finally, the importance of the non-structural cladding elements in the global seismic response of precast structures became evident, and was confirmed by recent Italian earthquakes (Bournas et al. 2013). Studying this problem and developing new and more rational strategies for designing the connections of the claddings has been the objectives of the recently activated project SAFECLADDING. A full-scale mock-up representative of an industrial building has been tested pseudodinamically with two different configurations of claddings (horizontal and vertical) and with a full range of conceptual and practical solutions for the connections (Negro and Lamperti Tornaghi 2017, Lamperti Tornaghi et al. 2022). The results of quite a huge sequence of tests provided the basis for a set of guidelines which were finally adopted as an ISO standard (ISO 2020).

5. Steel buildings

Conventional seismic design is based on dissipative response, which implies damage and possibly permanent deformation under the design earthquake, and consequently significant economic losses and downtime for repair. Structures with removable dissipative members and re-centring capability may overcome these problems. This concept was experimentally tested on a steel building where moment resisting frames provided the re-centring capability and bolted links provided the energy dissipation capacity. The tests were proposed by researchers at the Politehnica University of Timisoara within the SERIES project (Stratan at al. 2014).

The prototype structure was a three-storey steel-concrete composite building with three 6 m bays in the direction of testing (Figure 5) and eccentric braces in the central bay. The bolted links were designed, fabricated and erected using standard methods. One of the two frames was constructed so that the beam with the removable link was totally disconnected from the reinforced concrete slab, while the beam with removable links of the other frame was connected to the slab in a conventional way.

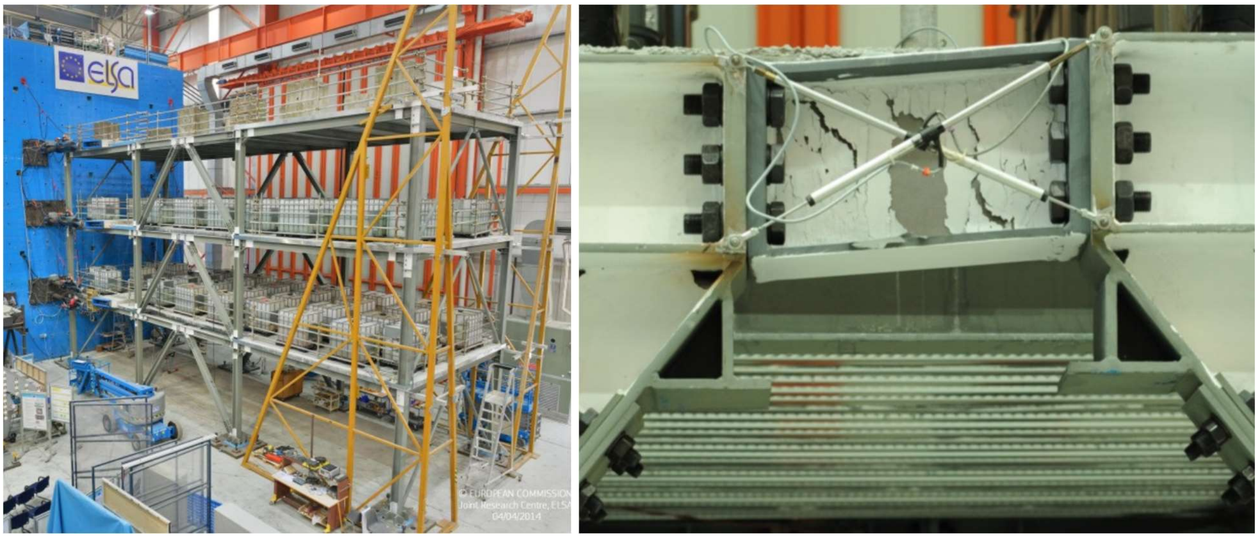

Figure 5. The three-storey frame building with eccentric braces (left) and the second storey link at peak displacement during the ultimate limit state test (right).

The main pseudodynamic tests aimed to assess the elastic response of the structure and its performance at the serviceability and ultimate limit states. No plastic hinges formed in the beams and/or in the columns, while the seismic links underwent plastic deformations without affecting the slab. Small permanent deformations demonstrated the self-centring capacity of the structure and were further reduced after the bolted links were removed. It was feasible to replace the damaged links by unscrewing the bolted connections or, after the ultimate limit state test, by flame cutting. Re-centring was better for the frame with links disconnected from the slab. Moreover, damage to the concrete was avoided in this case. Nevertheless, good re-centring and insignificant damage of the slab were observed even for the frame with the slab cast over the links.

Secondary effects triggered by earthquakes further impact already vulnerable communities. Notably, post-earthquake fires have historically caused significant damage and loss in terms of lives and economic costs. The EQUFIRE project selected as a case study a four-storey, three-bay steel building with concentric bracing in the central bay, representing an office building located in Lisbon, Portugal, in an area of moderate seismicity, with a storey height of 3 m, except for the first storey, which is 3.6 m high. Ten full-scale pseudodynamic seismic tests were carried out on the ground storey (Figure 6), with the remaining ones numerically simulated. The tests allowed the evaluation of the seismic response of different types of fire protection elements (calcium silicate boards with and without seismic design, spray-based fire protection, firewalls with and without seismic design) and their interaction with the structural elements. It was also possible to analyse the variations in seismic response induced by the non-structural elements subjected to a sequence of two identical shocks (main and aftershock) (Tondini et al. 2024).

Figure 6. The EQUFIRE three-bay steel building with concentric bracing in the central bay.

6. Reinforced concrete bridges

The experimental programme on bridges of the PREC8 project for prenormative research in support of Eurocode 8, brought together researchers from the University of Pavia, University La Sapienza of Rome, Polytechnic University of Madrid and Imperial College, and aimed to provide background and improvement to analysis and design methods as regards regularity, behaviour factors, asynchronous input motion, isolation and dissipation (Pinto 1996). Six large-scale (1:2.5) bridges were tested: a regular one, three irregular bridges with different simplified and refined design approaches, one irregular configuration with non-synchronous input motion and one irregular bridge with isolation/dissipation devices. The specimens were representative of highway bridges, had four identical spans of 50 m on three piers with rectangular hollow cross-section and height ranging from 7 to 21 m (Figure 7), and were designed according to the then version of Eurocode 8 – Part 2. Two pseudodynamic tests were performed for each structure: one corresponding to the design earthquake and one defined on the basis of the ultimate capacity of the bridges. These tests were the first large-scale experiments performed in the world using the substructuring technique.

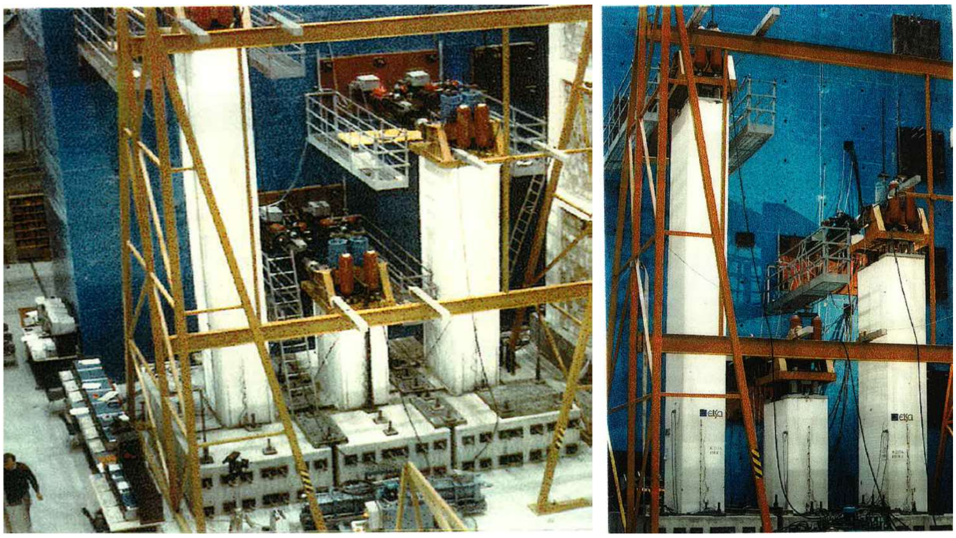

Figure 7. General view of the experimental setup for a bridge without (left) and with isolation devices (right).

The tests confirmed that a well designed (i.e. one where shear failure, bar buckling and loss of confinement are prevented) regular bridge is insensitive to the acceleration input level, with a proportional progression of damage. It was also demonstrated that the capacity design and detailing provisions of Eurocode 8 provide large strength and ductility margins, although minor variations of acceleration may result in significant damage of irregular bridges. The experimental and numerical investigations performed in the PREC8 project were the basis for recommendations for Eurocode 8 provisions and future research (Calvi and Pinto, 1996).

The VAB (Vulnerability assessment of bridges) project originated from the need to assess the existing building stock, as a result of the inadequate seismic design of older bridge structures and the revision of seismic hazard maps across Europe. The project partners were Arsenal Research, ISMES (Istituto Sperimentale Modelli e Strutture), University of Porto, ICTP (Abdus Salam International Center for Theoretical Physics), CIMNE (International Centre for Numerical Methods in Engineering) and SETRA (Service d'études sur les transports, les routes et leurs aménagements).

The test campaign concerned the seven-span Talübergang Warth Bridge in Austria that was designed prior to the modern generation of seismic codes. The prestressed deck is made of a single-spine box cross-section and is supported by elastomeric bearings at the piers and abutments. The reinforced concrete piers have a hollow rectangular cross-section with dimensions 6.8 × 2.5 m. Pseudodynamic tests on a large-scale (1:2.5) model of the bridge were performed using the substructuring technique (Pinto et al. 2004). Two physical pier models were tested, while the deck, abutments and remaining four piers were numerically modelled on-line (Figure 8). In order to reduce the computation effort, simplified numerical models for the substructured piers were calibrated on the basis of cyclic tests on large-scale models (Pinto et al. 2003). Three earthquake tests with increasing intensities were carried out on the bridge model, using asynchronous input motion for the abutments and the pier bases.

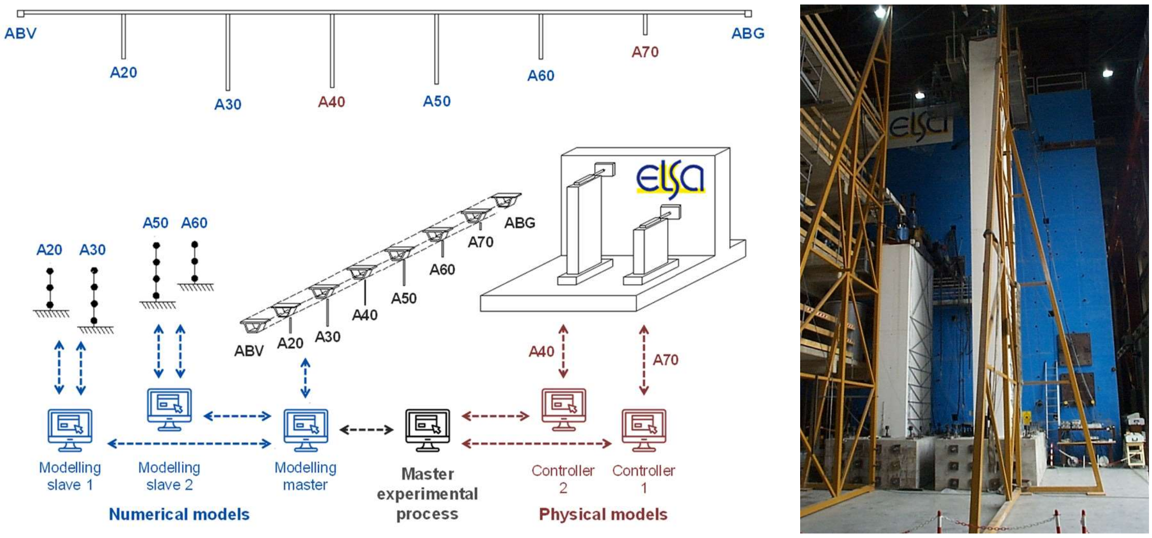

Figure 8. Implementation of pseudodynamic method with non-linear substructuring for the tests of the Talübergang Warth Bridge (left) and general view of the tested piers A40 and A70 (right).

These tests were the first to have been performed considering non-linear behaviour for the modelled substructure. The control system proved to be robust and adequate communication was established between the physical and numerical parts of the tested structure, using standard network capabilities available in the early 2000. The experimental results confirmed the poor seismic behaviour of the bridge (Pinto et al. 2003, 2004). Non-uniform distribution of damage and sudden change in damage patterns for increasing amplitudes of the input motion was observed. This reflects the absence of dynamic analysis methods and design strategies, which are presently included in the design codes for new structures. Due to the poor seismic detailing, the deformation capacities of the piers did not meet the requirements of modern codes and were reduced considerably due to cycling. Because of linear design, the vertical reinforcement of the pier was curtailed; this, combined with shear cracking, caused tension shift and then failure occurred at the cross-section above the bar cut-off. undesirable failure locations.

Subsequently, the research question investigated within the transnational access activities of the 7th framework programme SERIES project was the efficiency of alternative seismic retrofitting technologies, especially base isolation systems. The RETRO transnational access project was proposed by researchers from University Roma Tre, University of Sannio, University of Naples ‘Federico II’, University of Trento, Politecnico di Torino and Alga spa.

The case study was the Rio Torto reinforced concrete viaduct that was built in the 1960s between Florence and Bologna and designed essentially for gravity loads. It consists of a thirteen-span deck with two independent roadways supported by 12 couples of portal frame piers. Each pier is composed of two solid or hollow circular columns, connected at the top by a cap beam and at various heights by one or more transverse beams of rectangular section. The height of the piers varies between 13.8 m and 41 m. The deck is made of two T-shaped 2.75 m-high reinforced concrete beams interrupted by Gerber saddles at the second, seventh and twelfth bays. The deck is connected to the piers by two steel bars inserted in the concrete, and by fixed devices at the abutments. Plain steel reinforcement bars were used.

The tests were performed using the continuous PsD method with the non-linear substructuring technique (Abbiati et al. 2015, Paolacci et al. 2015). Two specimens (scale 1:2.5), a frame pier of two levels (height 5.8 m) and one of three levels (height 10.3 m), constituted the physical substructure. The as-built configuration and the configuration retrofitted with friction pendulum isolators were tested at the serviceability and ultimate limit states. The latter configuration required the simultaneous control of 18 actuator channels for four physical experimental substructures (two piers and two isolators) and represented a high level of complexity that was handled for the first time by the procedures developed at ELSA for continuous substructured PsD tests.

Extensive damage was observed on the as-built piers, namely severe shear damage of the transverse beam of the short pier and fix-end-rotation at the base of both piers because of bond slip of the plain steel reinforcement bars. The isolation system effectively protected the bridge by reducing base shear and displacement demand for both piers. Friction coefficients were found to vary significantly during the tests; the actual friction values can be twice the nominal values used in the design phase.

7. ELSA database

Experiments at ELSA use to be big in size and complexity and consequently they are expensive. We are conscious that the main deliverable that they produce is their results with all the accompanying data that help to understand them and use them for calibrating numerical models or directly derive conclusions. As described in previous sections, this has allowed for many of these experiments to be used for developing guidelines or standards for the design and construction of structures. Consider also that some experimental data has been used for scientific papers even 20 years after the execution of the experiments at ELSA.

The ELSA database of experimental data has evolved in the years, keeping always a file system platform as reference that sometimes has worked in parallel with web database applications. Our first web database was called ELSADB and was accessed since the early 2000s through the world wide web by authorised users for selected projects. Thanks to collaborative efforts in this topic within the European projects SERIES and SERA (Caverzan et al. 2020), where a data model was defined, and the distributed and centralised approaches were explored, a more developed tool called ELSADATA was launched by 2018. However, the maintenance of ELSADATA, especially regarding very tough security conditions for web applications, has become not affordable. In the current situation, the data are offered to the scientific community as selected portions of the file system platform that are shared through cloud services. The current data model within the file system is still very similar to the one defined for ELSADATA. Within the current European project ERIES, to which ELSA participates again offering the facility for transnational access experimental projects, the data of such experiments will be made public as a file system using the data model selected by the facility.

8. Conclusions

The collaborative research summarised in this paper has provided unique results from real- and large-scale experiments on the structural and seismic safety of existing and new structures (new materials and structural systems, irregularity, design and detailing, non-structural elements, isolation, damage-tolerant structures, fire after earthquake, etc.), and subsequently input for world-level standards for seismic design.

The investments in hardware and the continuous development of the pseudodynamic testing method have made possible the testing of large-scale buildings and bridges that account for the effect of higher-modes, realistic boundary conditions, failure modes and other aspects which cannot be studied in tests of scaled specimens or single elements.

The 30-year operation of the ELSA Reaction Wall facility has been fulfilling its guiding principles to provide access to a unique European research infrastructure in a fair and transparent way, advance knowledge on the seismic safety of structures, foster international collaboration, and train young researchers. At the onset of the fourth decade of operation of ELSA, we build on the long experience, unique capabilities and collaborative mind-set to address new research questions and societal needs, for instance by integrating the resilience of the built environment to earthquakes and other future risks with sustainability and the digital transition.

9. Acknowledgements

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