SHAKE-TABLE TESTING OF TWO U-SHAPED RC WALLS: OVERVIEW OF THE PROJECT ERIES-ALL4wALL

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Abstract: *This paper summarises the project ERIES-ALL4wALL, "Smart ALLoys for WALLs: towards durable structures with long service lives and minimal seismic residual displacements", which was funded through the Engineering Research Infrastructures for European Synergies (ERIES) Transnational Access program. The project advances the understanding of the seismic behaviour of reinforced concrete (RC) U-shaped core walls by investigating two factors that commonly contribute to poor structural response and limit post-earthquake serviceability, namely torsional effects and excessive residual displacements. The latter can be minimised through a mitigation principle that consists in replacing partially some of the longitudinal steel reinforcement at the wall base by smart alloy rebars. The project aims at demonstrating this technological innovation, contributing to ensure target performances for buildings with significantly longer service lives, which should be an aim for sustainable design and assessment. In scientific and technical terms, the project is concretized in three main fronts of research: (i) the shake-table testing of two large-scale U-shaped RC wall units in the National Laboratory for Civil Engineering (LNEC), in Lisbon – namely: one conventionally-reinforced unit, and a second one including the smart alloy rebars; (ii) the development of state-of-the-art and state-of-the-practice simulation models to estimate the response of the test units; (iii) the application of a set of novel instrumentation techniques, namely distributed fiber optic sensors along several reinforcing bars, video-based tracking measurements, an OptiTrack motion capture system, and extensive conventional instrumentation; in essence, it means these two units are the most extensively monitored walls so far tested in shake-table testing. The paper starts by addressing the project motivation, providing a global description, and listing its objectives. It then goes on to justify the sources of innovation and impact, as well as the articulation between the unique synergistic features of the assembled team of 15 user group members. It concludes with a description of the experimental programme, an overview of the employed numerical simulation techniques, and some leading results of the first wall unit tested. More complete and comparative results of the performance of both units, and of the associated blind prediction competition, will be unveiled during the conference presentation.*

1 Introduction and motivation

The many advantages of reinforced concrete (RC) make it irreplaceable for countless infrastructures, and led it to become, over the past hundred years, the dominant building material for medium-to-high rise construction around the world. Unfortunately, over the past 10-15 years, the challenges posed by this material for the sustainability of cities and communities became evident. Every three years, China alone produces more cement than the United States during the entire 20th century (Smil, 2014). With the rise of population, the global production of cement will reach close to an estimated 6 billion tonnes in 2050, which is roughly 5 times higher than in 1990. As concrete is the third-largest contributor to carbon dioxide emissions, measures that help curbing its production also combat climate change. Moreover, recycling concrete is difficult and expensive: a worrying prospect since this material comprises to roughly a third of all landfill waste. However, the most significant and costliest legacy for future generations is the maintenance, repair, and replacement of RC infrastructure, namely buildings and bridges (Smil, 2014). A key contribution to addressing these global challenges is the design and assessment of structures for significantly longer service lives (Flatt, Roussel and Cheeseman, 2012). This aligns with the current view on materials in general, which seeks quality and promotion of longevity, rather than quantity and short product lives (Smil, 2014). The challenges and the goal above set the general motivation for the project ERIES-ALL4wALL, "Smart ALLoys for WALLs: towards durable structures with long service lives and minimal seismic residual displacements", funded by the Engineering Research Infrastructures for European Synergies (ERIES; www.eries.eu) Transnational Access program.

Building longer-lasting structures faces material durability challenges, but also poses concern in terms of the UN sustainable development goal of safety and resilience for disaster risk reduction, namely seismic risk reduction. For example, increasing the design service life of a building from 50 to 100 years will roughly double the risk of structural collapse from earthquakes. Therefore, in order to keep identical safety levels, design codes increase the seismic demand for longer-lasting structures. This heightens the challenge to control the recent upsurge of seismic risk worldwide. In fact, the steady decline in the number of casualties from natural disasters over the 20th century has inverted its slope and started rising in this century due to the impact of earthquakes. Economic losses are also on a steep rise.

More confidence in the understanding and simulation of RC structures is therefore required, for a better definition and achievement of their target performance associated to design and assessment for longer service lives. The project ALL4wALL focuses on buildings with U-shaped walls, which is the most popular geometry among the possible shapes of core walls forming the backbone of millions of buildings internationally. As the global number of buildings is expected to double until 2060 (UN Environment, 2017), core walls will play a critical role in the resilience of the built environment. Moreover, the UN projects that around 2.5 billion more people will be living in cities by 2050, with the inevitable consequence in terms of increase of mid- and high-rise structures. It is noteworthy that RC core walls have also been, and will likely continue to be, the prime choice for the lateral-resisting-system in building typologies made of new or revived construction materials that, *per se*, provide insufficient structural stiffness and/or strength; they include mass timber structures that are steadily rising in popularity and in height (e.g., the recently completed 25-story Ascent skyscraper, the world's tallest, has an RC core), new typologies leveraging natural or less-processed materials (e.g., tree trunks, bamboo, among others), or even reinforced concrete buildings using alternative reinforcement, such as the up-and-coming fibre reinforced polymer rebars.

Despite the extensive research performed on the response of RC buildings and walls, two interconnected topics lack remarkably in terms of experimental investigation: 1) torsional response, which can increase critically the inelastic demands on some members in RC buildings; 2) residual displacements, which are key in determining the post-earthquake repairability of such structures. They are discussed below.

1.1 Torsional response

During seismic response, all vertical members in a building are unavoidably subjected to a torsional deformation component, which can be attributed to a "natural (or static) eccentricity" between the centre of mass (CM) of a storey and the centre of stiffness or rigidity (CS; important during elastic response) or the centre of resistance (CV; important during inelastic response). Torsion is inevitable even for full plan-wise symmetric structures due to "accidental eccentricities" that can be caused by, among others: (i) non-uniform distribution of the actual live loads in plan; (ii) asymmetric presence of infill walls; (iii) difference between the effective member stiffness and the design nominal stiffness; (iv) variation in the storey CS along the height; (v) shift in the storey CS with inelastic response; (vi) structural imperfections (Isaković *et al.*, 2021).

Torsion (or twisting) of a building is a dangerous mechanism as it imposes larger displacement demands on the so-called "flexible side" of the structure. Therein, member yielding will result in a reduction of the torsional stiffness and thus in a further exacerbation of torsion, potentially and eventually leading to member failure. After every strong earthquake, it is usually easy to find evidence of collapsed or severely damaged structures due to a critical contribution of torsional effects. Torsion is inherently and particularly relevant for RC U-shaped walls. As these non-rectangular elements are incomparably stiffer than the remaining vertical elements, the building torsional response can be extremely dependent on the torsional behaviour of individual core walls. This is a cause of concern in view of: (i) the usual occurrence of significant natural eccentricities in each storey; e.g., in regions of low-to-moderate seismicity it is common to find just a single, peripheral U-shaped wall; (ii) the potential for high amplification of overall building twist due to differential damage and stiffness degradation in the flanges or web during inelastic response; (iii) the often drastic change of the storeys' CS along the height, in buildings irregular in elevation, which can even fall outside the storey plan perimeter.

Some torsion-related experimental research has been conducted on RC U-shaped beams due to the wide application of these types of elements in rail viaduct engineering. However, the experimental results from beam specimens cannot be extrapolated to determine the expected performance on walls given the difference in boundary conditions and restraints, reinforcement detailing, axial load, and test scale. To the knowledge of the authors, only three experimental campaigns have ever focused on the torsional capacity of RC walls: however, two addressed rectangular walls (Peng and Wong, 2011; Türkay and Altun, 2022) – one of which under monotonic loads, while the other focused on core walls with H-shaped cross-sections and employed a questionable scale factor of 1:12 (Maruta *et al.*, 2000). While there has recently been some experimental testing on RC U-shaped walls (Beyer, Dazio and Priestley, 2008; Hoult *et al.*, 2020), only small twists were applied to these specimens to provide information on the torsional stiffness, not on torsional strength.

A recently concluded experimental programme with cyclic-reverse quasi-static tests (Hoult, Doneux and Pacheco de Almeida, 2023), led by part of the authors, contributed to determining the torsional capacity of U-shaped walls. However, the experimental gap on the torsional performance of RC U-shaped walls can only be efficiently bridged through evidence on the nonlinear dynamic response of these members (i.e. on a shake-table). Such need is further emphasized by findings from past experimental research on U-shaped walls, which showed that (i) the most critical loading direction is the diagonal one (Beyer, Dazio and Priestley, 2008), and (ii) shear deformation can be significantly larger for U-shaped walls than for rectangular ones (Constantin and Beyer, 2016).

1.2 Residual displacements

A part of the economic losses from earthquakes is attributable to excessive residual (or permanent) displacements in structures, which become apparent after the ground motion comes to a halt. They impose very costly repairs or require demolition followed by reconstruction. After a large earthquake event, it is common that buildings (Marquis *et al.*, 2017) and bridges (Kawashima, 2000) remain tilted, sometimes imperceptibly. As an example, after the New Zealand earthquakes of 2010–2011, approximately 25% of all buildings in the Central Business District of Christchurch were no longer vertical, with tilts equal or larger than 25 mm. In most cases, these out-of-plumb buildings were demolished after being declared "uneconomic to repair" (Marquis *et al.*, 2017). Many demolitions are not strictly related to structural engineering risk, but rather to aspects of building functionality and even psychological well-being impairment, e.g. headaches and dizziness due to perceived inclinations. It is disquieting to realise that most of the demolished structures performed satisfactorily according to existing regulations: criteria defined in all modern international codes are expressed in terms of maximum lateral displacement or force demands. This is also the case of the European codes regulating the design of new buildings (CEN, 2004), or the assessment of existing ones (CEN, 2005). In summary, even countries with modern seismic regulations and construction can incur in large economic losses during earthquakes, despite potentially limited human casualties. Coming back to the preceding example: the Christchurch Central Business District underwent estimated losses of more than $NZD 40 billion (20% of the country's GDP), demolition of approximately 60% of the multi-storey RC buildings, and closure of the core business district for over 2 years (Marquis *et al.*, 2017). This and other plentiful evidence have attracted increasing analytical and experimental research focused on residual displacements. Foreseeably, limits on residual displacements will be included in future international design codes. Recent studies point to strict maximum permissible residual drifts of 0.005 rad (≈ 0.3º) (Mccormick *et al.*, 2008).

Finally, it is relevant to point out the close connection between the two topics above. Relations between peak inelastic displacements and residual displacements have been known for more than 40 years (Mahin and Bertero, 1981), and confirmed by many studies ever since (Liossatou and Fardis, 2015). A prior study conducted by some of the authors of this paper (Hoult and Almeida, 2022) examined experimental results derived from a comprehensive dataset of conventional RC wall tests. This study revealed a direct correlation, indicating that the maximum residual drift of 0.005 radians was observed after the walls experienced an in-plane drift of approximately 1.5%. Therefore, a poor torsional response of the core walls, and consequently of the building with large displacement demands imposed on the flexible side, will inevitably generate large residual displacements, likely non-repairable and leading to demolition.

2 ERIES-ALL4wALL project description and objectives

2.1 Project description

The ERIES-ALL4wALL project revolves around the shake-table testing of two slender U-shaped walls, denoted UWS1 and UWS2, both subjected to increasing-intensity ground motions alternatively inducing unidirectional flexure and bidirectional flexure with torsion. The authors are not aware of past shake-table tests investigating the torsional response of U-shaped core walls. Some tests have been performed on U-shaped walls, namely those reported in the previous section, or the three U-shaped walls tested at the ELSA laboratory in 2000 (Ile and Reynouard, 2005), but they were all quasi-cyclic tests without direct consideration for torsion. As far as the authors are aware, the only shake-table tests on U-shaped walls to date were those performed at the Azalée shake-table at CEA (Ile, Plumier and Reynouard, 2002), where low ductility steel was used. The spacing of the stirrups was the only difference between the three units tested, and no bidirectional loading or natural eccentricity for torsion was considered. Therefore, the tests herein proposed will be the first where the torsional nonlinear dynamic response of U-shaped walls is assessed. A concurrent focus will be placed on the determination (UWS1) and minimization (UWS2) of the residual displacements. Incidentally, it is noted that the Azalée tests showed significant residual displacements.

The unit UWS1 will have a classical RC design according to EC8. The wall unit UWS2 will be similar, but some of the steel rebars will be replaced locally, along the base of the boundary elements of the wall, by iron-based shape memory alloy (Fe-SMA) rods. The working principle consists in prestressing the wall plastic hinge region, leveraging the unique self-prestressing characteristics of Fe-SMA upon heating, which will be in turn responsible for the intended wall self-centering and corresponding minimization of the resulting residual displacements (Raza *et al.*, 2023). This is accompanied by the sizeable energy dissipation capacity that Fe-SMA rebars can develop as they run through inelastic dynamic cycles. This technique requires minor adjustments to the current RC industry construction practices, which are mainly related with the casting sequence and application of the heat treatment (further details are provided in Section 4.1). Additionally, this new technology is expected to have a negligible impact on the overall structural cost, since Fe-SMA rebars are relatively cheap (and around five to ten times cheaper than their NiTi SMA counterparts). Unit UWS2 will be the first wall tested experimentally under realistic conditions of dynamic excitation, using this state-of-the-art self-centering technique. A very recent test has showed promising results in a previous publication (Vahedi, Ebrahimian and Saiidi, 2022). It should be mentioned that a different initial alternative was considered, which consisted in exploiting the superelastic response of NiTi SMA rebars in the plastic hinge region. This latter approach had been previously validated by some authors through quasi-static cyclic tests (Cortés-Puentes *et al.*, 2018; Almeida *et al.*, 2020). However, the financial limitations of the current project would restrict the length of the NiTi SMA rebars to the bottom of the plastic hinge region, hence forcing the use of couplers in this critical area. Specific concerns regarding the performance of couplers between SMA NiTi rebars and steel rebars, under dynamic response, led to the abandonment of this approach, in order to avoid an unexpected brittle failure with potential jeopardous consequences for the experimental facility. A novel friction-welding technique between SMA and steel rebars has the potential to avoid the use of mechanical couplers and their disadvantages (Lezaack *et al.*, 2022), but further investigations are required, which did not align with the timeline of the current project. Another very significant advantage of employing Fe-SMA rebars instead of NiTi-SMA rebars is that the modulus of elasticity of the former is much higher, with the consequent beneficial implications of ensuring a higher lateral wall stiffness. For reference, in the non-activated condition (i.e., before heating), the modulus of elasticity of the Fe-SMA rebars is just slightly inferior to that of steel rebars, and much higher than that of NiTi rebars, which turns around 25-40 GPa.

To complete the description of the project, a brief reference needs also to be made to the numerical simulation front, which is critically needed to estimate the response of the units prior to the tests (and for calibration after). This is an integral part of ERIES-ALL4wALL, wherein a host of alternative engineering and state-of-the-art models will be employed, including: refined FE models with shell or solid elements, nonlinear beam-truss models, MVLEM, the Applied Element Method, or the more classical beam-column models with fibre discretization, among others. The authors have extensive and complementary experience on the above diversity of models, as justified in Section 3.2, which is a strong asset of the current team. New contributions to numerical simulation of RC structures subjected to loading other than unidirectional (in this case bidirectional + torsional response) are therefore expected.

2.2 Objectives

According to the description above, the main objectives of the ERIES-ALL4wALL project are:

- To study the interaction of torsion and bi-directional flexure in the dynamic response of RC U-shaped core walls, and hence contribute to a better understanding of their target performance.
- To investigate, under realistic excitation conditions, a new technology that minimises the post-earthquake residual displacements of walls and structures. This will advance the technology readiness level (TRL) level for SMA rebars as a residual displacement-minimisation development in RC construction.
- To develop and calibrate numerical simulation techniques for walls under bidirectional + torsional response, using a wide range of state-of-the-art and state-of-the-practice approaches.
- To apply innovative instrumentation techniques, including DFOS, camera-based vibration measurements, and an OptiTrack motion capture system.

3 Relevance to ERIES research areas and research goals

This project is relevant to two research areas addressed by ERIES (www.eries.eu), namely for RA1, “Built Environment”, and RA4, “Advanced Technologies”. Regarding the former: a growing number of people live and work in RC multi-storey buildings with core walls, either included from original design or added as a strengthening measure (often coupled with functionality, e.g. to install elevators), frequently in the building periphery. A better understanding of the implications of torsional core wall response on the structural performance is needed, with a view to making building response Eurocode-compliant (see also the sub-section below, “Innovation and Impact”).

ALL4wALL also contributes to the research area RA4 since it advances the TRL of a recent seismic mitigation approach, testing it for the first time in RC walls under dynamic response. Additionally, the potential for capacity development of the research facility ST3D at LNEC will also be addressed; in particular, it is expected that significant technology transfer occurs regarding the application of camera-based dynamic identification, DFOS, and the OptiTrack motion capture system.

The two above paragraphs show the project contribution to the Research Goal 1, “Loss-driven design and mitigation approaches”. The perspective of sustainable development, for Research Goal 3, is given in the general project background and motivation (see Section “Introduction and motivation”), which aims at improving the design and assessment of structures for significantly longer service lives.

3.1 Innovation and Impact

ALL4wALL promotes multidisciplinarity, notably between Civil Engineering and Materials Science. It is considered that the evolution of concrete mixes and especially of new materials for reinforcing bars, are key to tackle the critical RC infrastructure challenges identified in the State-of-the-Art. They will include the use of alternative reinforcement to steel rebars, such as fibre reinforced polymer bars (which the next-generation of EC2 will regulate for the first time), or smart materials as investigated in the current project.

Many research programmes have focused on residual-minimisation systems for walls. In particular, the design idea of rocking behaviour made considerable impact, through the use of unbonded post-tensioned tendons. Post-tensioning provides a restoring force that brings the structural member back to its origin upon unloading.

The PRESSS research programme (Priestley *et al.*, 1999) validated this concept of hybrid wall, whereby vertical prestress enabling a bilinear elastic self-centring behaviour was complemented by energy dissipation devices to obtain a “flag-shaped” force-displacement cyclic response. Several variations of this system were proposed over the past decades and validated through shake-table tests (Twigden and Henry, 2019). However, such design approach is impaired by high peak displacements under strong ground motions, complex interaction between the wall and other parts of the structure, requires high costs and expert skills, among other factors that explain why transfer into practice has been so slow (Kurama *et al.*, 2018). Additionally, there are technical difficulties associated with the installation and post-tensioning of tendons, as conventional post-tensioning techniques require heavy mechanical equipment (hydraulic jacks, anchor heads, etc). More generally, ALL4wALL considers that design approaches to minimise seismic residual displacements based on the introduction or control of forces at the structural or element level (e.g., base isolation, rocking walls with prestress) will be too costly or require too much expertise and changes to the long-established design and building practices in RC industry. Instead, ALL4wALL proposes that the control and minimisation of residual displacements should be achieved at the material level, by replacing locally, in the wall plastic hinge, the steel rebars by rebars made of smart materials that provide both recentering and energy-dissipation capabilities (eventually combined with ECC concrete). As such, minimal adjustments are required to current construction practices, which is expected to increase the dissemination potential of this novel technology. They will be tested for the first time in realistic shake-table test conditions for RC walls. ALL4wALL thus promotes the development and application of new rebar materials, namely new types of SMAs, and opens the door to seismic design based on optimisation of reinforcement material type and properties according to local ductility demands.

Despite the importance of their economic impact, residual displacements are still almost completely disregarded in Eurocode 8 (CEN, 2004) and many other codes. ALL4wALL will contribute to justify the need for explicit consideration of residual displacements, and their minimisation, in future code versions. This project will also add to major advances already planned for the coming generation of the EC8, highlighting its timeliness. Namely, a new complete displacement-based design approach (Almeida *et al.*, 2022) will be included as an alternative/complement to the usual force-based design, which interplays with the also forthcoming changes to EC8 regarding the torsional classification of buildings. The latter now includes an engineer-friendly condition based on the effective modal masses, which can only be estimated through reliable numerical models with appropriate definition of elastic effective member stiffness, namely torsional – for which U-shaped core walls play a governing role.

3.2 Synergy

The project ERIES-ALL4wALL is composed of 15 user-group members from seven universities and institutes, complementary in their skills and in the synergistic value they bring to the project. They deliver uniquely distinctive contributions, which tackle specific and overarching areas.

Several of the user group members have broad experience on the field of experimental testing on Earthquake Engineering (Dan Palermo, Boyan Mihaylov, Tatjana Isaković, Ryan Hoult, Rui Pinho, Catherine Doneux), some of whom further overlap with long-established interests on the performance of RC walls (Dan Palermo, Ryan Hoult, Boyan Mihaylov). The development of the impressive host of complementary simulation techniques to estimate the response of the test units relies on hard-earned competences acquired by several user group members over multiple-year spans, as follows (and in brief): nonlinear beam-truss models (Ryan Hoult, Basile Payen, António Correia), refined finite element method (Ryan Hoult, Dan Palermo), multiple-vertical-line-element method (Tatjana Isaković, Antonio Janevski), applied element method (Andrea Orgnoni, Rui Pinho), and kinematics-based approaches (Boyan Mihaylov). Regarding instrumentation, the monitoring of spatially refined strain (and temperature, for Fe-SMA rebars) fields along the rebars is fundamental to capture evasive local insights on the wall response, without which model development and calibration will remain stunted. The LEMSC laboratory, which is part of the Institute of Mechanics, Materials, and Civil Engineering, at UCLouvain, headed by Catherine Doneux, has developed and accumulated expertise, throughout the recent years, regarding the application of DFOS along rebars (Alex Bertholet, Ryan Hoult). Welding expertise, in particular concerning friction weld between Fe-SMA and steel reinforcement – and corresponding characterisation, builds essentially on the expertise of user group member Aude Simar, with the collaboration of Ryan Hoult. It should also be underlined that the interaction with the staff of the ST3D research facility at LNEC (António Correia, Paulo Candeias, Filipe Ribeiro) has been faultless.

4 Summary of the experimental programme

This section includes an overview of the test units and test programme currently under development. Complementary extensive details can be found in the companion paper published in this same conference (Hoult, Almeida and Correia, 2024).

4.1 Test units and application of prestress in unit UWS2

A 3D representation of the test units is provided in Figure 1. A complete characterization, in terms of geometric and mechanical properties, is carried out in the above-mentioned paper (Hoult, Almeida and Correia, 2024). Each wall has a top mass of over 28 ton (the sum of roughly 3 ton of the wall collar and 25 ton from applied masses). The aforementioned reference also indicates the position of the centre of applied mass with respect to the geometric centroid of the wall, which induces an initial bending moment around the weak axis of the U-shaped cross section. Torsional demands, which will be activated during the bidirectional runs, can be estimated from the distance with respect to the cross-section shear centre. It is also worth noting that the top collar of the units follows the U-shaped wall section (necessarily in an enlarged form, to support the masses): the purpose of not connecting the flanges and the web with a collar-slab is to allow some warping, which is considered an important aspect of analysis, and more closely representative of building construction reality.

Whereas unit UWS1 is fully reinforced with conventional steel rebars, UWS2 will substitute some of them, as briefly mentioned in Section 2, by Fe-SMA rebars. With reference to the cross-section included in Figure 1 of Hoult, Almeida and Correia (2024), the 2×4 12-mm steel rebars at the two web-flange intersections and the 2×6 12-mm rebars at the flange ends will be replaced by 2×5 10.7-mm and 2×7 10.7-mm Fe-SMA rebars, respectively. This guarantees a similar reinforcement ratio between units UWS1 and UWS2. The Fe-SMA rebars extend from the foundation up to a lap splicing region above the first slab. The leveraging of the unique properties of the Fe-SMA rebars requires minimal adjustments to present-day RC-industry construction practices. The prestress will be applied after the entire wall unit has been cast. The Fe-based SMA rebars along the height of the wall ground storey (i.e., below the first-storey slab) will be shrink-wrapped, which effectively guarantees an unbonded behaviour with respect to the concrete. Only the rebar ends, i.e. along the foundation and the lap-splice region, will remain effectively clamped, preventing the strain recovery resulting from heating; instead, the shape memory effect induced by heating results in recovery stress and prestressing of the wall. In other research studies, the thermal activation of the Fe-SMA rebars was performed by gas flame heating, electrical resistive heating, or heating tapes. The second option – herein aimed at an activation temperature of 300ºC – will be used in UWS2 as it allows for a more precise and uniform temperature application; the latter will be monitored by thermocouples. It is noted that the prestrain level before activation, and the activation temperature, are recognized as the two fundamental parameters in terms of the recovery stress of Fe-SMA. Other studies have also considered the initial preload (Gu *et al.*, 2021), although it is accepted that this parameter only slightly influences the recovery stress. Unit UWS2 will employ rebars prestrained at 4%.

As discussed in the experimental study by Raza *et al.* (2023), the ratio of amount of steel to prestressed Fe-SMA reinforcement, ρ_{steel} / ρ_{SMA}, significantly affects the residual drift of the structural members. In their study, the column with ρ_{steel} / ρ_{SMA} =0.45 exhibited higher energy dissipation (32% more) compared with the column with ρ_{steel} / ρ_{SMA} =0.15. However, its residual drift at higher target drifts was also larger. It is noted that, for unit UWS2, the ratio ρ_{steel} / ρ_{SMA} is equal to 0.53. However, the cross-section of UWS2 is not symmetric, nor is the percentage of Fe-SMA steel, and therefore it is expected that these asymmetries will affect distinctly the residual displacements depending on the loading direction.

4.2 Instrumentation

Both common and state-of-the-practice instrumentation techniques will be employed. The former include LVDTs, string pots, accelerometers, optical sensors, and, for UWS2, three concrete strain gauges at the wall-foundation interface (placed at mid-length of the two flanges and web). The latter consist of distributed fibre optic sensing (DFOS), target tracking, digital image correlation, and a motion capture system.

The DFOS will assume distinct forms for the two wall units: (i) for UWS1, these sensors will be glued along small 1-mm slits cut along the entire length of the longitudinal ribs of four rebars that run from the foundation to the collar; the same technique was employed in the preceding quasi-static cyclic tests on U-shaped walls (Hoult, Doneux and Pacheco de Almeida, 2023), providing unique insights on the strain distribution along the rebars during loading; the installation of the DFOS, and preparation of the DFOS exit points, is a delicate time-consuming procedure, with some photos included in Figure 1. (ii) for UWS2, four composite DFOS sensors along the height of the wall (two at the web-flanges intersections, two at the flanges' boundary elements), with strain range up to 4% and a modulus elasticity not influencing the structural behaviour (E = 3 GPa), will monitor the concrete strains. The measurement rate will be set to around 25 Hz. To the authors' knowledge, this will be the first time DFOS will be used on RC wall shake-table tests.

Additionally, dynamic identification based on video analysis will be performed; a network of two types of calibrated cameras, positioned around the structure, are used to measure the wall's 3D motion: (i) high-speed high-resolution cameras, and (ii) for performance comparison, lower-resolution cameras of type Basler ace acA1300-200uc. An OptiTrack motion capture system will also be employed, using approximately 100 markers. Finally, it is mentioned that several thermocouples along the Fe-SMA rebars of UWS2 were used to monitor the application of resistive heating up until the target temperature of 300ºC.

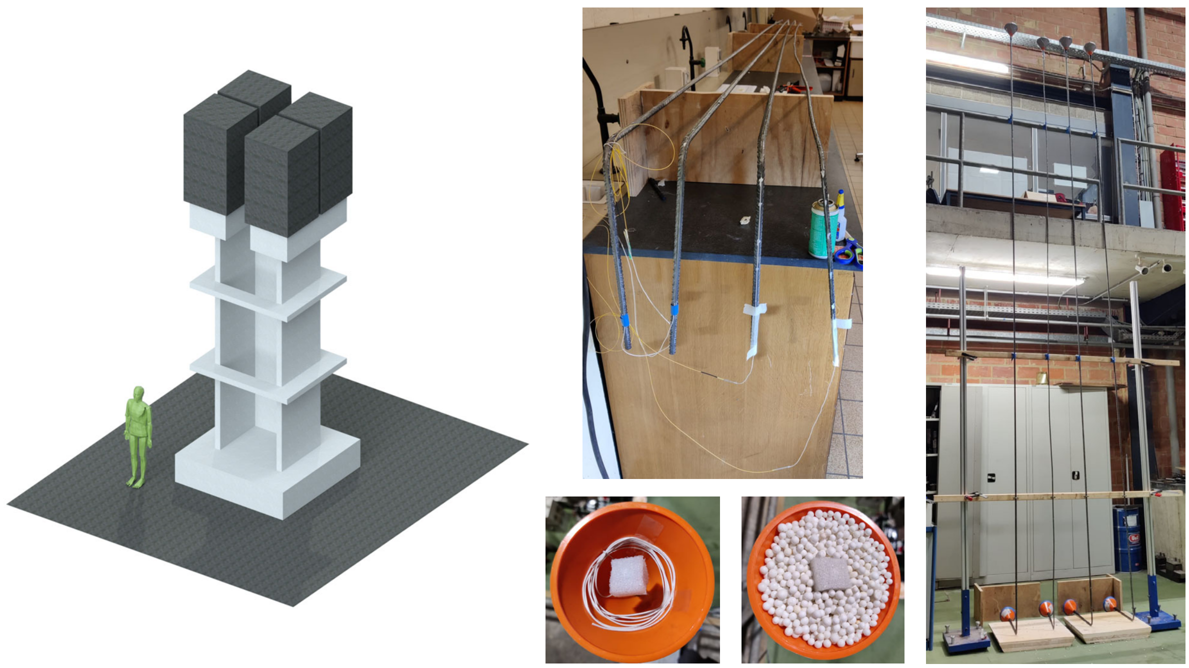

Figure 1. Three-dimensional sketch of the test units (left), some details of the DFOS installation process in the longitudinal steel rebars for UWS1 (middle), and final overview of the four instrumented rebars (right).

4.3 Test programme

Again due to page limitations, the reader is directed to the companion paper (Hoult, Almeida and Correia, 2024) for a detailed description of the input ground motions, and the combination of the (increasing) scale factors applied for each run, both in the east-west and the north-south directions of the shake-table.

5 Numerical simulations and blind prediction competition

A set of advanced numerical modelling techniques, covering a wide spectrum of state-of-the-practice and state-of-the-art modelling approaches in Earthquake Engineering, are used in the project to simulate the nonlinear dynamic response of the test units during the several runs. They fall within domains of expertise of the user group members, and include: (i) nonlinear beam-truss models (Hoult, Correia and Almeida, 2023); (ii) detailed finite element models (Hoult and Almeida, 2022); (iii) multiple-vertical-line-element method (Isaković and Fischinger, 2019), and (iv) applied element model (Orgnoni and Pinho, 2024). Figure 2 depicts a representation of such models.

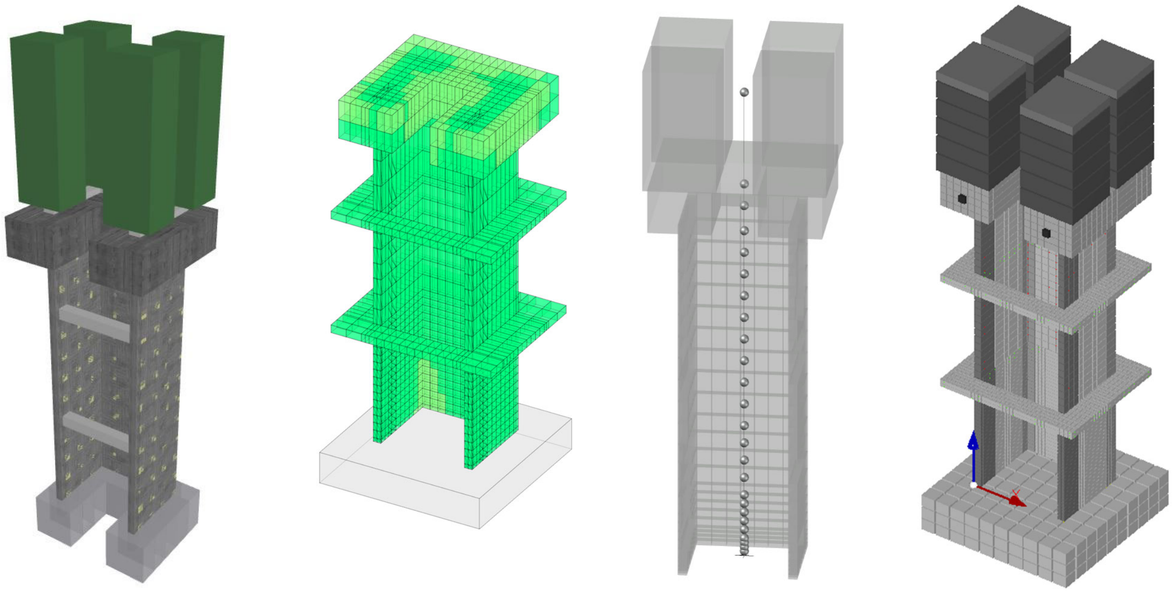

Figure 2. Representations of four types of modelling strategies used by the authors to estimate the nonlinear dynamic response of the two test units. From left to right: nonlinear beam-truss model, detailed finite element model, MVLEM model, and applied element model.

On an initial phase, the above approaches – developed independently by the relevant team sub-groups – were of key assistance in reaching a confident design of the test units and the planning of the experimental program. Figure 3 provides a summary of the collar-displacement time-histories of UWS1 for a low-intensity ground motion (GM1) and the highest-intensity one (GM7), as obtained with the four modelling techniques, before the testing of the unit. The results correspond to preliminary simulations (with a target 30 MPa concrete compressive strength) and consider damage accumulation throughout the ground motions. The details of the different simulation approaches and models are skipped due to space constraints, but they will be discussed in future publications. As the shake-table experiments unfold, and global and local measurements become available, extensive comparative numerical-experimental studies will be performed for calibration and verification of the different approaches. Some of these methods do require advanced expertise, software, and computational time. Other approaches, like the beam-truss models, strike a balance between complexity and practical use. As such, these methods can directly aid practicing engineers in simulating RC core wall buildings. ERIES-ALL4wALL, building upon these investigations, aims to provide valuable modelling insights and guidance to the engineering community.

In the wake of a prior successful blind prediction competition (http://www.uclouvain.be/blind-prediction), a new international blind prediction competition was launched in July 2023 (https://uclouvain.be/en/research-institutes/immc/blind-prediction2023.html). More details can, once more, be found in the companion paper (Hoult, Almeida and Correia, 2024), whereas a full presentation of the participants' predictions and corresponding discussion will be performed during the conference. The experimental test results of both units UWS1 and UWS2 will be presented during the conference.

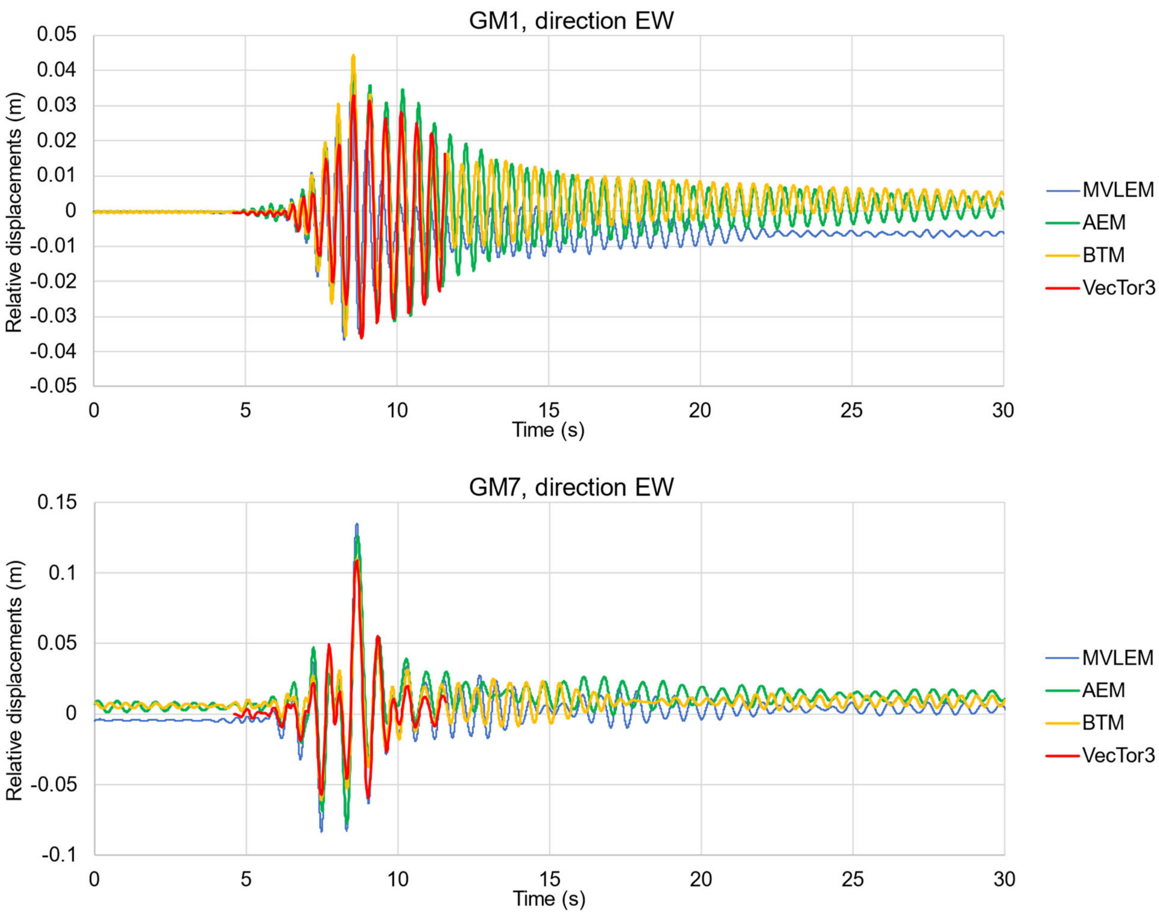

Figure 3. Numerical predictions of the collar-displacement time-history of UWS1 obtained for GM1 (corresponding to a scale factor of 25% along the east-west direction) and for GM7 (corresponding to a scale factor of 100% along the east-west direction), as obtained before the tests with four modelling techniques.

6 Concluding remarks

This paper provides an overview of the project ERIES-ALL4wALL, which is driven by a rather unique combination of an extensive set of specialised and complementary-in-skills user group members. The description ranges from a more conceptual motivational level, down to specific details of the experimental and numerical tests, several of which are still ongoing at the present manuscript's closing deadline. This project delivers unrivalled global and local measurements – using state-of-the-practice instrumentation – of the shake-table response of two large-scale 40-ton reinforced concrete (RC) U-shaped core walls, tested at LNEC, Portugal. UWS1 is a conventionally reinforced specimen, and the associated test design philosophy aims at exploring two interconnected topics that singularly lack in terms of investigation: torsional response and residual displacements. Whilst the focus of UWS1 is placed on assessment, the goal of UWS2 is reciprocally set on the investigation of a new technology aiming at minimizing residual displacements – under the overall condition of requiring minimal adjustments to present-day RC industry construction practice. More in detail, it relies on the distinctive self-prestressing characteristics of iron-based shape-memory alloy rebars – which will be activated upon electrical resistive heating; the latter will deliver the intended prestressing of the wall plastic hinge region responsible for overall member self-centring.

Furthermore, ERIES-ALL4wALL develops a no-less ambitious parallel goal of assembling, comparing, and improving some of today's most advanced – whilst compatible with engineering practice (at least in the medium term) – numerical modelling approaches. Once again, this is only possible due to the exceptional user group members' expertise assembled for this project.

It is worth noting that other initiatives, linked with the current project or more generally with the behaviour of RC core walls, are ongoing. Namely: (i) a special issue in the Bulletin of Earthquake Engineering, to which around 20 papers are expected to be contributed; (ii) a dedicated technical session in the present WCEE2024; (iii) an ongoing international blind prediction competition (https://uclouvain.be/en/research-institutes/immc/blind-prediction2023.html), which builds on the user group experience with this type of events. The modelling methods submitted by the participants, together with those developed in the context of the present project, are being collected and analysed for critical discussion with a view to evidence-based evolution of engineering models.

ERIES-ALL4wALL is set in the conviction that the global challenges of maintenance, repair, and replacement of the proliferating RC infrastructure, can be partly addressed by designing and assessing structures for significantly longer service lives while non-negotiating the currently codified safety levels and probabilities of failure.

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8 References

Almeida, J. P. de *et al.* (2020) 'Shape-memory NiTi alloy rebars in flexural-controlled large-scale reinforced concrete walls: Experimental investigation on self-centring and damage limitation', *Engineering Structures*, 220(May), p. 110865. doi: 10.1016/j.engstruct.2020.110865.

Almeida, J. P. de *et al.* (2022) 'Harmonising force-based and displacement-based design approaches for the next generation of Eurocode 8: Application to reinforced concrete moment resisting frames', *Engineering Structures*, 272.

Beyer, K., Dazio, A. and Priestley, M. J. N. (2008) 'Quasi-static cyclic tests of two U-shaped reinforced concrete walls', *Journal of Earthquake Engineering*, 12(7), pp. 1023–1053. doi: 10.1080/13632460802003272.

CEN (European Committee for Standardization) (2004) *Eurocode 8 — Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings*.

CEN (European Committee for Standardization) (2005) *Eurocode 8 — Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings*.

Constantin, R. and Beyer, K. (2016) 'Behaviour of U-shaped RC walls under quasi-static cyclic diagonal loading', *Engineering Structures*, 106, pp. 36–52. doi: 10.1016/j.engstruct.2015.10.018.

Cortés-Puentes, L. *et al.* (2018) 'Cyclic loading testing of repaired SMA and steel reinforced concrete shear walls', *Engineering Structures*, 168(1), pp. 128–141.

Flatt, R. J., Roussel, N. and Cheeseman, C. R. (2012) 'Concrete : An eco material that needs to be improved', 32(11), pp. 2787–2798. doi: 10.1016/j.jeurceramsoc.2011.11.012.

Gu, X. L. *et al.* (2021) 'Stress recovery behavior of an Fe-Mn-Si shape memory alloy', *Engineering Structures*, 243, p. 112710. doi: 10.1016/j.engstruct.2021.112710.

Hoult, R. *et al.* (2020) 'Seismic performance of slender RC U-shaped walls with a single-layer of reinforcement', *Engineering Structures*, 225. doi: 10.1016/j.engstruct.2020.111257.

Hoult, R., Correia, A. A. and Almeida, J. P. (2023) 'Beam-truss models to simulate the axial-flexural-torsional performance of RC U-Shaped wall buildings', *CivilEng*, 4(1), pp. 292–310. doi: 10.3390/civileng4010017.

Hoult, R. D. and Almeida, J. P. (2022) 'Residual displacements of reinforced concrete walls detailed with conventional steel and shape memory alloy rebars', *Engineering Structures*, 256(January). doi: 10.1016/j.engstruct.2022.114002.

Hoult, R. D., Almeida, J. P. and Correia (2024) 'Overview and blind prediction from shake table tests of a large-scale RC U-shaped core wall', in *18th World Conference of Earthquake Engineering (WCEE2024)*.

Hoult, R., Doneux, C. and Pacheco de Almeida, J. (2023) 'Tests on reinforced concrete U-shaped walls subjected to torsion and flexure', *Earthquake Spectra*, pp. 1–26. doi: 10.1177/87552930231195315.

Ile, N., Plumier, C. and Reynouard, J. M. (2002) 'Test program on U-Shaped walls leading to model validation and implications to design', in *12th European Conference on Earthquake Engineering*.

Ile, N. and Reynouard, J. M. (2005) 'Behaviour of U-shaped walls subjected to uniaxial and biaxial cyclic lateral loading', *Journal of Earthquake Engineering*, 9(1), pp. 67–94.

Isaković, T. *et al.* (2021) 'Shake table test of RC walls' coupling provided by slabs', *Gradjevinski materijali i konstrukcije*, 64(4), pp. 225–234. doi: 10.5937/grmk2104225i.

Isaković, T. and Fischinger, M. (2019) 'Assessment of a force–displacement based multiple-vertical-line element to simulate the non-linear axial–shear–flexure interaction behaviour of reinforced concrete walls', *Bulletin of Earthquake Engineering*, 17(12), pp. 6369–6389. doi: 10.1007/s10518-019-00680-7.

Kawashima, K. (2000) 'Seismic design and retrofit of bridges', in *12h World Conference on Earthquake Engineering*, pp. 265–285.

Kurama, Y. C. *et al.* (2018) 'Seismic-Resistant Precast Concrete Structures: State of the Art', *Journal of Structural Engineering*, 144(4), p. 03118001. doi: 10.1061/(asce)st.1943-541x.0001972.

Lezaack, M. B. *et al.* (2022) 'Dissimilar friction welding of NiTi shape memory alloy and steel reinforcing bars for seismic performance', *Science and Technology of Welding and Joining*. doi: 10.1080/13621718.2022.2061692.

Liossatou, E. and Fardis, M. N. (2015) 'Residual displacements of RC structures as SDOF systems', *Pacific Conference on Earthquake Engineering*, 44(5), pp. 713–734. doi: 10.1002/eqe.

Mahin, S. A. and Bertero, V. V. (1981) 'An evaluation of inelastic seismic design spectra', *Journal of the Structural Division*, 107(9), pp. 1777–1795.

Marquis, F. *et al.* (2017) 'Understanding post-earthquake decisions on multi-storey concrete buildings in Christchurch, New Zealand', *Bulletin of Earthquake Engineering*, 15(2), pp. 731–758. doi: 10.1007/s10518-015-9772-8.

Maruta, M. *et al.* (2000) 'Structural Capacities of H-Shaped Rc Core Wall Subjected To', in *12th World Conference in Earthquake Engineering*, pp. 1–8.

Mccormick, J. *et al.* (2008) 'Permissible residual deformation levels for building structures considering both safety and human elements', in *14th World Conference on Earthquake Engineering*. Beijing, China.

Orgnoni, A. and Pinho, R. (2024) 'Numerical modelling of U-shaped RC walls using the Applied Element Method (AEM)', in *18th World Conference of Earthquake Engineering (WCEE2024)*.

Peng, X. N. and Wong, Y. L. (2011) 'Behavior of reinforced concrete walls subjected to monotonic pure torsion-An experimental study', *Engineering Structures*, 33(9), pp. 2495–2508. doi: 10.1016/j.engstruct.2011.04.022.

Priestley, M. J. N. *et al.* (1999) 'Preliminary results and conclusions from the PRESSS five-story precast concrete test building', *PCI Journal*, 44, pp. 42–67. Available at: https://doi.org/10.15554/pcij.11011999.42.67.

Raza, S. *et al.* (2023) 'Self-centering technique for existing concrete bridge columns using prestressed iron-based shape memory alloy reinforcement', *Engineering Structures*, 294(July), p. 116799. doi: 10.1016/j.engstruct.2023.116799.

Smil, V. (2014) *Making the Modern World - Materials and Dematerialization*. John Wiley & Sons, Ltd. Available at: http://library1.nida.ac.th/termpaper6/sd/2554/19755.pdf.

Türkay, A. and Altun, F. (2022) 'Experimental study of seismic torsional behavior of reinforced concrete walls', *Bulletin of Earthquake Engineering*, 20(8), pp. 4213–4235. doi: 10.1007/s10518-022-01366-3.

Twigden, K. M. and Henry, R. S. (2019) 'Shake table testing of unbonded post-tensioned concrete walls with and without additional energy dissipation', *Soil Dynamics and Earthquake Engineering*, 119, pp. 375–389. doi: 10.1016/j.soildyn.2018.05.007.

UN Environment (2017) *Global Status Report 2017*, *Global Status Report 2017: Towards a zero-emission, efficient, and resilient building and construction sector*. Available at: www.globalabc.org.

Vahedi, M., Ebrahimian, H. and Saiidi, M. S. (2022) 'Experimental-Analytical Investigation of Accelerated Bridge Construction Concrete Columns with Self-Centering Fe-SMA Bars Subjected to Near-Fault Ground Motions', *Smart Materials and Structures*, 299(January 2023), p. 117127. doi: 10.1016/j.engstruct.2023.117127.