ONGOING EXPERIMENTAL PROGRAMMES ON RC WALLS REINFORCED WITH IRON-BASED SHAPE MEMORY ALLOY REBARS

R. Hoult[1] and J. Pacheco de Almeida[2]

[1] Institute of Mechanics, Materials and Civil Engineering, UCLouvain, Belgium, ryan.hoult@uclouvain.be

[2] Institute of Mechanics, Materials and Civil Engineering, UCLouvain, Belgium

Abstract: *Reinforced concrete (RC) construction plays, and will keep on playing for the next decades, a pivotal role in building safe and resilient cities in both developed and developing countries, due to the extraordinary properties that make it irreplaceable for countless infrastructure. Presently, RC walls are the backbone of millions of mid- and high-rise buildings around the world, primarily resisting the lateral loads from wind and earthquakes. Some recent large seismic events have led engineers to propose a revision to design performance objectives, which requires an evolution from the current "life safe" approach to seismic design. Engineers will progressively design for serviceable and operational building performance for rarer earthquake events, which is also linked to the expected increase in design service life. Yet, to achieve these targets, engineers will not only have to design for larger seismic loads, but also implement better structural technologies and materials. This paper presents some ongoing research at UCLouvain, Belgium, investigating the seismic performance of RC walls partially detailed with iron-based shape memory alloy (F_e-SMAs) rebars, with the central goal of minimizing residual displacements. The approaching large-scale shake-table test of a 40-ton RC wall is first introduced (results will be shown at the conference). Some preliminary results are then provided from a recent experimental investigation on material tests and RCprisms, detailed with F_e-SMA and steel rebars. Testing RC prisms representing wall boundary regions under uniaxial loading is a cost-effective and simplified approach to assess key failure modes of flexurally-dominated walls that has been adopted by many researchers. The RC prisms are detailed similarly to previous tests with conventional steel rebars, allowing for some direct comparisons with regards to residual deformations. Quasi-static cyclic tension-compression axial displacements are applied. State-of-the-art high-definition fibre optic sensing is used to accurately determine the strains and temperature evolution of the rebars throughout testing. The authors present some promising results showing that this novel and economically competitive substitutive-reinforcement material for robust RC wall structures can minimise residual displacements.*

1. Introduction

Reinforced concrete (RC) construction is set to assume a pivotal role in the creation of safe and resilient future urban landscapes, not only in high-income countries but also in newly emerging economies. While some global construction practices are gradually transitioning towards more sustainable materials for the primary load-bearing elements of structures, such as engineered timber for gravity-resisting frames, the significance of RC core walls in effectively withstanding substantial lateral forces remains unchallenged (Connolly *et al.*, 2018). Currently, RC walls serve as the backbone for countless mid- and high-rise buildings worldwide, primarily resisting the lateral loads from wind and earthquakes. In the face of significant seismic events, modern RC buildings are designed to sustain severe damage while preventing collapse and safeguarding against loss of life (Abdulridha & Palermo, 2017).

As an example, consider the February 2011 M_w 6.2 earthquake in Christchurch, New Zealand. This seismic event generated ground motions that exceeded the design accelerations stipulated by modern building codes (Kam *et al.*, 2011). Despite this, the majority of contemporary RC buildings demonstrated their intended performance, allowing occupants to safely evacuate. However, the aftermath of such seismic events often leaves buildings with substantial and permanent relative deformations with respect to their foundations. These "residual displacements" (or drifts *δ*, Figure 1a) necessitate costly repairs and, in some cases, require the complete demolition and reconstruction of the affected structures. To put this into perspective, following the 2010-2011 earthquake sequence in New Zealand, approximately 25% of the buildings in the city of Christchurch were no longer in an upright position (Muir-Wood, 2015). Many of these structures had tilted to such an extent that they were deemed "uneconomic to repair," resulting in the demolition of 60% of RC buildings with three or more stories (Gonzalez *et al.*, 2021). From an engineer's perspective, the primary goal of ensuring "life safety" was achieved. However, the impact on citizens was profound. The scale of damage resulting from this event exceeded $NZD 40 billion in losses (Gonzalez *et al.*, 2021), necessitated the cordoning off of the city as a public exclusion zone, disrupted essential services, and tragically led to the loss of lives within the community. Indeed, Christchurch is just one of numerous instances where significant damage to RC buildings has been witnessed, leading to the demolition of many structures. Similar scenarios have occurred in various recent earthquake events around the world, including, but not limited to: the 1985 Mexico City earthquake in Mexico (Rosenblueth & Meli, 1986), the 1994 Northridge earthquake in the United States (Mitchell *et al.*, 1995), the 1995 Kobe earthquake in Japan (Kazuhiko, 2000), the 2009 L'Aquila earthquake in Italy (Di Ludovico *et al.*, 2021), and the 2010 Maule earthquake in Chile (de la Llera *et al.*, 2017).

In response to the aforementioned challenges, there have been proposals for revised building performance targets (Buchanan *et al.*, 2011). These proposed changes call for a fundamental shift in the current approach to seismic design. Instead of solely aiming for "life safety", engineers are prompted to design structures that can maintain their functionality and operational capacity with minimal damage, even under rare and severe earthquake events. These updated performance objectives share similarities with those being proposed for the next generation of Eurocode 8 building standards (CEN, 2023). However, achieving these ambitious targets will require more than just designing for larger seismic loads, associated to a desirable increase in building design service life. Engineers will also need to implement advanced structural technologies and materials to ensure the resilience and integrity of buildings in the face of such extreme seismic challenges.

This paper focuses on the ongoing research project "SMA-RC-WALLs", funded by a Marie Skłodowska-Curie Actions (MSCA) postdoctoral fellowship. The goal of the research project is to test novel and economically competitive substitute materials for resilient reinforced concrete wall structures that can minimise residual displacements, leading to a much-needed evolution in the seismic design of engineering structures. A significant aspect of the proposed project is the global aim of developing innovative and adaptable incremental design changes that can be readily implemented in construction. Incremental innovation of structural design practices has played a critical role in improving the performance of structures (Henry, 2021), where engineers implement incremental changes to established practices to encourage industry acceptance rather than radical innovation, which might face resistance in industry adoption. The aim of incorporating *adaptability* of the proposed design into the criteria of chosen solutions is to increase the feasibility of streamlining the widespread adoption of the design solution. The authors believe that adaptability can be achieved if the design approach (i) is cost-effective, using materials requiring only a marginal increase of the total construction costs, and (ii) requires an incremental adjustment to the established design and building practices internationally. Specifically, this research project focuses on investigating the seismic performance of RC walls detailed with iron-based Shape Memory Alloys (F_e-SMAs) rebars. This interdisciplinary research is carried out at the Université catholique de Louvain (UCLouvain), Belgium, in the Institute of Mechanics, Materials and Civil Engineering (iMMC). This project encompasses a comprehensive experimental program, including the testing of large-scale RC wall units. The introduction and description of some preliminary tests, however, is the central focus of this conference paper. In the next section, a brief overview and justification of the proposed application, for embedding F_e-based SMA rebars in RC walls is provided, with the plans of some preliminary material testing of the F_e-SMA rebars discussed. An overview of different large-scale testing programmes at

UCLouvain incorporating Fe-SMAs in walls, or components of walls (i.e., boundary elements or prisms), is given in Section 3.

2. Fe-SMA rebars for newly designed RC walls

2.1 Background and Working Principles

A common design feature of modern RC walls are “boundary elements” (Figure 1b) detailed with additional steel longitudinal reinforcement (Sritharan *et al.*, 2014). In earthquake events, these boundary regions of the wall are subjected to the largest tensile strains (Rosso *et al.*, 2020), and thus the yielding and inelasticity occurring in the steel rebars within these zones are typically the source of residual displacements for the member and the building (e.g., Δ_{res} in Figure 1a,b).

A conventional approach to develop self-centring characteristics of RC walls is the use of unbonded post-tensioned tendons. The most renowned project on this topic was the Precast Seismic Structural Systems (PRESS) research programme (Priestley *et al.*, 1999), which helped to validate this concept, and many improved variations of this system have been proposed over the past two decades (Andrea Belleri & Robert, 2014; Holden *et al.*, 2003; Restrepo & Rahman, 2007; Wael & Hiroshi, 2002). There are, however, several challenges to effectively implementing this system on a large scale, including large initial associated costs, practical application, maintenance, and required expertise. Other challenges include a reduction of the post-tensioned strength under cyclic loading (Erkmen & Schultz, 2009; Priestley & Tao, 1993), excessive uplift (Encina *et al.*, 2016), and rocking motion causing localised concrete crushing at the toe (Smith *et al.*, 2013). Given the aforementioned challenges, the authors deem this solution to not be applicable with the global project aim of *adaptability* (Section 1). The interested reader can find more information regarding unbonded post-tensioned concrete systems in a recent state-of-the-art review on the topic (Kurama *et al.*, 2018).

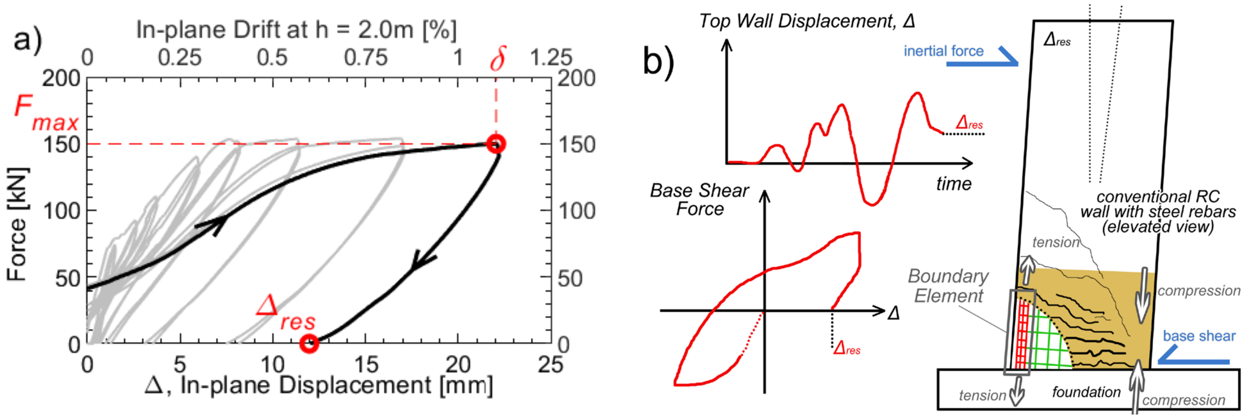

Figure 1 Residual displacements (Δ_{res}): (a) as a function of the in-plane drift (δ) from the reverse-cyclic force-displacement relationship of a wall; (b) in ordinary reinforced concrete walls with boundary elements

SMA reinforcing bars (“rebars”) have recently attracted some interest from researchers and structural engineers primarily due to their ability to: (i) recover displacements: either through superelastic response – typically for NiTi alloys, or via the leveraging of the unique self-prestressing features of Fe-SMA upon heating, (ii) dissipate energy through hysteretic damping, and (iii) provide strength and displacement capacities comparable to conventional carbon-steel reinforcement. It is for these reasons that SMA bars have the potential to be used as the reinforcement in wall boundary ends (Figure 1b), with the aim of reducing residual displacements and ultimately decreasing societal and economic impacts after seismic events. There were several research programmes that have experimentally tested RC walls detailed with SMAs. Abdulridha and Palermo (2017) tested two walls, namely one conventional unit reinforced with steel and the other detailed with Nickel Titanium (NiTi) rebars, to investigate seismic performance improvement. For imposed drift levels up to 4%, a displacement recovery of 92% was reported for the SMA wall in comparison to just 31% for the conventional-steel wall. In a follow-up study, Cortés-Puentes *et al.* (2018) repaired the two walls tested by Abdulridha and Palermo (2017), with the repaired NiTi SMA unit showing displacement recoveries up to 80% for drift ratios less than 2%. Amongst the different reinforcing material solutions Kian and Cruz-Noguez (2018) tested for the purpose of recentring capabilities, the single wall unit with NiTi SMAs was observed to exhibited the highest drift capacity with reductions of the permanent deformations. One of the authors of the present paper recently directed a research program that involved testing a wall unit with a considerable shear span. This wall was detailed with NiTi SMAs, aiming to diminish residual displacements compared to a companion wall detailed with conventional steel reinforcement (Almeida *et al.*, 2020). Dina *et al.* (2023) tested two RC walls detailed with NiTi SMA rebars over a length of approximately 400 mm in the plastic hinge zone (i.e., base of the wall) and shear spans of 1.9. Most recently, Soto-Rojas *et al.* (2023) repaired two previously tested RC walls from Morcos (2021) with engineered cementitious composites, one wall reinforced with NiTi SMAs.

The existing research programs exploring the utilisation of SMAs in RC walls have certain limitations. Firstly, the research is constrained by the limited testing conducted on a sparse number of walls, all of which possess a planar cross-section. It is important to note that RC core walls in mid- and high-rise buildings commonly feature non-planar designs, exhibiting distinctly different behaviour compared to their planar counterparts (Hoult, 2021). Secondly, although the NiTi alloy has been the most widely studied of the SMAs, its high manufacturing costs pose a challenge in its practical consideration for widespread construction applications. Hence, the use of NiTi SMAs fail to meet the adaptability criteria set by the SMA-RC-WALLs project.

Iron-based shape memory alloys (F_e-SMA) have recently received significant attention from the research community due to its substantial potential for large-scale applications. This is largely attributed to its cost-effectiveness, notably in contrast to the NiTi counterpart, along with its consistent recovery stress (Liu *et al.*, 2023). Recent cost assessments conducted by the authors revealed that the 12.7 mm diameter NiTi-based SMA costs approximately €450 per meter of material, whereas the 16 mm F_e-based SMA costs only €69 per meter. Another significant advantage of F_e-SMAs lies in the generation of prestress through temperature-induced crystalline phase transitions (Liu *et al.*, 2023), eliminating the requirement for on-site tensioning using specialised equipment and expertise. If the deformation of the F_e-SMA rebar is constrained by, for example, surrounding bonded or unbonded concrete, the prestresses generated after high-temperature activation can be transformed into recovery stresses (Liu *et al.*, 2023). This prestressing technique does not depend on hydraulic jacks for prestressing, resulting in a significant simplification and acceleration of the process, while also eliminating frictional losses (Schranz *et al.*, 2020). For example, F_e-SMA reinforcement sourced from the Swiss company re-fer AG (re-fer, 2023) was recently used to retrofit existing bridge columns in Raza *et al.* (2023). The additional F_e-SMA rebars were installed and grouted into the foundation and loading blocks of the columns, heated ("activated") to a temperature of range of 200–220°C by gas torch, subsequently achieving axial prestress on the concrete of the reinforcing member ranging from 4.1 MPa to 10.1 MPa for the three specimens (note: the cross-sectional diameter of the columns were approximately 260 mm during the activation period). This technique used by Raza *et al.* (2023) was successful in adding self-centring capabilities to the columns, which recorded residual drifts that were 50-75% and 30-60% smaller than those achieved by the conventional-steel column after achieving in-plane drifts of 3% and 5%, respectively. The activated F_e-SMAs subjected to high cycle-fatigue loads have been found to exhibit a negligible decrease in stiffness under cyclic loading (Raza *et al.*, 2022c). It is also anticipated that the sourced F_e-SMA will exhibit enhanced corrosion resistance compared to conventional steel, attributed to the presence of 10% chromium (Raza *et al.*, 2022c) – however, further studies are required to validate this assumption.

2.2 Material Testing

The ribbed F_e-SMA rebars offered by re-fer AG Swiss company (re-fer, 2023), alloy composition Fe-17Mn-5Si-10Cr-4Ni-1 (V,C) (in mass-%), align with the *adaptability* objectives set forth in this project. Hence, this material will be the focal point of the SMA-RC-WALLs project, aimed at diminishing the residual displacement capacity of RC walls, consequently bolstering the resilience and robustness of these structures. These F_e-SMA bars were prestrained by the manufacture to a minimum of 4% (Shahverdi *et al.*, 2018) in order to obtain the warranted shape memory effect after "activation" (i.e., ability to undergo substantial reversible deformation and recover their original shape). All of the rebars attained are Φ16 mm in diameter and the surface geometry complied with the British Standard 6744:2001 (BSI, 2209).

As explained in more detail in Section 3, the team at the iMMC, UCLouvain intend to use the F_e-SMAs for the specific purpose of newly designed structures in seismic regions, which somewhat deviates from prior applications largely focused on retrofitting existing structures. As suggested in Raza *et al.* (2022c), exploring the effectiveness of F_e-SMAs for prestressing RC structures holds promise in enhancing their self-centring potential. Hence, the objective of these material tests is to acquire vital insights into the mechanical characteristics of F_e-SMA rebars that are specifically intended for newly designed RC structures, which are key to understand their response under extreme earthquake loading conditions. The proposed material testing primarily focuses on examining the F_e-SMAs uniaxial behaviour under various conditions: (i) different activation levels (i.e., varying applied temperatures) and (ii) different loading protocols.

Regarding the former of these conditions: the Fe-SMA rebars will undergo testing at varying activation temperatures to attain distinct recovery stresses. Previously, it has been demonstrated that the rise in recovery stress of the F_e-SMA reaches a plateau within the temperature range of 250°C to 300°C (Raza *et al.*, 2023). Moreover, as indicated by Gu *et al.* (2021), the recovery stress of F_e-SMA strips did not exhibit an increase when the activation temperature exceeded 350°C. To demonstrate this observation, the authors have collated data from previous experiments conducted by several researchers (Gu *et al.*, 2021; Michels *et al.*, 2018; Raza *et al.*, 2023) to generate a graphical representation in Figure 2a, plotting the maximum recovery stress achieved against the activation temperature used. Therefore, the authors expect to test three Fe-SMA rebars of total length 500 mm at three different target activation temperatures: 200°C, 240°C, and 280°C. As explained in Raza *et al.* (2023), it is difficult to use a gas torch to precisely control the application of heat and to activate the prestressing of the F_e-SMA rebars. Instead, using Electric Resistive Heating (ERH) can more precisely control the temperature and activation applied to the rebars. ERH has been used in previous research projects to activate Fe-SMA rebars (Liu *et al.*, 2023; Raza *et al.*, 2022a). ERH is also more compatible with the proposed instrumentation, involving the bonding of distributed fibre optic sensors (DFOS) along the longitudinal rib of the rebar to accurately record high-resolution strain and temperature information. This state-of-the-art data acquisition technique was successfully used by the authors with conventional steel (Hoult *et al.*, 2023a). For reference, the operating temperature of the HD Strain Sensors from LUNA (2023) ranges from -40°C to 300°C. Various researchers in the past have also employed different "holding times," referring to the duration during which the maximum warranted activation temperature is attained and maintained. Raza *et al.* (2022b) used a holding time of 30 minutes with a target activation temperature of 160°C. In contrast, Liu *et al.* (2023) recommended a hold time of only 120 seconds. The various aspects and findings from previous research will be considered when formulating the proposed material testing methods.

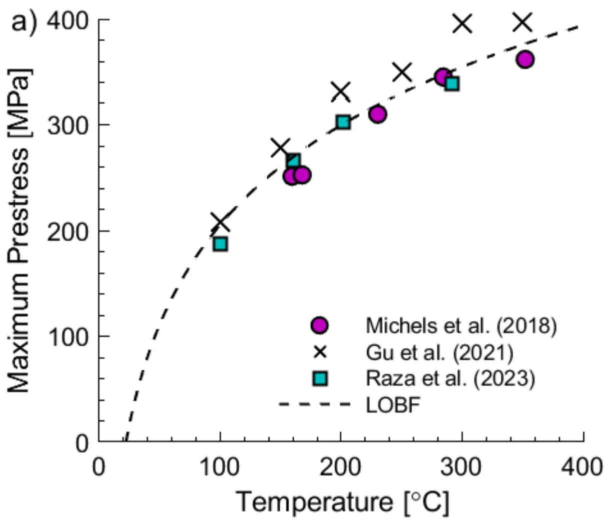

Figure 2 (a) Maximum prestress (P) of the Fe-SMA rebars as a function of temperature (T) for 4% prestrained F_e-SMAs; line-of-best-fit (LOBF) was found to be a log function [P=136log(T)-421] with r^2 of 0.89

The loading protocol for these material tests was also treated as a variable. Typical monotonic and cyclic strain histories will be investigated, as will the loading rate: strain rates of 0.03%/s and 0.8%/s are chosen for strain demands below and above 2%, respectively, which have been informed by previous material testing (Rosa *et al.*, 2021) and conform with different international material testing standards (ASTM, 2016; CEN, 2001). Additionally, these tests will be supplemented by one using a strain rate of 8%/s, which has been approximated as a typical strain rate experienced by steel structures during seismic events (Lamarche & Tremblay, 2011). Other dynamic strain histories will be considered, including those based on the work by Suzuki (2019) and De Castro E Sousa *et al.* (2020), which have been established from nonlinear response history analyses. A novel consideration will be the strain history estimated from truss elements, representing the F_e-SMA rebars, of a finite element model of the ERIES-ALL4wALL U-shaped core wall tests (see Section 3.1) subjected to a nonlinear dynamic time-history analysis. In total, four F_e-SMA rebars will be tested with a varying loading protocol. In these rebar tests, the designated activation temperature is set consistently at 240°C.

At present, the authors are in the preliminary phase of test preparation, and due to the paper submission deadlines, no results can be submitted. However, the authors anticipate presenting some of the material testing outcomes during the WCEE conference proceedings in July 2024.

3. Proposed Large-Scale Experimental Programs

This section provides a concise preview of forthcoming large-scale tests scheduled to be conducted between 2023-2024 at the iMMC at UCLouvain, specifically relevant to the sourced F_e-based SMAs. At the time of writing, the authors have not yet carried out these large-scale tests. However, it is expected that some results will be available to present at the WCEE2024 conference, aligning with the earlier discussion on material testing in Section 2.2.

3.1 ERIES ALL4wALL Dynamic Core Wall Test

An experimental campaign focusing on the dynamic behaviour of RC core walls will be conducted in early 2024 and primarily funded by ERIES (Engineering Research Infrastructures for European Synergies) Transnational Access program. The project is called "ALL4wALL – Smart ALLoys for WALLs: towards durable structures with long service lives and minimal seismic residual displacements" (Almeida *et al.*, 2024). The user group of the ERIES – ALL4wALL is composed of seven institutions: Université catholique de Louvain (UCLouvain), ENPC ParisTech, ISAE-Supméca - Institut supérieur de mécanique de Paris, University of Liège, University of Ljubljana, University of Pavia, and York University (Canada). The U-shaped core wall units, depicted in Figure 3, are approximately 4.54 m high, excluding the foundation and the 1.38 m tower of additional mass atop of the walls (Figure 3a). The cross-section and reinforcement detailing of the initial wall unit, UWS1, mirror those of units previously tested in 2023 using quasi-static, reverse-cyclic loading (Hoult *et al.*, 2023b). In a manner, this dynamic experimental program serves as an extension of these earlier quasi-static tests. UWS1 is also part of a blind prediction competition organized by the authors (https://uclouvain.be/en/research-institutes/immc/blind-prediction2023.html).

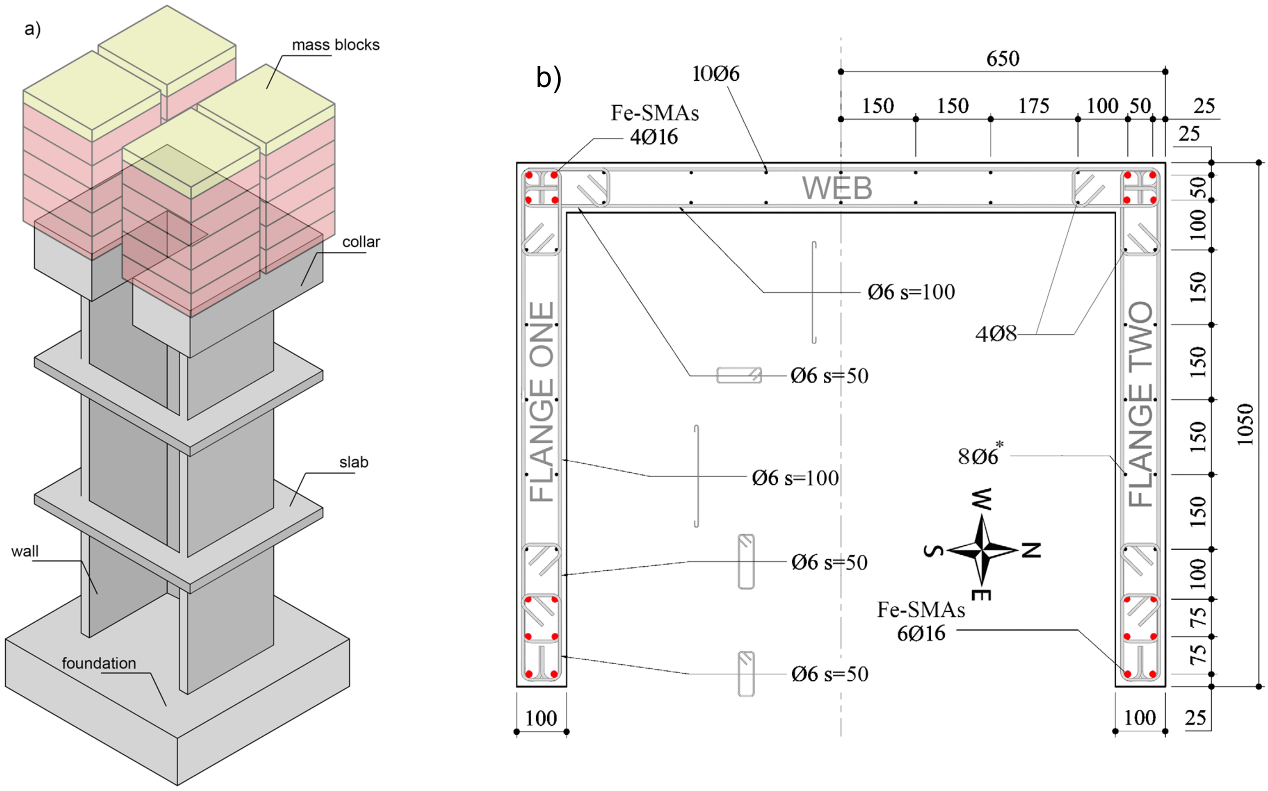

Figure 3 Unit UWS2 (a) three-dimensional elevation view with mass blocks and (b) cross-section and reinforcement detailing (red-shaded bars indicate Fe-SMA rebars) (dimensions in mm)

A companion conference paper, slated for the WCEE2024 (session CMS-1), encapsulates the experimental program and details of the initial test unit utilizing conventional steel (Hoult *et al.*, 2024). To maintain conciseness, this information is not reiterated here. Instead, specific details regarding the second wall unit, UWS2, are shown. Analogous to the first wall unit, UWS2 will mirror the same cross-section and reinforcement detailing. However, there is a notable alteration: the Φ12 mm longitudinal conventional steel rebars situated in the boundary ends of the wall will be substituted with Φ16 mm Fe-SMA rebars. During the construction phase of the wall unit, these SMAs will be prestressed (activated) by heat, leveraging the material's shape memory effect response to minimise residual displacements while ensuring a large energy dissipation capacity. DFOS will be bonded to several of the rebars, which will help monitoring the temperature application. The testing of UWS2 is anticipated to take place around April 2024 at the National Laboratory for Civil Engineering (LNEC), Portugal.

3.2 Boundary Element (Prism) Tests

Testing RC prisms under uniaxial loading, which represent loading in wall boundary regions, is a cost-effective and simplified approach to assess key failure modes of flexurally-dominated walls that has been adopted by many researchers (Carlos & Jack, 2023; Chrysanidis, 2020; Haro *et al.*, 2018; Menegon *et al.*, 2019; Rosso *et al.*, 2018; Tarquini *et al.*, 2019; Tripathi *et al.*, 2020; Welt *et al.*, 2017; Williams *et al.*, 2022). One of the limitations of this method is that a constant distribution of cross-sectional strains is applied, which is a simplification of the actual axial strain demands on wall boundaries. Nevertheless, these cost-effective experimental tests will provide salient results on crack-pattern evolution, as well as on the deformation and failure modes of RC-SMA walls. The latter include SMA and concrete-triggered flexural compression failure modes as well as out-of-plane buckling of wall boundary ends detailed with F_e-SMA bars rather than conventional steel. Quasi-static cyclic tension-compression axial displacements will be applied, similar to the loading regime used in previous research (Rosso *et al.*, 2018; Tripathi *et al.*, 2020). As with the material tests in Section 3.1, high-definition fibre optic sensing will be used to accurately determine the strains and temperature of the rebars throughout testing.

The approach taken in this experimental program is to test both more common "Long Boundary Elements" (LBEs) as well as Short Boundary Elements (SBEs). The SBE tests, as illustrated in Figure 4, are designed to conduct uniaxial tests until failure, specifically aiming to evaluate the compressive behaviour of prisms that model the boundary elements of thin structural walls. Meanwhile, the LBEs are predominantly oriented toward controlled large tension and low compression strains, with the aim of assessing the susceptibility of SMA-detailed boundary ends to out-of-plane instability, particularly in comparison to those detailed with typical steel.

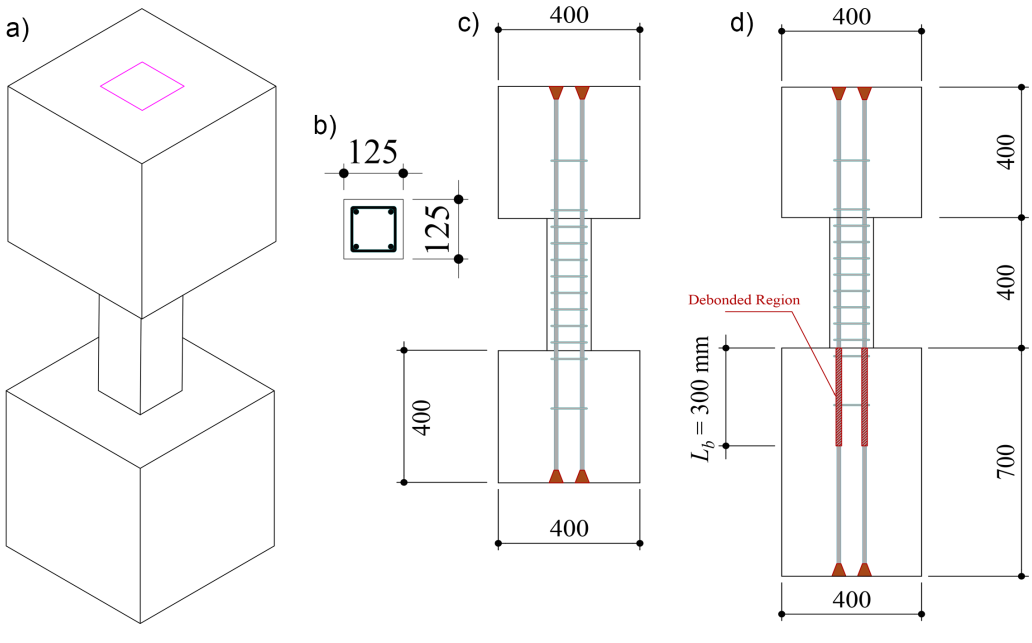

Figure 4. Short Boundary Elements (SBEs) (a) isometric 3-dimensional elevation view (b) cross-section with reinforcement detailing (c) typical unit with reinforcing material used over the entire length (d) F_e-SMAs debonded from concrete over specified height (not to scale) (dimensions in mm)

Under uniaxial tension-compression loading, the prestressed F_e-SMA rebars are expected to undergo compression reversals that could potentially trigger buckling and an associated softening response in compression (Raza *et al.*, 2022b). However, this speculation lacks any existing observations or quantitative results to support this behaviour, hence emphasising the significance of the SBE tests under substantial compressive loads. The 125 mm x 125 mm cross-section in Figure 4b should allow for a full crushing failure mode of the confined concrete zone to be achieved using a 1000 kN MTS actuator. The proposed testing variables of the SBE tests include (i) materials (i.e., with reference to Figure 4c: conventional steel, F_e-SMA, and combination of steel + F_e-SMA), (ii) loading protocol, and (iii) bonding/debonding of the F_e-SMA rebars (Figure 4d).

The proposed LBE units have similar cross-sections and design properties to the conventional units tested by Haro *et al.* (2018). Figure 5b presents the 300 mm x 125 mm cross-sections proposed for the LBE tests, and the unsupported length of 1600 mm is shown in Figure 5c-e. These design values represent half-scale dimensions of the boundary end of the wall in the first (ground) storey of a building in accordance with Eurocode 2 (CEN, 2004a) and Eurocode 8 (CEN, 2004b) for medium ductility (Varsamis & Papanikolaou, 2021). The proposed variables of the LBE tests include: (i) materials (i.e., conventional steel, F_e-SMA, and combination of steel + F_e-SMA), (ii) loading protocol, (iii) materials amalgamated using a friction weld technique (Lezaack *et al.*, 2022) (Figure 5d), and (iv) bonding/debonding of the F_e-SMA rebars (Figure 5e). The authors note that this testing program is currently in a preliminary stage, and so leave a word of caution as the testing variables may undergo potential changes. The authors expect to share some of the results from these tests at the WCEE conference in July of 2024.

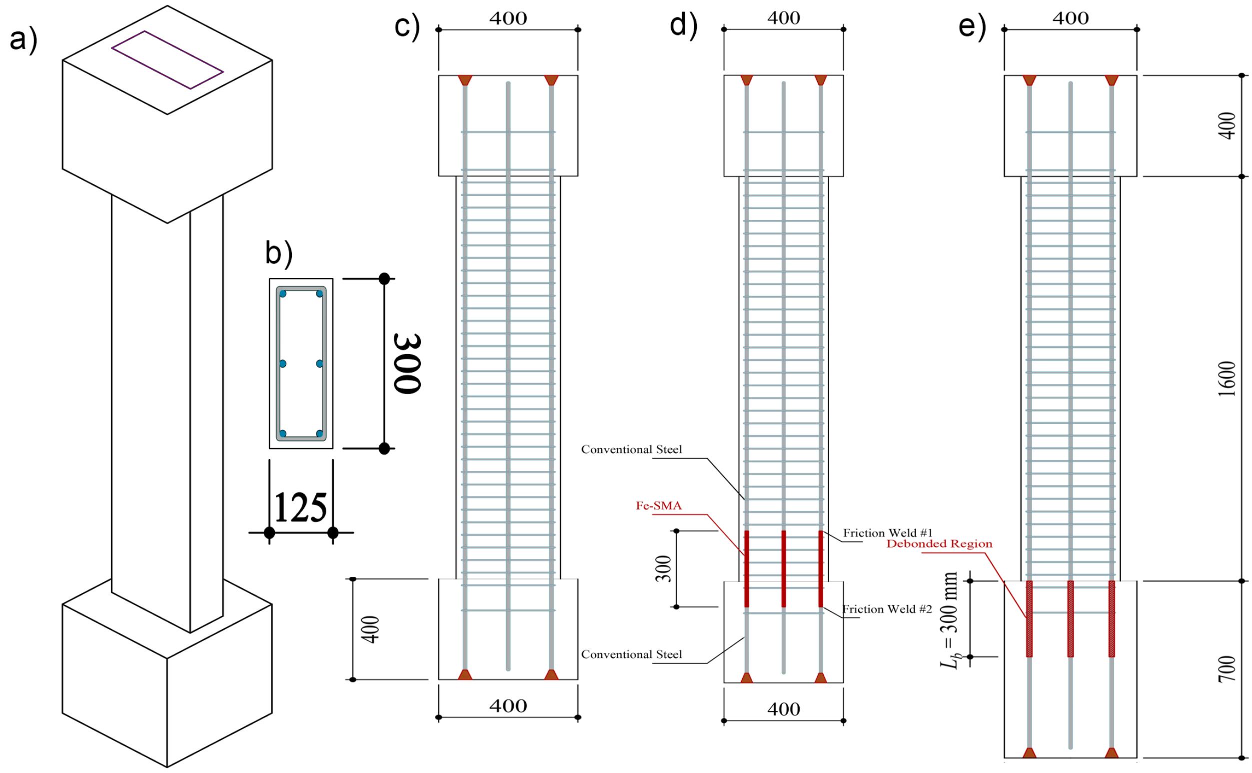

Figure 5. Long Boundary Elements (LBEs) (a) isometric 3-dimensional elevation view (b) cross-section with reinforcement detailing (c) typical unit with reinforcing material used over the entire length (d) Fe-SMA material used over small length at base (e) F_e-SMAs debonded from concrete over specified height (not to scale) (dimensions in mm)

3.3 Quasi-Static, Reverse-Cyclic Wall Unit Tests

To conclude the experimental phase of the SMA-RC-WALLs project, large-scale RC walls, detailed with F_e-SMA rebars at the boundary ends, will undergo testing using reverse-cyclic, quasi-static loading protocols. Presently, the authors lack further details about these tests as they are in the early preliminary design stages, including both for the units and the setup. Additionally, the authors plan to utilise results from the material testing (Section 2.2), large-scale dynamic tests (Section 3.1), and boundary end ("prism") tests (Section 3.2) to inform and guide the ultimate design of these wall units. These tests are anticipated to take place in late 2024 in the technological platform LEMSC (at iMMC, UCLouvain).

4. Conclusions

Structural response during recent earthquake events in regions with strong and robust building standards have generally met the expectations of earthquake engineers, prioritising life safety. However, the significant damage in specific building regions, designed for energy dissipation. has led to substantial economic losses, service disruptions, and the reconstruction of many RC structures. This has prompted a fundamental reassessment of performance targets for seismic engineering: instead of solely focusing on "life safety" performance, engineers are now also urged to design structures that sustain minimal damage under severe earthquake conditions, signifying a paradigm shift in seismic design approaches. To achieve these objectives, engineers need to employ advanced structural technologies and materials.

The iMMC team at UCLouvain is currently researching the effectiveness of iron-based shape memory alloy ("F_e-SMAs") rebars as an alternative to conventional steel. This material aligns with one of the global aims of the "SMA-RC-WALLs" project by promoting incremental innovations in construction practices, rather than radical changes. Activating F_e-SMAs through heat treatment generates recovery stresses in the rebars, exhibiting the desired shape memory effect, which applies the global prestressing responsible for structural self-centring. Hence, this cost-competitive material holds the potential to significantly decrease residual displacements in RC walls when used as the primary reinforcement. The outcomes of this research could contribute to a more resilient global building stock, enhancing community resilience and promoting the development of research and technology to mitigate the impacts of natural disasters.

This conference paper provides an overview of upcoming experimental tests planned at the iMMC at UCLouvain, ranging from small-scale material testing on F_e-SMAs to large-scale quasi-static and dynamic tests on RC wall units detailed with F_e-SMA rebars. As the authors are in the initial phase of test preparation and due to paper submission deadlines, no results are included in this conference paper. However, the authors anticipate presenting some results during the WCEE conference presentations in July 2024. The authors also plan to disseminate the test program results through various journal papers in 2024 and 2025. Interested readers can contact the corresponding author for updates or further information.

5. Acknowledgments

Most of the research programmes described in the present paper were funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement number 101061439.

6. References

Abdulridha, A., & Palermo, D. (2017). Behaviour and modelling of hybrid SMA-steel reinforced concrete slender shear wall. *Engineering Structures, 147*, 77-89. doi:10.1016/j.engstruct.2017.04.058

Almeida, J. P. d., Hoult, R., Bertholet, A., Candeias, P., Carvalho, A., Correia, A. A., . . . Sousa, M. L. (2024). *Shake-Table Testing of Two U-Shaped RC Walls: Overview of the Project ERIES-ALL4wALL*. Paper presented at the 8th World Conference on Earthquake Engineering (WCEE2024), Milan, Italy.

Almeida, J. P. d., Steinmetz, M., Rigot, F., & de Cock, S. (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*, 110865. doi:10.1016/j.engstruct.2020.110865

Andrea Belleri, M. J. S. J. I. R., & Robert, B. F. (2014). Dynamic Behavior of Rocking and Hybrid Cantilever Walls in a Precast Concrete Building (with Appendix). *ACI Structural Journal, 111*(3). doi:10.14359/51686778

ASTM. (2016). *E8/E8M - 16a - Standard test methods for tendion testing of metallic material* West Conshohocken, PA, USA.

BSI. (2209). *Stainless steel bars for the reinforcement of and use in concrete — Requirements and test methods* British Standards BS 6744:2001 + A2:2009: 28.

Buchanan, A., Bull, D., Dhakal, R., MacRae, G., Palermo, P., & Pampanin, S. (2011). Base Isolation and Damage-Resistant Technologies for Improved Seismic Performance of Buildings, Report to the Royal Commission for the Canterbury Earthquakes, New Zealand, August 2011. In.

Carlos, A. A., & Jack, P. M. (2023). Compressive Behavior of Thin Rectangular Boundary Elements. *ACI Structural Journal, 120*(2). doi:10.14359/51737236

CEN. (2001). EN 10002-1:2001 Metallic material Tensile testing Part 1: method of test at ambient temperature. In. European Committee for Standardization, Brussels, Belgium.

CEN. (2004a). Eurocode 2: Design of concrete structures, Part 1-1, EN 1998-1. In.

CEN. (2004b). Eurocode 8: Design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings 1998-1:2004. In.

CEN. (2023). Eurocode 8: Design of structures for earthquake resistance. Part 1: general rules and seismic action FprEN 1998-1-1:2023. In.

Chrysanidis, T. A. (2020). Evaluation of Out-of-Plane Response of R/C Structural Wall Boundary Edges Detailed with Maximum Code-Prescribed Longitudinal Reinforcement Ratio. *International Journal of Concrete Structures and Materials, 14*(1), 3. doi:10.1186/s40069-019-0378-4

Connolly, T., Loss, C., Iqbal, A., & Tannert, T. (2018). Feasibility Study of Mass-Timber Cores for the UBC Tall Wood Building. *Buildings, 8*(8), 98. doi:10.3390/buildings8080098

Cortés-Puentes, L., Zaidi, M., Palermo, D., & Dragomirescu, E. (2018). Cyclic loading testing of repaired SMA and steel reinforced concrete shear walls. *Engineering Structures, 168*. doi:10.1016/j.engstruct.2018.04.044

De Castro E Sousa, A., Suzuki, Y., & Lignos, D. (2020). Consistency in Solving the Inverse Problem of the Voce-Chaboche Constitutive Model for Plastic Straining. *Journal of Engineering Mechanics, 146*(9). doi:10.1061/(ASCE)EM.1943-7889.0001839

de la Llera, J. C., Rivera, F., Mitrani-Reiser, J., Jünemann, R., Fortuño, C., Ríos, M., . . . Cienfuegos, R. (2017). Data collection after the 2010 Maule earthquake in Chile. *Bulletin of Earthquake Engineering, 15*(2), 555-588. doi:10.1007/s10518-016-9918-3

Di Ludovico, M., De Martino, G., Prota, A., Manfredi, G., & Dolce, M. (2021). Damage assessment in Italy, and experiences after recent earthquakes on reparability and repair costs. In *Advances in assessment and modeling of earthquake loss* (pp. 65-84).

Dina, A. A., Ahmed, F. Z., Issa, M., & El-kashif, K. (2023). Self-centric cyclic resistance of reinforced concrete shear wall with Shape Memory Alloy: Numerical and experimental large-scale model. *Case Studies in Construction Materials, 19*. doi:10.1016/j.cscm.2023.e02365

Encina, E., Lu, Y., & Henry, R. S. (2016). Axial elongation in ductile reinforced concrete walls. *Bulletin of the New Zealand Society for Earthquake Engineering, 49*(4). doi:10.5459/bnzsee.49.4.305-318

Erkmen, B., & Schultz, A. E. (2009). Self-Centering Behavior of Unbonded, Post-Tensioned Precast Concrete Shear Walls. *Journal of Earthquake Engineering, 13*(7). doi:10.1080/13632460902859136

Gonzalez, R., Stephens, M., Toma, C., Elwood, K., & Dowdell, D. (2021). Post-earthquake demolition in Christchurch, New Zealand: A case-study towards incorporating environmental impacts in demolition decisions. In *Advances in Assessment and Modeling of Earthquake Loss* (pp. 47-64).

Gu, X.-L., Chen, Z.-Y., Yu, Q.-Q., & Ghafoori, E. (2021). Stress recovery behavior of an Fe-Mn-Si shape memory alloy. *Engineering Structures, 243*. doi:10.1016/j.engstruct.2021.112710

Haro, A. G., Kowalsky, M., Chai, Y. H., & Lucier, G. W. (2018). Boundary Elements of Special Reinforced Concrete Walls Tested under Different Loading Paths. *Earthquake Spectra, 34*(3), 1267-1288. doi:10.1193/081617eqs160m

Henry, R. (2021). Innovation - the next big thing or the next big failure? *SESOC Journal, 34*(2). doi:10.3316/informit.095544209048367

Holden, T., Restrepo, J., & Mander, J. B. (2003). Seismic Performance of Precast Reinforced and Prestressed Concrete Walls. *Journal of Structural Engineering, 129*(3). doi:10.1061/(ASCE)0733-9445(2003)129:3(286)

Hoult, R. (2021). A Universal Plastic Hinge Length for Reinforced Concrete Walls. *Submitted to ACI Structural Journal*.

Hoult, R., Bertholet, A., & Almeida, J. P. d. (2023a). Core versus Surface Sensors for Reinforced Concrete Structures: A Comparison of Fiber-Optic Strain Sensing to Conventional Instrumentation. *Sensors, 23*(3).

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

Hoult, R. D., Almeida, J. P. d., & Correia, A. A. (2024). *Overview and Blind Prediction from Shake Table Tests of a Large-Scale RC U-Shaped Core Wall*. Paper presented at the 18th World Conference on Earthquake Engineering (WCEE2024), Milan, Italy.

Kam, W. Y., Pampanin, S., & Elwood, K. J. (2011). Seismic performance of RC buildings in the 22 February Christchurch (Lyttelton) earthquake. *Bulletin of the New Zealand National Society for Earthquake Engineering, 44*(4).

Kazuhiko, K. (2000). Seismic design and retrofit of bridges. *Bulletin of the New Zealand Society for Earthquake Engineering, 33*(3). doi:10.5459/bnzsee.33.3.265-285
Kian, M. J. T., & Cruz-Noguez, C. (2018). Reinforced Concrete Shear Walls Detailed with Innovative Materials: Seismic Performance. *Journal of Composites for Construction, 22*(6), 04018052. doi:doi:10.1061/(ASCE)CC.1943-5614.0000893
Kurama, Y. C., Sritharan, S., Fleischman, R. B., Restrepo, J. I., Henry, R. S., Cleland, N. M., . . . Bonelli, P. (2018). Seismic-Resistant Precast Concrete Structures: State of the Art. *Journal of Structural Engineering, 144*(4). doi:10.1061/(ASCE)ST.1943-541X.0001972
Lamarche, C.-P., & Tremblay, R. (2011). Seismically induced cyclic buckling of steel columns including residual-stress and strain-rate effects. *Journal of Constructional Steel Research, 67*(9). doi:10.1016/j.jcsr.2010.10.008
Lezaack, M. B., Simar, A., Marchal, Y., Steinmetz, M., Faes, K., & Pacheco de Almeida, J. (2022). Dissimilar friction welding of NiTi shape memory alloy and steel reinforcing bars for seismic performance. *Science and Technology of Welding and Joining, 27*(6). doi:10.1080/13621718.2022.2061692
Liu, Z., Dong, Z., Sun, Y., Zhu, H., Wu, G., Sun, C., & Soh, C.-K. (2023). Effect of resistive heating on the bond properties between iron-based shape memory bars and cement mortar. *Journal of Building Engineering, 66*. doi:10.1016/j.jobe.2023.105895
LUNA. (2023). High-Definition Fiber Optic Strain Sensors. Retrieved from https://lunainc.com/product/hd6s (accessed on 31/10/2023).
Menegon, S. J., Wilson, J. L., Lam, N. T. K., & Gad, E. F. (2019). Experimental Testing of Nonductile Reinforced Concrete Wall Boundary Elements. *ACI Structural Journal, 116*(6). doi:10.14359/51718008
Michels, J., Shahverdi, M., Czaderski, C., & El-Hacha, R. (2018). Mechanical Performance of Iron-Based Shape-Memory Alloy Ribbed Bars for Concrete Prestressing. *ACI Materials Journal, 115*(6). doi:10.14359/51710959
Mitchell, D., DeVall, R. H., Saatcioglu, M., Simpson, R., Tinawi, R., & Tremblay, R. (1995). Damage to concrete structures due to the 1994 Northridge earthquake. *Canadian Journal of Civil Engineering, 22*(2), 361-377.
Morcos, M. (2021). *Seismic Behaviour of SMA-Reinforced Slender Concrete Shear Walls.* (MASc). York University, Toronto, Ontario, Canada.
Muir-Wood, R. (2015). The Christchurch earthquakes of 2010 and 2011. The Geneva risk reports. Risk and insurance research. Extreme events and insurance: 2011 Annus horribilis. Courbage C, Stahel WR, Geneva. In.
Priestley, M. N., Sritharan, S., Conley, J. R., & Pampanin, S. (1999). Preliminary results and conclusions from the PRESSS five-story precast concrete test building. *Pci Journal, 44*(6).
Priestley, M. N., & Tao, J. R. (1993). Seismic response of precast prestressed concrete frames with partially debonded tendons. *Pci Journal, 38*(1).
Raza, S., Michels, J., Schranz, B., & Shahverdi, M. (2022a). Anchorage behavior of Fe-SMA rebars Post-Installed into concrete. *Engineering Structures, 272*. doi:10.1016/j.engstruct.2022.114960
Raza, S., Michels, J., & Shahverdi, M. (2022b). Uniaxial behavior of pre-stressed iron-based shape memory alloy rebars under cyclic loading reversals. *Construction and Building Materials, 326*. doi:10.1016/j.conbuildmat.2022.126900
Raza, S., Shafei, B., Saiid Saiidi, M., Motavalli, M., & Shahverdi, M. (2022c). Shape memory alloy reinforcement for strengthening and self-centering of concrete structures—State of the art. *Construction and Building Materials, 324*. doi:10.1016/j.conbuildmat.2022.126628
Raza, S., Widmann, R., Michels, J., Saiid Saiidi, M., Motavalli, M., & Shahverdi, M. (2023). Self-centering technique for existing concrete bridge columns using prestressed iron-based shape memory alloy reinforcement. *Engineering Structures, 294*. doi:10.1016/j.engstruct.2023.116799
re-fer. (2023). re-bar method for concrete structures. Retrieved from https://www.re-fer.eu/en/re-bar/ (accessed on 30/10/2023).
Restrepo, J. I., & Rahman, A. (2007). Seismic Performance of Self-Centering Structural Walls Incorporating Energy Dissipators. *Journal of Structural Engineering, 133*(11). doi:10.1061/(ASCE)0733-9445(2007)133:11(1560)
Rosa, D. I. H., Hartloper, A., de Castro e Sousa, A., Lignos, D. G., Motavalli, M., & Ghafoori, E. (2021). Experimental behavior of iron-based shape memory alloys under cyclic loading histories. *Construction and Building Materials, 272*. doi:10.1016/j.conbuildmat.2020.121712
Rosenblueth, E., & Meli, R. (1986). The 1985 Mexico Earthquake. *Concrete International, 8*(5).
Rosso, A., Jiménez-Roa, L. A., Almeida, J. P. D., & Beyer, K. (2020). Instability of Thin Concrete Walls with a Single Layer of Reinforcement under Cyclic Loading: Numerical Simulation and Improved Equivalent

Boundary Element Model for Assessment. *Journal of Earthquake Engineering*, 1-32. doi:10.1080/13632469.2019.1691679

Rosso, A., Jiménez-Roa, L. A., Almeida, J. P. d., Zuniga, A. P. G., Blandón, C. A., Bonett, R. L., & Beyer, K. (2018). Cyclic tensile-compressive tests on thin concrete boundary elements with a single layer of reinforcement prone to out-of-plane instability. *Bulletin of Earthquake Engineering, 16*(2), 859-887.

Schranz, B., Czaderski, C., Vogel, T., & Shahverdi, M. (2020). Bond behaviour of ribbed near-surface-mounted iron-based shape memory alloy bars with short bond lengths. *Materials & Design, 191*. doi:10.1016/j.matdes.2020.108647

Shahverdi, M., Michels, J., Czaderski, C., & Motavalli, M. (2018). Iron-based shape memory alloy strips for strengthening RC members: Material behavior and characterization. *Construction and Building Materials, 173*. doi:10.1016/j.conbuildmat.2018.04.057

Smith, B. J., Kurama, Y. C., & McGinnis, M. J. (2013). Behavior of Precast Concrete Shear Walls for Seismic Regions: Comparison of Hybrid and Emulative Specimens. *Journal of Structural Engineering, 139*(11). doi:10.1061/(ASCE)ST.1943-541X.0000755

Soto-Rojas, M. A., Ferche, A. C., & Palermo, D. (2023). Behavior of NiTi Shape Memory Alloy- and Steel-Reinforced Shear Walls Repaired with Engineered Cementitious Composite. *ACI Structural Journal, 120*(4). doi:10.14359/51738745

Sritharan, S., Beyer, K., Henry, R. S., Chai, Y. H., Kowalsky, M., & Bull, D. (2014). Understanding Poor Seismic Performance of Concrete Walls and Design Implications. *Earthquake Spectra, 30*(1), 307-334. doi:10.1193/021713EQS036M

Suzuki, Y. (2019). *Earthquake-induced collapse of steel moment resisting frames with conventional and high performance steel columns.* (Ph.D.). McGill University, Montreal, Canada.

Tarquini, D., Almeida, J. P., & Beyer, K. (2019). Uniaxial Cyclic Tests on Reinforced Concrete Members with Lap Splices. *Earthquake Spectra, 35*(2). doi:10.1193/041418eqs091dp

Tripathi, M., Dhakal, R. P., Dashti, F., & Gokhale, R. (2020). Axial response of rectangular RC prisms representing the boundary elements of ductile concrete walls. *Bulletin of Earthquake Engineering, 18*(9), 4387-4420. doi:10.1007/s10518-020-00868-2

Varsamis, C. D., & Papanikolaou, V. K. (2021). Evaluation of current Eurocode 8 provisions on R/C ductile wall design. *Structures, 33*. doi:10.1016/j.istruc.2021.04.072

Wael, A. Z., & Hiroshi, M. (2002). Residual Displacements of Concrete Bridge Piers Subjected to Near Field Earthquakes. *ACI Structural Journal, 99*(6). doi:10.14359/12338

Welt, T. S., Massone, L. M., LaFave, J. M., Lehman, D. E., McCabe, S. L., & Polanco, P. (2017). Confinement Behavior of Rectangular Reinforced Concrete Prisms Simulating Wall Boundary Elements. *Journal of Structural Engineering, 143*(4). doi:10.1061/(ASCE)ST.1943-541X.0001682

Williams, I. D., Arteta, C., Shao, Y., & Ostertag, C. P. (2022). Hybrid fiber reinforced concrete special shear wall boundary element in compression. *Engineering Structures, 252*. doi:10.1016/j.engstruct.2021.113726