Blind prediction results of two RC U-shaped walls subjected to flexure and torsion

Ryan D Hoult[1], Catherine Doneux[1], and João Pacheco de Almeida[1]

1. Institute of Mechanics, Materials and Civil Engineering, UCLouvain, Louvain-la-Neuve, Belgium.

Abstract

An extensive experimental campaign was recently undertaken in the LEMSC laboratory of the iMMC institute at UCLouvain, Belgium, testing several large-scale reinforced concrete U-shaped walls subjected to flexure and torsion. A blind prediction competition was organised by the authors to promote the testing campaign and also provide salient information and data to improve future numerical models and critique any uncertainty of analytical models for structural and earthquake engineering design. The blind prediction results are thought to be particularly important for the wall unit subjected to torsion, where there is currently a very limited amount of experimental evidence for structural walls undergoing twisting. This paper provides a summary of the experimental tests and a look at some of the results of the blind prediction competition.

Keywords: U-shaped; core walls; torque; earthquake; seismic; twist; simulation; modelling

1 Introduction

Blind prediction competitions (BPCs) are important events that have the potential to capture the state of practice in structural and earthquake engineering, providing meaningful information on the range of different simulation approaches that are used, and also the accuracy of the results that these different approaches can provide.

In 1981, a BPC was organised by the IABSE Symposium in Delft focusing on simulating the structural performance of four reinforced concrete (RC) panels subjected to rather simplified loading conditions (Collins *et al.*, 1985). Nevertheless, a wide variation in predictions of the panel's shear strength and load-deformation response was observed from the 30 or so entries. In 1995, a BPC was organised by the Nuclear Power Engineering Corporation of Japan, which involved simulating the seismic performance of a large-scale non-planar "squat" wall subjected to dynamic cyclic loading (Kitada *et al.*, 1997). Over 30 teams participated in the challenge, where the predictions of strength to the experimental test appeared to be overall reasonably well correlated, whereas there was a large scatter of results for the estimation of the displacement capacity. In 2006, a BPC was organised by University of California at San Diego (UCSD) focusing on the simulation of a portion of a full-scale 7-story RC building tested on a large unidirectional shake table (Kelly, 2007; Restrepo, 2006; Waugh & Sritharan, 2006). A range of under- and over-estimating predictions were submitted by the applicants in this challenging contest (Waugh & Sritharan, 2010). More recently, a BPC was organised by the Pacific Earthquake Engineering Research (PEER) Center in 2021, in conjunction with other organisations (e.g., Maffei Structural Engineering, California State University Long Beach, and others), focusing on the simulation of a RC gravity, non-ductile column (PEER, 2021a). Again, a wide range of results were collected from over 100 entries, in particular with regards to the prediction of the shear strength and initial stiffness (PEER, 2021b). A variation of predictions in all of the abovementioned BPCs provides invaluable information that can not only lead to improved building standards for assessing or designing RC structures, but also salient information and data to improve future numerical models and critique any uncertainty of analytical models for structural and earthquake engineering design.

In April of 2022, the Civil and Environmental Engineering (GCE) group in the Institute of Mechanics, Materials, and Civil Engineering (iMMC) at the Université catholique de Louvain (UCLouvain) opened a BPC focusing on the prediction of the response of two RC U-shaped walls subjected to cyclic flexural and torsional actions up to failure. This competition was designed to cater to a wide range of participants, from those with limited time that wish to use simplified models, to those willing to employ more refined simulation tools. To this end, participants were allowed to predict the response of one or both wall units, and to submit just a compulsory set of basic data or, optionally, a full set of information including more refined data. Participants could consist of individuals or teams, and three categories were considered: practicing engineers, researchers, and students (up to and including doctoral level). An incentive in the form of a monetary reward was attributed to the winning participants without distinction of category (but with an additional reward for the student category). The aims of the UCLouvain 2022 BPC included assessing the state of practice in evaluating RC walls subjected to flexure and torsion, to observe the range of approaches that engineers use, and to analyse the results that these approaches provide. This prediction competition gained insight into the methods for assessing the behaviour – both at the global/structural level and at the local/strain level, strength, deformation, and rotation capacity of RC U-shaped walls.

This paper summarises some of the predictions from the participants in this event. In the next section, a short summary of the experimental program involving the testing of two large-scale RC U-shaped walls is provided. In Section 3, an overview of the blind prediction results is provided. Some conclusions are provided in Section 4.

2 Summary of Experimental Program

U-shaped RC walls are the most popular geometry among the possible shapes of core walls forming the backbone of millions of buildings internationally. They are well suited to accommodate elevator shafts or staircases and represent the structural lateral-load bracing system, namely against wind and seismic loads. RC core walls are unavoidably subjected to a torsional deformation component (i.e., twisting) during the seismic response of the building. The additional stresses induced in the wall from warping could result in a premature failure when combined with the stresses already generated from the flexural response of the structure. There is a very limited amount of research that has focused on the torsional performance and capacity of RC walls. Therefore, an experimental campaign was conducted at UCLouvain, Belgium, in the technological platform LEMSC (Laboratoire Essais Mécaniques, Structures et Génie Civil) of the iMMC (Institute of Mechanics, Materials and Civil Engineering). The program, which was carried out between March and August 2022, consists of testing three large-scale RC U-shaped walls subjected to different combinations of flexure and torsion (M-T): 1-0 (i.e., pure flexure), 0-1 (i.e., pure torsion), and 1-1. The international BPC was run in parallel to predict the seismic behaviour and performance of these two wall specimens, denoted here as UW1 and UW2, subjected to flexure and torsion, respectively.

Some information related to the design, construction, and testing of the two wall units is provided here. For the sake of brevity, this information is limited, and more detailed information about the specifics of the tests, as well as the experimental observations, can be found in a recently submitted Data Paper (Hoult *et al.*, 2022). It is worth noting that the corresponding dataset is now also available from the open access repository *Dataverse*: https://doi.org/10.14428/DVN/FDJ4EU

Specimens UW1 and UW2 are half-scale specimens of a 6-story prototype core wall that was initially analysed. The test specimens are approximately 1.4-stories tall (Figure 1a), where an overturning moment was applied to the head collar of test specimen UW1 to increase the shear span. The overturning moment (M_x) was achieved through three vertical actuators (Figure 1b), whereas two horizontal actuators applied the lateral cyclic displacements to the wall (F_y).

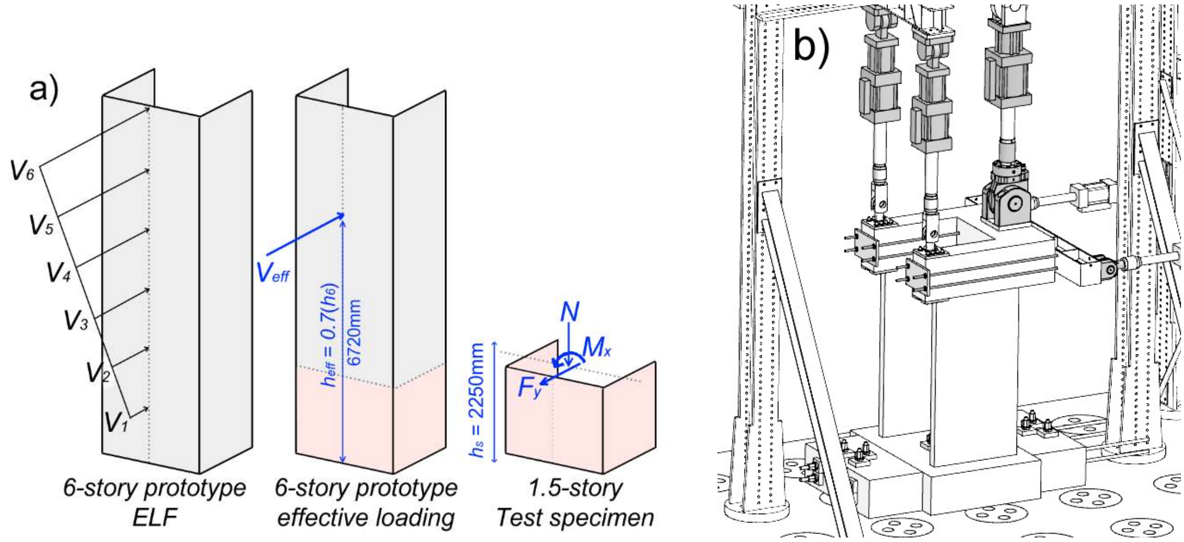

Figure 1. (a) Wall prototype and test specimen (b) 3D view of the laboratory setup with five actuators

The half-scale U-shaped wall test specimens have a thickness (t_w) of 100 mm, web length (L_w) of 1300 mm, and flange length (L_f) of 1050 mm. The geometry with reinforcement detailing is illustrated in Figure 2a, and the elevation view of the test specimens is given in Figure 2b.

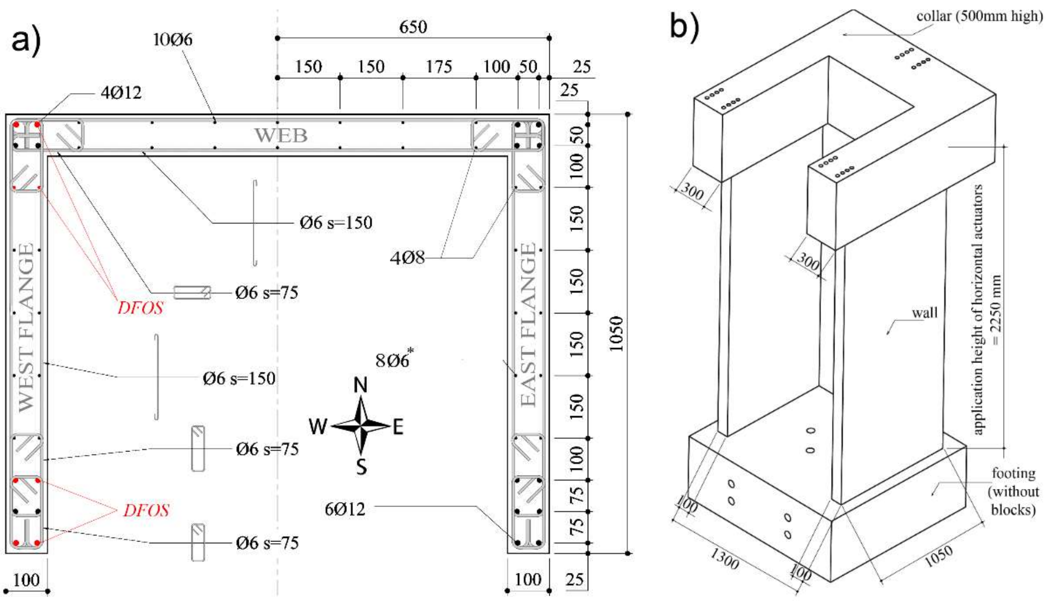

Figure 2. (a) cross-section and reinforcement detailing of the wall specimens (b) elevation view (not to scale)

In total, five actuators are used to test the two wall specimens. The three vertical actuators (i.e., A1, A2, and A3 in Figure 3a) were used to apply a simultaneous overturning moment and axial load to specimen UW1, which is subjected to pure flexure, whereas only an axial load is applied to specimen UW2. A total axial load ratio (*ALR*) of 5% was subjected to both wall units and held constant throughout testing. The *ALR* was evenly distributed to each of the three vertical actuators. The two horizontal actuators (i.e., NS-W and NS-E actuators in Figure 3a) are used to apply the reverse cyclic lateral displacement and the reverse cyclic torsional rotation to specimens UW1 and UW2, respectively. Unit UW1 is pushed to positions C and D (Figure 3b), whereas unit UW2 is rotated to position O+ (clockwise) and position O- (counterclockwise). The horizontal actuators are connected to a steel beam, depicted in Figure 3a, to increase the torque lever arm, which is at an application height of h_s=2250 mm from the foundation (Figure 2b).

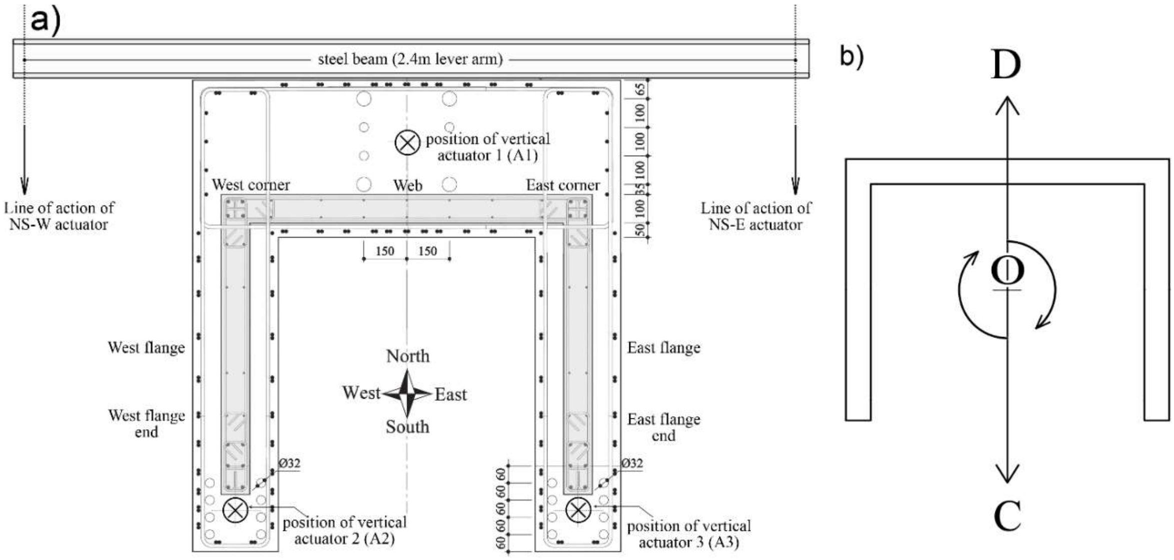

Figure 3. (a) cardinal points, sign convention for forces, displacements, and torques, denomination of wall sections (b) loading positions

3 Blind Prediction Results

In total, 15 participants submitted estimates for the BPC. Figure 4 shows the locations of all applicants from around the world. The participants included four individual students, one group of students, two individual researchers, and eight groups of researchers. Most of the participants noted that their estimates were achieved through numerical modelling, where only one participant mentioned the use of Eurocodes to help with some responses. There was a number of different software used, including: *XDEEA* (finite element), *OpenSees* using Multiple-Vertical-Line-Element-Model (MVLEM) (Kolozvari *et al.*, 2018; Kutay Orakcal & Joel), *OpenSees* using beam-truss models, *OpenSees* using fiber beam-column element models, *OpenSees* using multi-layered shell elements, *FE-MultiPhys* using beam-truss models, *VecTor4* with heterosis shell elements, *VecTor3* with hexahedral solid elements, and *Perform3D*.

As mentioned in the introduction, the BPC asked for two sets of different information: compulsory information (e.g., peak lateral force, ultimate displacement, peak torque, ultimate rotation), and additional information (e.g., plastic hinge lengths, residual displacements/rotations, energy dissipated, maximum tensile strain in a specific longitudinal reinforcing bar). For sake of brevity, not all results will be provided here. For additional information, please visit the website: https://uclouvain.be/en/research-institutes/immc/gce/blind-prediction.html.

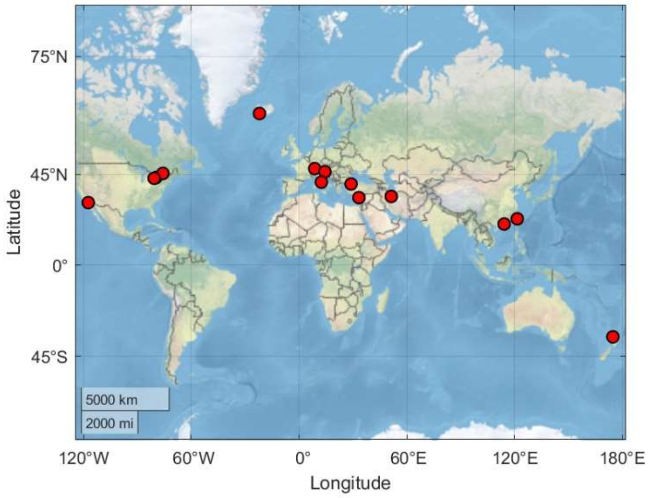

Figure 4. World map showing the locations of all the participants

3.1 Compulsory Information

Figure 5a presents the BPC estimates of peak lateral strength towards position C (see Figure 3b) for UW1, while Figure 5b presents the estimates of the peak torque for UW2. A dashed line is provided in these figures, which represents the average of all responses. Some participants have vastly overestimated the peak force in Figure 5a, which was likely a consequence of not modelling the wall to its effective height of approximately 6.72m, and instead modelling the wall to the application height of the horizontal actuators of just 2.25m, skewing the average (dashed line in Figure 5a). While some scatter exists for the peak torque estimates in Figure 5b, it is interesting to see that the average of the responses is close to the experimentally attained peak torque (solid line).

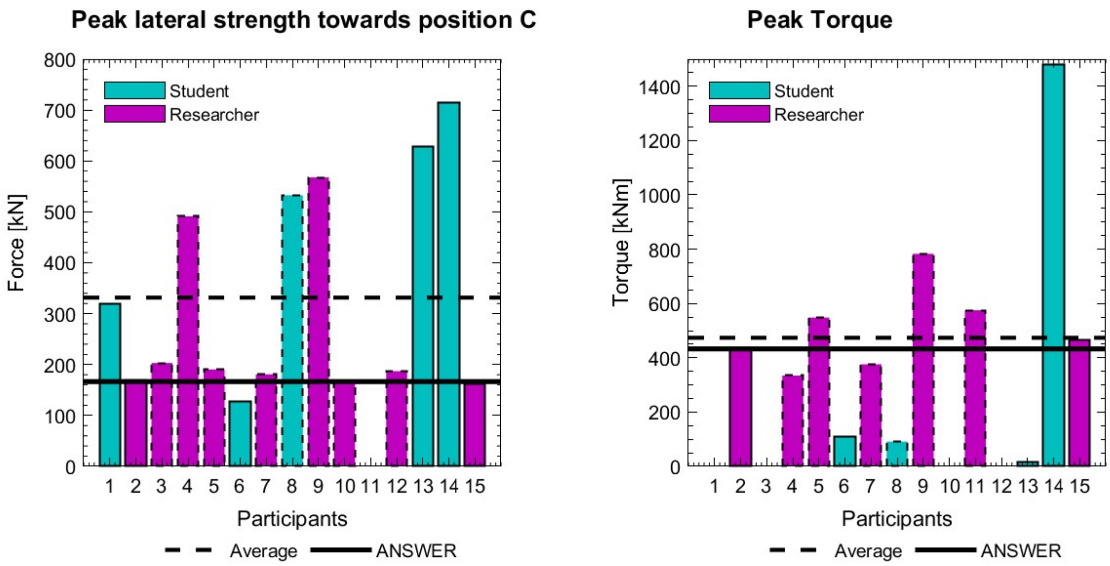

Figure 5. Blind prediction results, compulsory information: (a) peak lateral strength towards Position C for UW1 (b) peak torque for UW2. The bar plots with dashed-line borders represent teams, rather than individuals.

The estimates from the BPC of the ultimate displacement of UW1 and ultimate rotation of UW2 are given in Figure 6. Most applicants appear to have overestimated the displacement capacity of UW1 (Figure 6a), likely a result of the models not being able to accurately capture the buckling failure mode of this wall unit. In this respect, it is worth mentioning that construction errors resulted in a smaller confinement area and significantly reduced cover of longitudinal bars, in comparison to the design specifications, in the boundary end of the West flange for this wall unit, which likely contributed to a smaller displacement capacity than what was expected. Similar to the ultimate torque estimates, the varying ultimate rotation values provided by the different participants in Figure 6b resulted in an overall average that is very close to the experimental derived value (no distinction can be observed in Figure 6b).

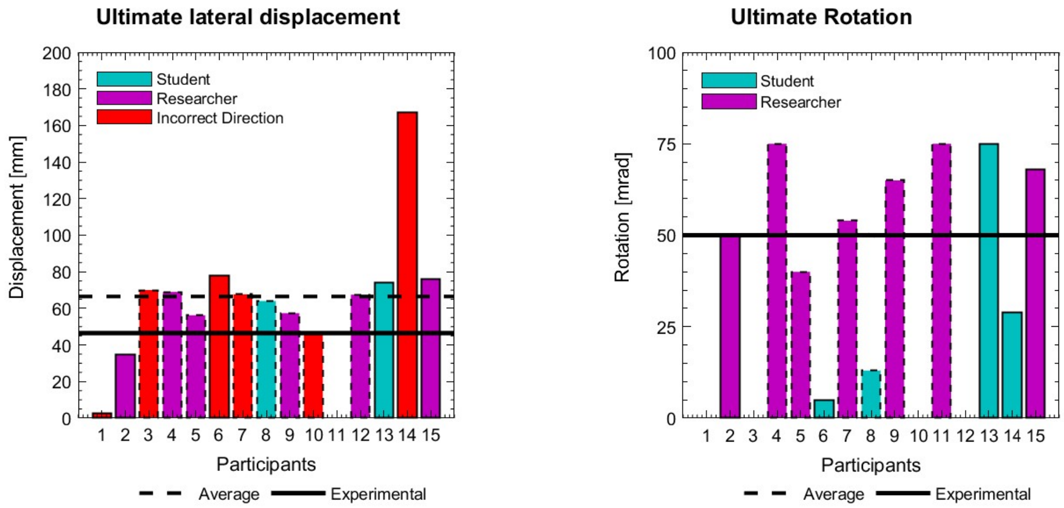

Figure 6. Blind prediction results, compulsory information: (a) ultimate lateral displacement towards position C for UW1 (b) ultimate rotation for UW2

3.2 Optional Information

As part of the optional information of the BPC, participants were asked to provide force or torque values corresponding to specific levels of drift (up to 3%) or rotation (up to 40 mrad) for UW1 and UW2, respectively. Figure 7 plots all of these values provided by participants as a force-displacement envelope (Figure 7a) and torque-rotation envelope (Figure 7b) in grey, which is compared to the experimental envelope in solid-black. Only the values up to experimental failure were considered in awarding points, however, all of the values provided by the participants have been plotted in Figure 7.

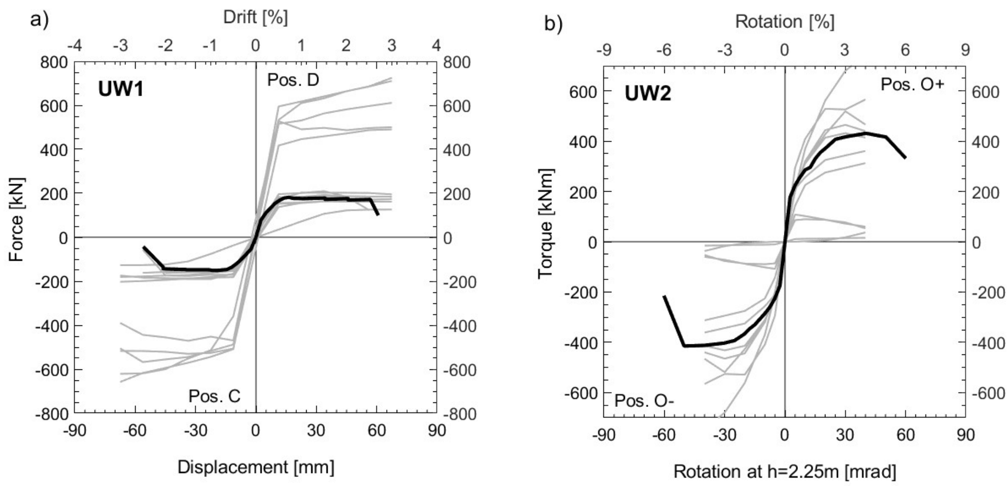

Figure 7. Blind prediction results, optional information of the response envelope: (a) force-displacement of UW1 (b) torque-rotation of UW2. Grey-shaded lines represent the different applicant estimates, while the solid black line represents the experimentally derived values.

Similarly, for the specific drift or rotation levels, the corresponding residual displacement or rotation (i.e., the displacement or rotation of the wall upon unloading towards position O and a zero force or torque is attained) was asked as part of the optional information. Figure 8a and Figure 8b plot the residual displacements for UW1 and rotations for UW2, respectively, as a function of the maximum imposed drift and rotation at consecutive displacement/rotation levels. A scatter of results exists in both figures from the values provided by the different participants compared to the experimentally derived values (black line with square markers). The grey-dashed line in Figure 8a represents the estimates from an equation derived in Hoult and Almeida (2022) using a large database of experimental RC walls.

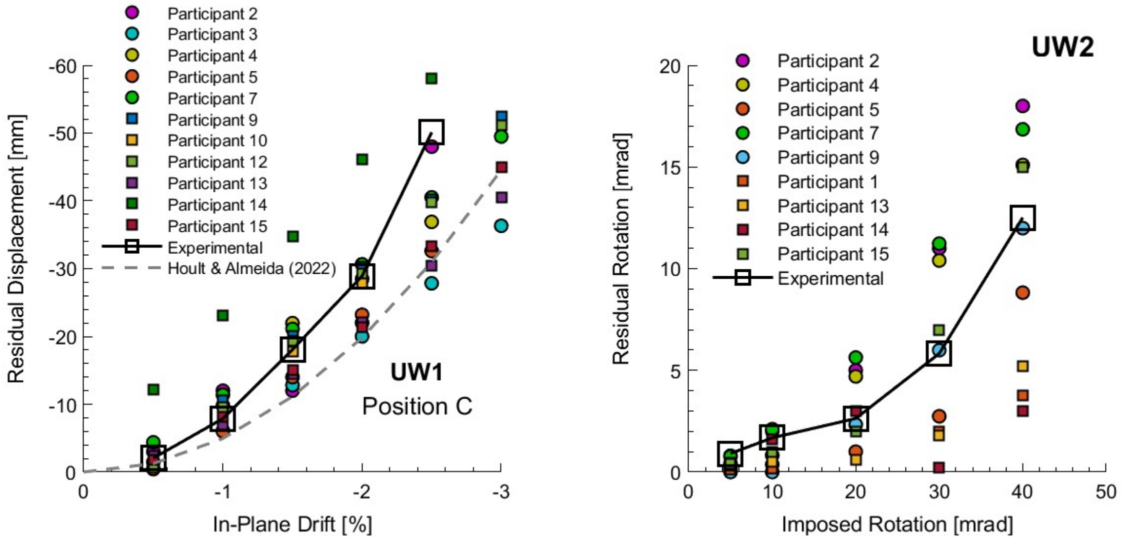

Figure 8. Blind prediction results, optional information: (a) residual displacements coming back to centre from position C for UW1 (b) residual rotations for UW2

Another optional information asked by the BPC was the maximum tensile strain in the longitudinal rebars of the West flange boundary end. For UW1, the maximum strain was taken as the average of the two layers of rebars at the same distance from the neutral axis (on each face of the flange) and for a drift (δ) of 0.5% at position D (Figure 3). For UW2, the maximum strain in the outer-most (from the centroid of the section) rebar was warranted, and for a drift (θ) of 10mrad at position O+ (Figure 3). These strain values were obtained experimentally with high-definition distributed fibre-optic sensors (DFOS) installed on eight longitudinal rebars for each wall unit (see Figure 2a). Figure 9a and Figure 9b present the longitudinal strain profiles of the aforementioned two layers of longitudinal rebars in the extreme tension fibre region measured by the DFOS for UW1 and UW2, respectively. For UW1 (Figure 9a), the strain profiles from both bars match reasonably well (and therefore only the average is presented), whereas for UW2 (Figure 9b), the strain profiles vary between both rebars, owing to the warping and circulatory torsion that governed the wall performance. A number of strain values were provided by the participants, shown in Figure 9a,b, with a large scatter. However, some participants provided very reasonable estimates in comparison to the maximum strain derived experimentally, represented by the white circle marker in Figure 9a,b.

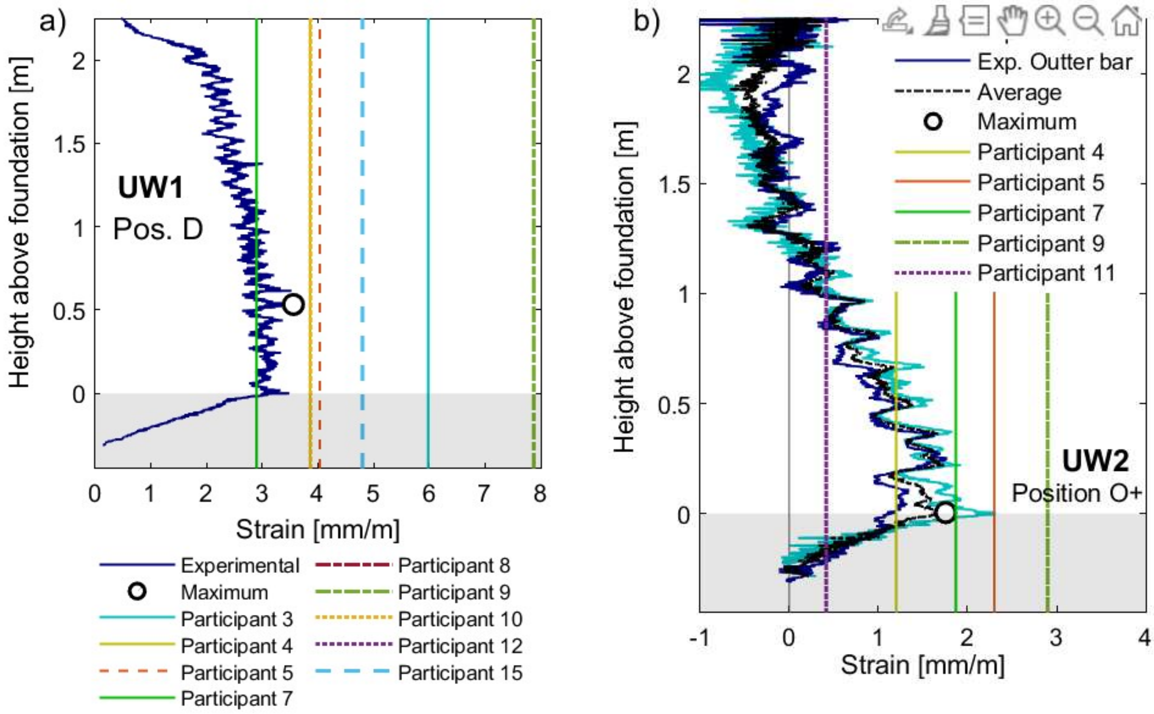

Figure 9. Blind prediction results, largest tensile strains in the reinforcing bars of the West flange boundary end, optional information: (a) UW1, average, position D at δ=0.5% (b) UW2, outer-most, position O+ at θ=10mrad

4 Conclusion

A Blind Prediction Competition was organised by the GCE group in the institute iMMC at UCLouvain, focusing on the flexural and torsional response of two RC U-shaped wall units. The resulting estimates provided by the participants show a range of values computed by a series of different software. In particular, a larger scatter of results could be observed attempting to capture the torsional performance of the second wall unit, UW2. Whilst some of the results compared quite well to the experimentally-derived values, the results also emphasised the importance of conducting laboratory experiments and the corresponding data that can be captured from such experimental tests. The winners of the competition were announced in October of 2022 – congratulations to Marios Mavros (University of Cyprus), Juan Murcia-Delso (Polytechnic University of Catalonia), and Marios Panagiotou (Nabih Youssef Associates). A detailed report, containing all of the blind prediction results, is now available from the website: https://uclouvain.be/en/research-institutes/immc/gce/blind-prediction.html.

It is difficult to draw any major conclusions about the current state of education or research practice in simulating RC core walls from the low number of total participants in this BPC. However, it was possible to appreciate the accuracy of the predictions made by the top applicants. The low rate of submissions for this BPC was likely due to a number of factors, including a short timeline provided to the participants to conduct their analyses (i.e., approximately 3-4 months were given, which also occurred over the European summer months). The authors intend to open another BPC for 2023 that focuses on simulating the nonlinear dynamic behaviour of RC U-shaped walls with the same design parameters as those reported here. The participants from the 2022- and 2023-BPCs will then have the opportunity to discuss and disseminate their prediction (and postdictions) of these wall tests in a special issue planned for the Bulletin of Earthquake Engineering. It is hoped that this special issue will help in advancing the current state of practice for simulating RC core walls in education, research, as well as industry.

5 Acknowledgements

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