# UWS2 Specimen Description

This document summarizes the description of the design parameters of the second wall unit, UWS2.

**GEOMETRY AND REINFORCEMENT LAYOUT**

Test specimen UWS2 has a thickness ($t_w$) of 100 mm, with web and flange lengths ($L_w$ and $L_f$) of 1300 mm and 1050 mm, respectively, as defined in Figure 1a. Differing from previous quasi-static units, these units for dynamic tests have two 100 mm thick intermediate slabs spaced 1.5 m apart, as illustrated in Figure 1b. Each slab measures 1900 mm x 1620 mm and is hollow inside the core wall. The slabs were reinforced with two layers of mesh of 6mm diameter, with a square spacing of 100 mm. The foundation block, measuring 2.1 m x 2.1 m as depicted in Figure 1b, was fastened to the shake table floor using sixteen M30 threaded bars evenly spaced at 500 mm intervals. Instead of a loading stub (or slab), a top collar (i.e., increased wall thickness at the head) was used, which is expected to only partially restrain warping. The dimensions of the top collar, as shown in Figure 1b, include a depth of 500 mm. The wall height from the top of the foundation to the centre of the wall collar is 4290 mm.

The design of the test units followed a similar approach to others. Rather than adhering to a specific code, the design aimed for high ductility using capacity design principles deemed reasonable. For instance, as shown in Figure 1a, the wall units were designed with boundary elements containing a higher concentration of longitudinal and transverse reinforcement to ensure the development of high compressive strains in these regions, necessary for a ductile wall response.

UWS2 was reinforced with $\Phi$10.7 iron-based shape memory alloys (FeSMA), as depicted in Figure 1a. The FeSMA material was selected to reduce the residual displacements of the wall, as explained in the following section. Additionally, the units differed in the amount of vertical rebars in the boundary elements, commonly expressed in terms of reinforcement ratio ($\rho_{wv}$), which is the ratio of the area of the lumped longitudinal rebars to the area of concrete in the boundary regions. For example, the flange boundary ends of UWS1, detailed with 6 × 12 mm steel rebars, have a $\rho_{wv}$ of approximately 2.3%, whereas the 7 × 10.7 mm FeSMA rebars (with an effective area of 89.9 mm²) in UWS2 result in a $\rho_{wv}$ of 2.1%. The 4 × 12 mm steel rebars at each web-flange intersection of UWS1 was replaced by 5 × 10.7 mm FeSMA rebars in UWS2. The specific amount of longitudinal reinforcement in each wall was chosen to achieve similar strengths, as predicted from sectional analyses.

The FeSMA rebars extend from the foundation up to a lap-splicing region above the first slab above the foundation; along the height of the wall ground story (i.e., below the first-story slab) they were shrink-wrapped to promote an unbonded behavior with respect to the concrete. Only the rebar ends, i.e. along the foundation and the lap-splice region, remained effectively clamped, preventing the strain recovery resulting from the heating process that will be described after; instead, the shape memory effect induced by heating results in recovery stress and the prestressing of the wall. A detailed description of the FeSMA material, including the heating process and its role in inducing the shape memory effect, is provided in the next section.

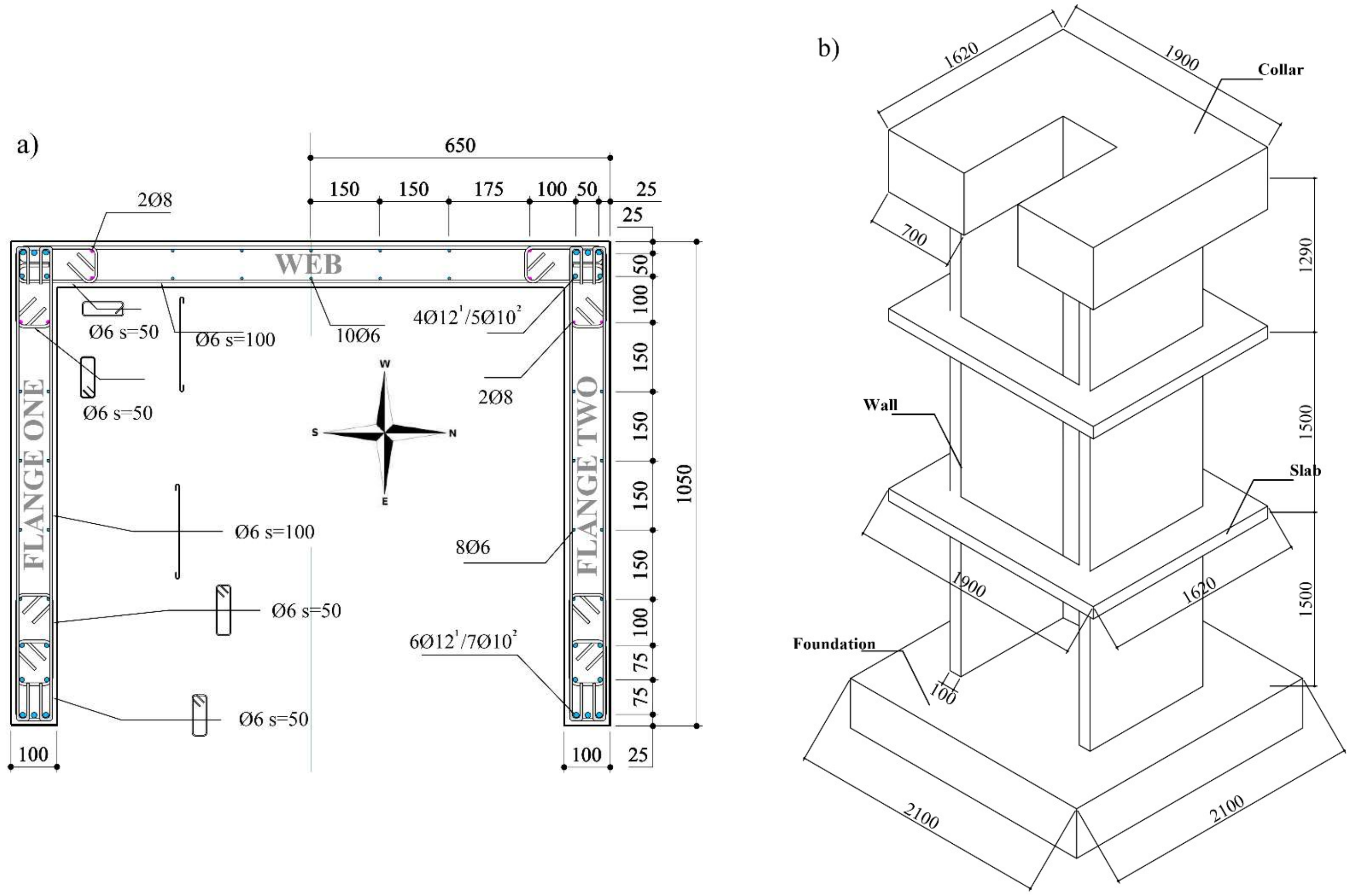


**Figure 1 Test unit UWS1 (a) cross-section and reinforcement layout and (b) elevation view. All dimensions are in millimetres.**

## MATERIAL PROPERTIES

The design concrete strength, defined as the 28-day cylinder strength, for the wall units was 30 MPa. Table 1 presents the compressive strengths ($f'_c$) of the different wall components, measured from testing cylinders at 28 days. For each wall component, three cylinders were tested, and the mean values of these tests are listed in Table 1. Note that the test for unit UWS2 was conducted 28 days after casting the concrete.

**Table 1 Mean values of the concrete cylinder compressive strengths.**

| | Cylinder compressive strength ($f'_c$, MPa) | | |
|---|---|---|---|
| | Foundation | Wall | Collar |
| UWS2 | 24.7 | 30.3 | 29.5 |

Table 2 lists the yield strength ($f_y$), ultimate strength ($f_u$), yield strain ($\varepsilon_{sy}$), ultimate strain ($\varepsilon_{su}$), and Young's modulus ($E_s$) for the different materials and bar diameters, where applicable. Additionally, the hardening strain ($\varepsilon_{sh}$), indicating the end of the constant strength yield plateau for steel, is provided in Table 2. In compliance with the requirements of Eurocode 8 to ensure ductility and energy dissipation, Class C steel was used for the longitudinal reinforcing steel bars in unit UWS2 and for all the transverse (shear and confinement) reinforcement.

Ribbed FeSMA rebars were sourced from the Swiss company re-fer AG with an alloy composition of Fe-17Mn-5Si-10Cr-4Ni-1 (V,C) (in mass-%). These FeSMA bars were prestrained by the manufacturer to a minimum of 4% to achieve the desired shape memory effect after "activation," allowing them to undergo substantial reversible deformation and recover their original shape. The shape memory effect refers to the FeSMA's ability to return to its pre-deformed shape when exposed to a specific stimulus, such as stress. "Activation" involves applying a stimulus, such as heat, to trigger the recovery of the bars' original shape. When the deformation of the FeSMA is constrained—such as by the encasing concrete—recovery stresses develop in the FeSMA. These stresses are used to effectively apply a prestressing effect to the wall, thus harnessing the shape memory effect of the material. All the FeSMA rebars have a diameter of 10.7 mm, and their surface geometry complied with the British Standard 6744:2001.

The FeSMA rebars underwent heating at a specific activation temperature to achieve the desired recovery stresses. 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 FeSMA. Previous research has shown that the recovery stress of FeSMA reaches a plateau of approximately 350 MPa within the temperature range of 250°C to 300°C. Additionally, others have indicated that the recovery stress of FeSMA strips does not increase when the activation temperature exceeds 350°C. In other research studies, the thermal activation of the FeSMA rebars was performed by gas flame heating, electric resistive heating (ERH), or heating tapes. The second option was used in unit UWS2 as it allows for a more precise and uniform temperature application; the latter was monitored by thermocouples. ERH is used to control the temperature and activation applied to the rebars, a method previously employed in research projects to activate FeSMA rebars. Different researchers have used varying "holding times," which refer to the interval during which the maximum activation temperature is attained and maintained. For instance, some used a holding time of 30 minutes with a target activation temperature of 160°C, while others recommended a holding time of only 120 seconds.

Laboratory tensile material tests were conducted on the 10.7 mm FeSMA rebar. The activation temperature using ERH in the laboratory exceeded 450°C, perhaps considerably, as the bar was observed to glow red from the heat. This high temperature value was not intended and can be explained by a malfunctioning of the thermocouple data acquisition system. The corresponding mechanical properties are provided in Table 2. It is worth noting that the tensile testing machine reached its stroke limits while testing the FeSMA bar over an effective gauge length of approximately 625 mm, so the ultimate stress and strain are not accurately depicted in Figure 2a.

**Table 2 Mechanical properties of the reinforcing bars**

| Material | $d_{bl}$ | $f_y^a$ | $f_u$ | $\varepsilon_{sy}$ | $\varepsilon_{sh}$ | $\varepsilon_{su}$ | $E_s$ | $n$ |
|---|---|---|---|---|---|---|---|---|
| - | [mm] | [MPa] | [MPa] | [mm/mm] | [mm/mm] | [mm/mm] | [GPa] | – |
| Steel | 6* | 577 | 623 | 0.0028 | – | 0.046 | 208 | 5 |
| Steel | 6# | 550 | 676 | 0.0027 | – | 0.095 | 207 | 3 |
| Steel | 8 | 538 | 664 | 0.0027 | 0.0268 | 0.12 | 196 | 3 |
| FeSMA^ | 10 | 555 | 830 | 0.0035 | - | 0.160 | 157 | 1 |

* transverse steel (i.e., shear reinforcement, confinement ties)

# longitudinal steel

^ values reported are constrained by the limitations of the testing apparatus

**TEST SETUP**

The wall unit, one of which is shown in Figure 2, were tested on the large shake table at the National Laboratory for Civil Engineering (LNEC) in Lisbon, Portugal. The maximum capacities of the horizontal actuators are 700 kN in the west-east (WE) direction and 500 kN in the north-south (NS) direction. Figure 1a illustrates the orientation of the wall relative to these cardinal directions. The positive axis conventions are defined as north to south and west to east. The shake table can achieve maximum displacements and velocities of ±200 mm and ±700 mm/s, respectively, in either direction. The table has a maximum payload capacity of approximately 40 tons.

To generate the required lateral inertial forces and reach the flexural capacity of the scaled wall units, several mass blocks were used. These included 1.13-ton and 0.59-ton blocks, which were connected to the collar (head) of the wall. These mass blocks have a cross-section of 840 mm × 840 mm, with thicknesses of 250 mm for the 1.13-ton blocks and 130 mm for the 0.59-ton blocks. A total of 20 (arranged in a 4 x 5 grid) 1.13-ton mass blocks were placed on the collar of the wall unit, along with four 0.59-ton mass blocks. This setup results in a total mass of 24.96 tons above the collar. Including the mass of the wall unit's collar, which is 3.27 tons, the total mass at the top of the wall is 28.23 tons.

As noted previously, the FeSMA rebars in unit UWS2 required heating for activation and to induce the desired shape memory effect upon cooling, thereby prestressing the wall. A 15 kW power supply, originally designed for welding, was repurposed for Electrical Resistive Heating (ERH) of the FeSMA bars. Several thermocouples were attached to some of the embedded rebars to monitor the heating process, targeting a temperature of 250°C.

To isolate the FeSMA rebars from the surrounding steel reinforcement (e.g., confinement, shear, longitudinal reinforcement, and foundation elements), the bars were primarily wrapped in plastic heat shrink. However, a later inspection of construction photos—taken in the absence of the authors—revealed that some FeSMA bars were in contact with steel reinforcement near the lap splice region above the first intermediate slab. This unintended contact resulted in inconsistent heating, as the ERH system lacked sufficient power to effectively heat the rebars when they were not fully isolated.

The maximum recorded temperatures from thermocouples at each wall corner were: South-east: 98.1°C, south-west: 97.8°C, north-west: 399.2°C, north-east: 63.5°C. These readings indicate that the ERH system was largely ineffective. However, some indirect signs of heat transfer were observed—such as the concrete surfaces at the south-east flange boundary and the north-west web-flange intersection becoming warm to the touch during heating.

Ultimately, the authors conclude that only partial precompression was achieved due to the inconsistent activation of the FeSMA rebars. This uneven heating likely contributed to the observed torsional rotation and increased displacement demand in the northward direction.

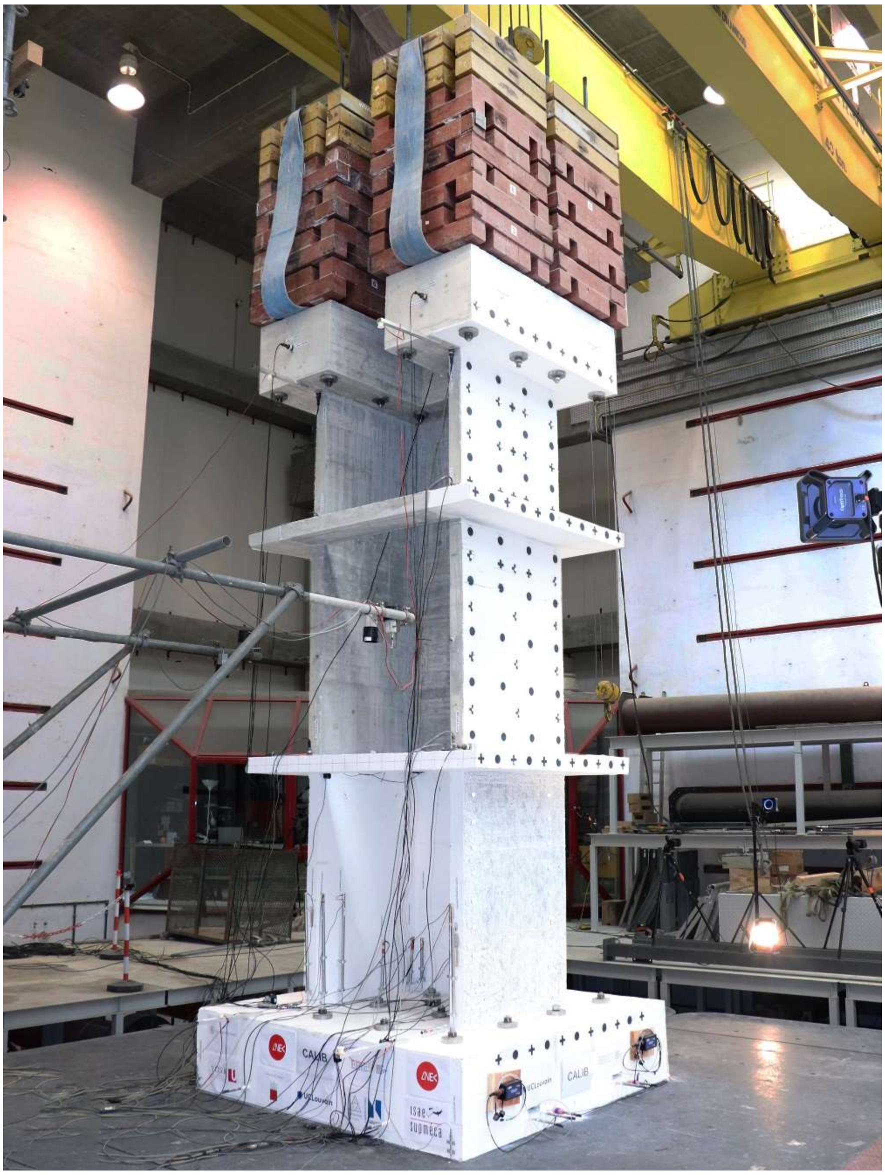

**Figure 2 Photo of test unit UWS2 taken from the north-east prior to testing.**