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Preliminary study on multi-axial hybrid simulation of a shear wall in the auxiliary building of APR1400-type NPP subjected to lateral force

Junyan Xiao[1], Oh-Sung Kwon[2], Evan Bentz[2], and Tae-Hyun Kwon[3]

[1] Doctoral Student, Department of Civil & Mineral Engineering, University of Toronto, Toronto, Canada
[2] Professor, Department of Civil & Mineral Engineering, University of Toronto, Toronto, Canada
[3] Principal Researcher, Advanced Structural Seismic Safety Division Korea Atomic Energy Research Institute, Republic of Korea

ABSTRACT

Reinforced concrete (RC) shear walls are one of the critical components of the lateral-force-resisting system in a nuclear power plant (NPP). Many experimental studies have been carried out in the past to understand the behaviour of RC shear walls subjected to a lateral force. The shear wall tests have been conventionally conducted using predefined boundary conditions without considering the interaction of the specimen with the rest of the structural system. Hybrid simulation is a recently developed testing method that can integrate various numerical modelling and experimental testing techniques, providing means of capturing the system-level interactions during the element-level testing. The past hybrid simulation studies mainly emphasized controlling lateral and rotational degree-of-freedoms (DOFs) during the test, with limited emphasis on the axial DOF. In this study, a preliminary study on the effect of the complete set of boundary conditions on an RC shear wall is presented. A reference wall was selected from the auxiliary building of the Advanced Power Reactor 1400 (APR1400) type NPP. To simulate the wall under a conventional test setup, the wall was modelled in VecTor4. The model was subjected to constant axial load and increasing lateral force. To represent realistic boundary conditions, Abaqus-VecTor4 multi-platform FE analyses were carried out such that the interaction of the global model and the wall can be simulated. The simulation results reveal a substantial difference in the post-cracking behaviour of the reference wall, justifying the need to introduce realistic boundary conditions in the RC shear wall tests. This study is a part of an ongoing research project in which a multi-platform multi-axial hybrid simulation and the conventional RC shear wall test will be conducted to verify the preliminary conclusion above. The experimental test plan is briefly discussed in the paper.

INTRODUCTION

Reinforced concrete (RC) shear walls are essential parts of the lateral load resisting system in nuclear power plant (NPP) structures. The RC shear walls of NPP have larger section sizes and reinforcement ratios compared to those for commercial uses, as they are designed to remain linear-elastic under design basis earthquakes (DBE). According to Chopra (2007), the structural members with a short fundamental period, like the shear walls in the NPP structures, may face considerably high ductility demands even if the structure yields slightly. In fact, earthquake events from the past showed that the NPP structures could be damaged due to the earthquake itself or the subsequent disasters (ANSTO 2021). Thus, understanding the ultimate strength, ductility, and failure mode of the RC shear wall is vital for the case where the structure experiences greater seismic demands than those considered in the design.

The seismic performance of the RC shear walls was studied extensively in the past decades through experimental tests, where typically the lateral/shear degree-of-freedom (DOF) is controlled with a constant vertical load applied at the top of the wall (Looi et al. 2017). In recent years, the conventional shear wall testing method has been advanced by introducing predefined multi-axial loadings to the controlling degree-of-freedoms (DOFs). Chae and Park (2022) performed five multi-axis cyclic loading tests for RC walls of NPP structures. Bi-directional lateral loadings and the vertical forces were introduced to the specimen simultaneously. The authors concluded that the varying vertical and out-of-plane loadings can alter the behaviour of the RC shear walls in terms of their in-plane shear strength, ductility, effective stiffness, and equivalent damping ratio. One of the major limitations of the conventional shear wall test setup is that it cannot consider the interaction of the specimen with the surrounding structural system. The system-level behaviour can be validated via full-scale tests, but such tests are very restrictive.

A hybrid simulation can be performed instead to evaluate an RC shear walls in a structural system. It combines various numerical modelling and experimental testing techniques. The simulation provides the means of a more realistic prediction on the element-level responses in a laboratory environment without having the entire structure constructed. However, experimental hybrid simulation is rarely performed on the RC shear walls due to their high axial and shear stiffness, which makes the hybrid simulation difficult to control. Whyte and Stojadinovic (2013) have performed a large-scale single DOF hybrid simulation with a squat RC shear wall from a typical nuclear facility structure. Mass and damping were modelled numerically in OpenSees to simulate the effect of the entire structure. The wall was physically tested in the lab. With no axial load applied, high-precision encoders were employed to achieve accurate control of deformation in the lateral direction. The result proved the effectiveness of hybrid simulation on understanding the behaviour of the RC shear wall. Fatemi et al. (2021) conducted a hybrid test on an RC shear wall which was part of the SFRS of an eight-story RC reference building. The analytical model was built in OpenSees, while the real specimen was constructed in the lab. The horizontal and rotational DOFs of the specimen were controlled during the hybrid simulation, while a constant vertical load was applied through a unique sectional analysis-based controlling algorithm.

During the hybrid simulation, researchers mainly focused on controlling lateral and rotational DOFs, with only a limited emphasis on the axial DOF. One potential source of the varying axial load is the restraining effect imposed by the surrounding structural components (e.g., floor slabs) as the cracks form in the inclined compression strut and the wall starts to expand in height. A detailed description of the underlying mechanics of the axial restraining effect can be found in Malcolm et al. (2014). It should be noted that the effect is more profound for NPP structures because many intact shear walls and slabs can constrain the shear walls that undergo failure, and high vertical forces can be developed in the shear wall. Thus, simply ignoring the vertical load variation may make the analysis deviate from the real behaviour and can, in some cases, result in unconservative predictions of the RC shear wall.

In this study, an RC shear wall from the auxiliary building in APR1400-type NPP was selected. The behaviour of the selected RC shear wall was investigated under realistic boundary conditions through a multi-platform multi-axial hybrid simulation method in comparison with the conventional shear wall testing method. The wall was intentionally selected at the region where a large variation of vertical loadings was anticipated. To simulate the wall under a conventional test setup, the wall was modelled in VecTor4. The model is subjected to constant axial load and increasing lateral force. To represent realistic boundary conditions, Abaqus-VecTor4 multi-platform FE analyses are carried out such that the complete interaction of the global model and the wall can be simulated. Results from each test are provided and discussed. Admittedly, accurately modelling the behaviour of the shear wall is often challenging (Gallitre et al. 2019). Therefore, the study presented in this paper serves as the first step of an ongoing research program in which a multi-platform multi-axial experimental hybrid simulation will be conducted in comparison with the conventional experimental test to verify the preliminary conclusion from the numerical simulation. The experimental test plan is briefly discussed in the paper.

PROTOTYPE STRUCTURE AND GLOBAL PUSHOVER ANALYSIS

The prototype structure used in this study was modified based on the auxiliary building in the APR1400-type NPP. The auxiliary building accommodates safety systems that are connected with the containment building. The building consists of heavily reinforced concrete walls (shear walls) in each direction which act as the primary seismic force-resisting system. The structure was previously modelled numerically as an Abaqus-VecTor4 hybrid model. The detailed model description can be found in Cheng (2020). The global pushover analysis was initially carried out in the Y-direction for investigating the seismic performance of the auxiliary building. The Y-direction fundamental mode was used to formulate the loading patterns, according to Equation 1. $\boldsymbol{f}$ denotes the pushover nodal force vector; α denotes the load scaling factor; $\boldsymbol{m}$ denotes the mass matrix; $\boldsymbol{\Phi}_1$ denotes the 1st mode shape vector. Figure 1 presents the relationship between the base shear and the roof drift ratio. Gravity loadings were applied to the model prior to the pushover analysis. The pushover analysis was terminated at the lateral force corresponding to 2.5g of spectral acceleration, because the lateral force surpassed three times the DBE level and the structure was behaving in a ductile failure mode. In the current study, this 2.5g pushover analysis was used to represent the expected behaviours of the structural components during an earthquake event, which was utilized later to generate realistic boundary conditions for the RC shear wall of interest.

$$\boldsymbol{f} = \alpha \boldsymbol{m} \boldsymbol{\Phi}_1 \tag{1}$$

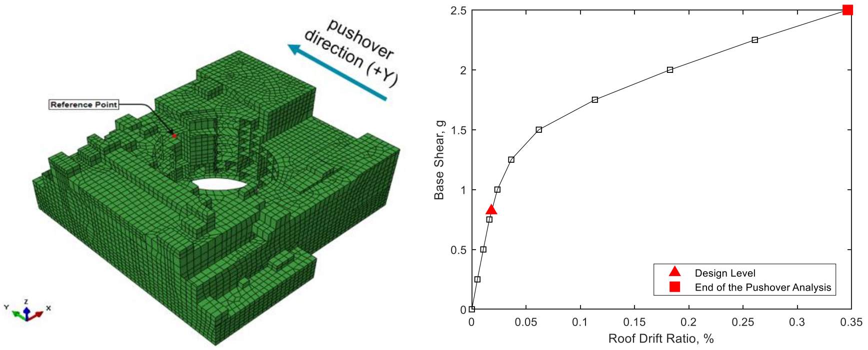


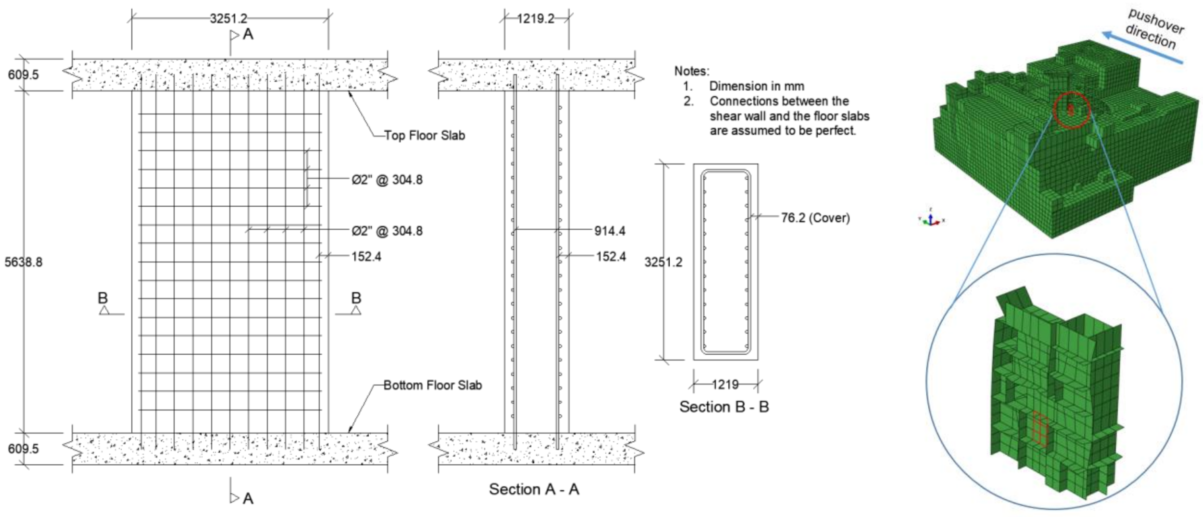
Figure 1: The relationship between base shear and roof drift ratio from the pushover analysis

THE REFERENCE RC SHEAR WALL

The RC shear wall studied herein was taken from the auxiliary building. The building contains an extensive amount of RC shear walls interconnected in two horizontal directions. To simplify the analysis and represent the worst-case scenario, a portion of the walls were disconnected from the surrounding walls. Only the top and bottom of the walls were connected to the rest of the structure. A global pushover analysis was carried out to select a reference wall, which was selected with two considerations: 1) the level of anticipated nonlinear responses (e.g., concrete and reinforcement stress level) according to the pushover analysis result; 2) the location of the wall within the building. Such criteria ensure the wall is imposed to multi-axial loading with relatively complicated boundary conditions, making it have a high potential to behave in the nonlinear range. Table 1 and Figure 2(a) depict the properties of the selected wall. As shown in Figure 2 (b), the wall was located on the second floor near the edge of the building, where additional axial forces were expected to be carried by the wall to balance the overturning moments.

Table 1: Information on the selected wall

		Selected Wall
Height (mm)		5639
Width (mm)		3251
Thickness (mm)		1219
Concrete	Max. Compressive Stress, f'_c (MPa)	34.5
	Max. Tensile Stress, f'_t (MPa)	1.94
Horizontal and Vertical Reinforcement	Rebar Diameter (mm)	50.6
	Spacing (mm)	305
	Number of Layers	4 (2H+2V)
	Reinforcement Ratio	1.08%
	Yielding Stress (MPa)	384



(a) (b)

Figure 2: (a) Geometry details of the reference wall. (b) Location of the wall in the building

ANALYSIS METHOD

A set of numerical analyses were performed on the reference wall to simulate the conventional experimental shear wall tests and the prospective multi-axial hybrid tests with realistic boundary conditions.

Numerical Conventional Test

To simulate the conventional RC shear wall test, a stand-alone wall model was built in VecTor4. VecTor4 is a nonlinear finite element analysis software specialized in the analysis of three-dimensional reinforced concrete planar continuum structure, which was developed by Professor Frank Vecchio and his team at the VecTor Analysis Group at the University of Toronto (Hrynyk 2013). The program uses high-order shell elements with a layered thick-shell element formulation to model structures possessing irregular or curvilinear geometries resulting in a complicated displacement field. The modified compression field theory is the main basis of the constitutive model in VecTor4 (Vecchio and Collins 1986).

A total of 24 three-dimensional 8-noded 20-layered shell elements were used in the wall model to represent the concrete with smeared reinforcement. The concrete was modelled with a parabolic stress-strain relationship with the concrete compression softening and tension stiffening effect included. The steel was modelled with an elastic-plastic stress-strain relationship. As a replication of the real conventional wall test, the bottom of the wall was fully constrained. The top of the wall was only allowed to deform in the axial and in-plane shear direction. Beam elements with high rigidity were added to the model's top to facilitate the boundary conditions and prevent local concrete failure during the analysis. The gravity load of 5970 kN, obtained from the gravity analysis of the global model, was imposed on the wall. This force is equivalent to the concrete compressive stress of 1.224 MPa (4% of the concrete peak stress). The gravity load was applied to the top of the wall, which remained constant while the shear gradually increased in a displacement-controlled manner. For comparison purposes, the displacement step size for the first 10 steps was chosen to be the same as the observed displacement increments from the hybrid simulation. Then, a constant step size of 4.0 mm was used for the rest of the analysis until the failure had occurred.

Numerical Hybrid Simulation

To simulate the shear wall test with realistic boundary conditions, the aforementioned global pushover analysis was carried out on the auxiliary building model in Abaqus ("the integration model") with the reference wall substructured as a separate VecTor4 model ("the substructured model"). The substructured model was identical to the shear wall model used in the conventional test. The two interface nodes were at the center of the top and bottom boundaries of the wall. All DOFs of the wall were controlled by the integration model through the interface nodes. Beam elements with high rigidity were added along the boundaries of the wall to prevent localized effects.

An Abaqus-VecTor4 numerical multi-platform analysis framework was adopted in this study. The framework integrated the Abaqus finite element analysis (FEA) software developed by Dassault Systèmes and the VecTor4 (Abaqus 2014). Abaqus offers a range of element types and material models. It can handle models with a large number of elements. However, the built-in concrete material models may not accurately predict concrete shear behaviour, and users often report that the calibration can be challenging (Vilnay et al. 2016). Previous applications have proven VecTor4's accuracy in predicting the behaviour of concrete shear walls or similar structures like floor slabs (Hrynyk 2013). According to the MCFT, only a few parameters are required for the constitutive model. However, the current version of VecTor4 is poor at handling a very large number of elements or some special geometries such as the connection of shell elements with a sharp angle such as slab-to-wall connection or wall-to-wall connection. The two separate software packages are integrated through the University of Toronto Simulation (UT-SIM) Framework (Huang and Kwon 2018), utilizing communication protocols to facilitate data exchange during the analysis. A set of verification examples has been provided in Cheng (2020) to confirm the efficacy of the framework.

RESULTS COMPARISON

Shown in Figure 5, the load-displacement curves of the reference wall from the numerical hybrid test confirm that the wall behaves in the nonlinear range. The relative deformation was calculated by removing rigid body motions from the two interface nodes. The result suggested that the wall was primarily subjected to varying axial compression, in-plane shear, and in-plane bending during the global pushover analysis. The detailed pushover curve comparisons are shown in Figure 4. The lateral and vertical displacement at the end of the hybrid simulation was +14.5 mm and +2.17 mm, respectively. The in-plane rotation corresponding to this displacement is -0.00025 rad. The shear load carried by the wall at the last step was 16.5 MN with an axial compression of 19.1 MN (320% of the gravity load). For the RC shear wall under the conventional test, the analysis was failed to converge at an in-plane shear load of 14.8 MN, which was 89.7% of the load carried by the wall at the last step of the hybrid simulation. The maximum lateral and vertical displacement at the top of the wall was +35.4 mm and +11.2 mm, respectively. It should be noted that the wall under the conventional test had more significant vertical deformations under the same in-plane shear deformation level compared to the hybrid simulation result. One major contributing factor was the restraining effect, where the axial elongation of the RC shear wall was reduced due to the floor systems.

Differences were observed in the pushover curves after the first set of cracks formed as the in-plane shear reached 4.32 MN. This was mainly due to the difference in the vertical compression resulting from the interaction of the reference wall with the rest of the structural system. Figure 6 presents the variation of post-cracking effective stiffness (i.e., secant stiffness) of the reference wall. The result indicated that the wall under the hybrid simulation had a higher post-cracking effective stiffness than the conventional test one at the same in-plane shear deformation level. This observation is consistent with the general experimental observations from the literature (Looi et al., 2017; Chae and Park, 2022).

Both walls formed significant cracks during the analyses. Figure 8 shows the crack development and pattern at the in-plane shear displacement level of 14.5 mm, which corresponds to the displacement level at the last step of the hybrid simulation. The 3D plane represents the directions of the crack, while the colour of the planes was assigned based on crack width. In both tests, cracks first appeared at the opposite corners and kept developing, propagating towards the center of the wall due to excessive shears. The formation of diagonal shear cracks in the web region was the main reason for both walls to deform upward in the axial directions. As expected, a rotational symmetrical crack distribution was observed in the conventional test, where the double-curvature assumptions held. A less uniformed crack field was obtained from the hybrid simulation, indicating more complicated boundary conditions were presented. Figure 7 shows the history of averaged crack width within the wall. At the same in-plane shear displacement level, the wall with the conventional test setup had larger average crack width than the hybrid simulation one.

Maximum reinforcement strain values were used to assess the damage level within the reinforcement, calculated based on Equation 2. The maximum reinforcement strain comparison is shown in Figure 9. Both tests had a similar maximum reinforcement strain at the same in-plane shear displacement level. For the displacement level at the last step of the hybrid simulation, the most elongated reinforcement from both tests reached the steel yielding strain. Crushing indexes were utilized to assess the damage level within the concrete due to excessive compression, with the effect of compression softening considered, calculated based on Equation 3. Figure 10 shows the variation of the crushing index of the two tests. The increasing axial load caused the wall from the hybrid simulation to develop higher average principal compressive stresses in concrete at the early stage. A crushing index of 0.92 was observed at the last step of the hybrid analysis. On the contrary, the wall from the conventional test maintained a lower crushing index at the same in-plane shear displacement level due to the smaller vertical loading.

$$\text{Maximum reinforcement strain} = \max_{\mathrm{i}}(\text{averaged reinforcement strain } (\varepsilon_{s,i})) \tag{2}$$

$$\text{Crushing index} = \max_{i}\left(\frac{\text{concrete principal compressive stress } (f_{c3,i})}{\text{concrete peak compressive stress } \left(f'_{p,i}\right)}\right) \tag{3}$$

Notes: i is the Gauss point number within the wall elements

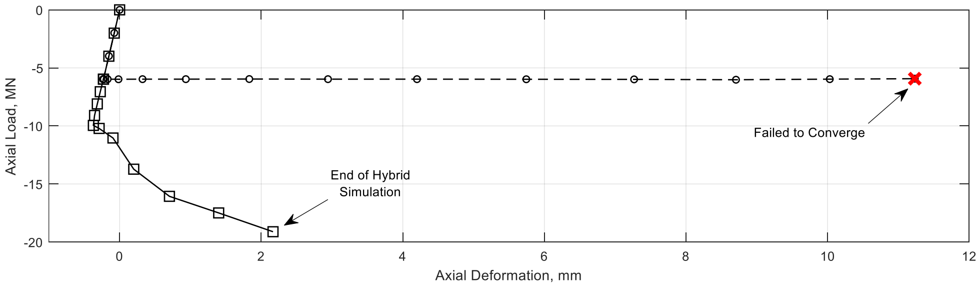


Figure 3 (a): Comparison of the load-displacement curves for the axial direction

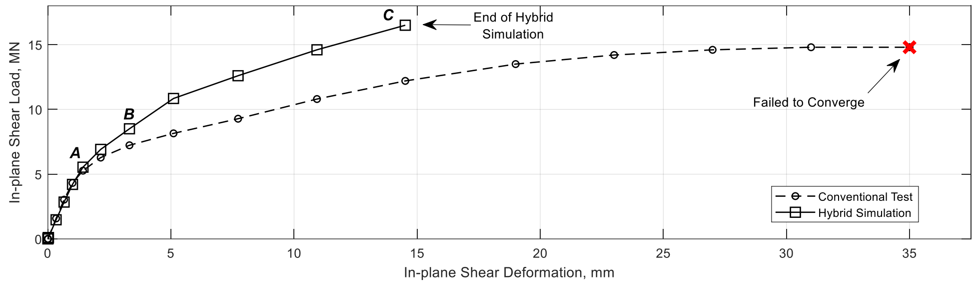
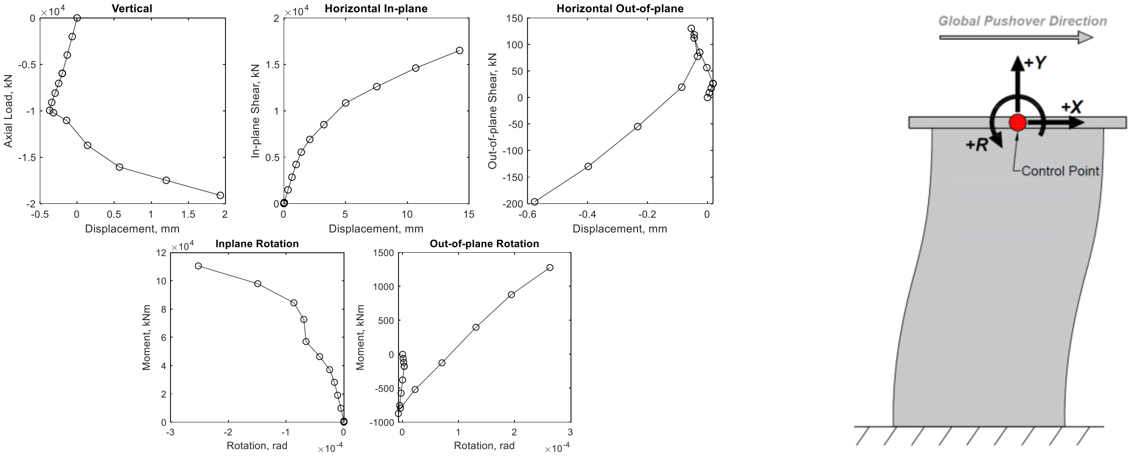


Figure 4 (b): Comparison of the load-displacement curves for the in-plane shear direction.



(a) (b)

Figure 5: (a) Load-displacement curves for the reference wall under the hybrid simulation. (b) Sign convention

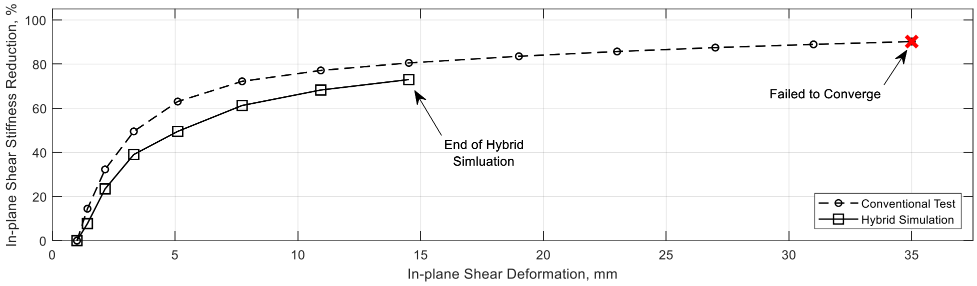


Figure 6: Comparison of post-cracking effective in-plane shear stiffness (secant)

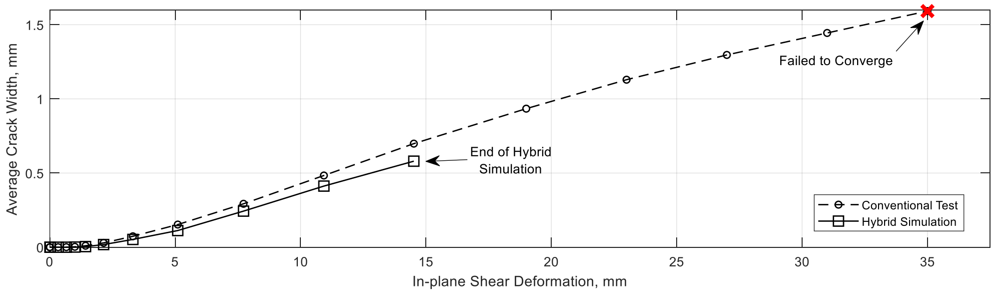
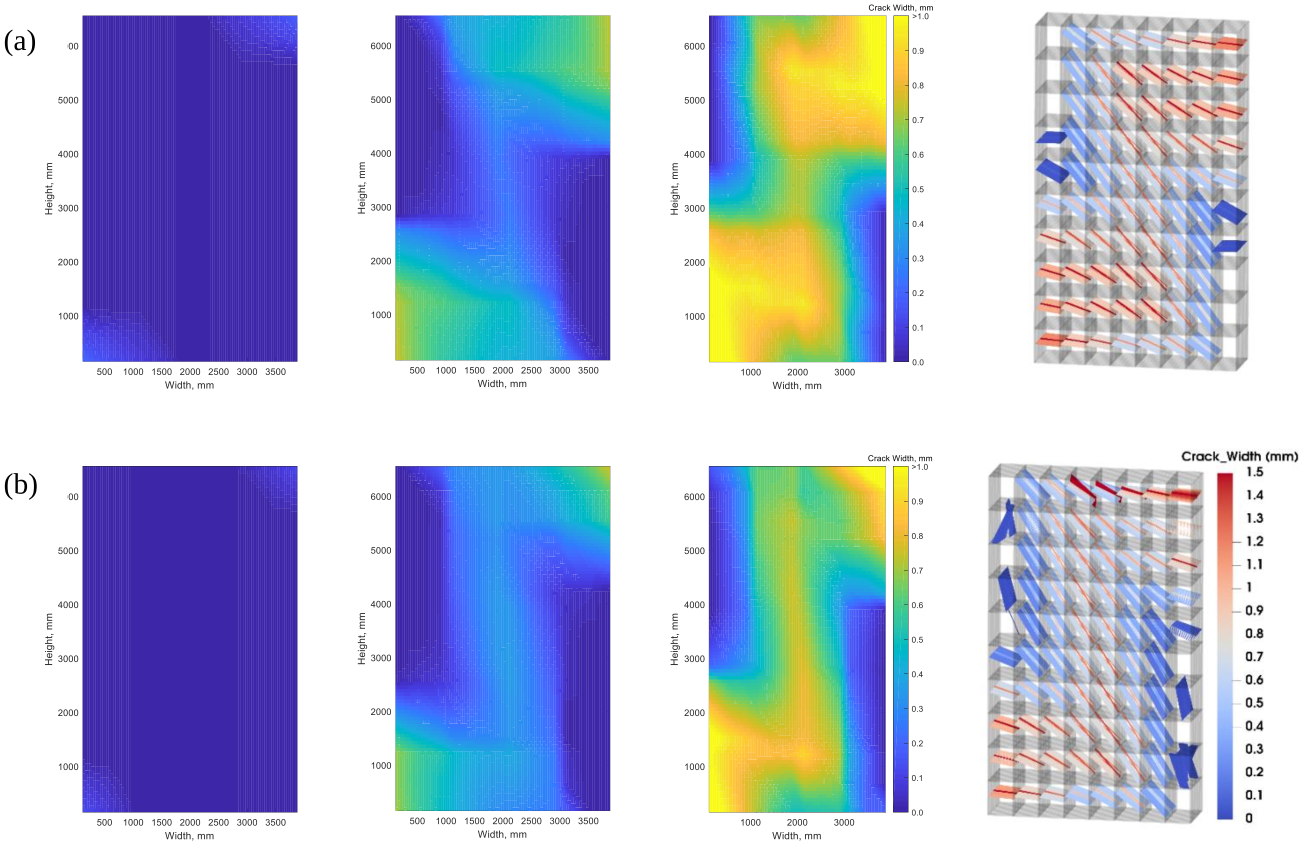


Figure 7: Average crack width comparison



$d = 1.42mm$ $d = 7.73mm$ $d = 14.5mm$ $d = 14.5mm$

Figure 8: Crack development from the (a) conventional test; (b) hybrid simulation

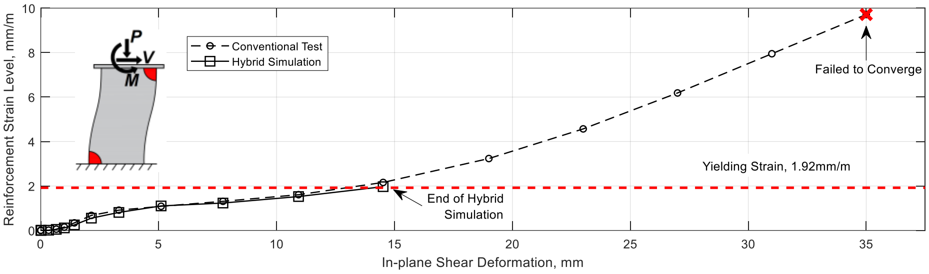


Figure 9: Maximum reinforcement strain level comparison

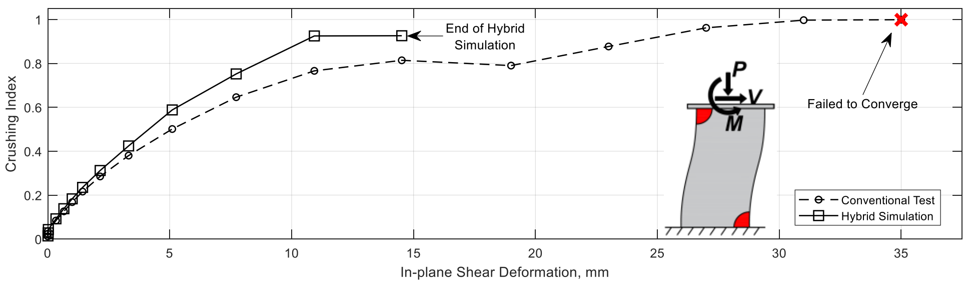


Figure 10: Concrete crushing index comparison

PLANNED EXPERIMENTAL TESTS

In the second part of the ongoing research project, the observations from the numerical analysis will be verified through the experiment, in which the schematic drawing of the experimental test is presented in Figure 11. Shell Element Tester (SET) at the University of Toronto Structural Lab will be used as testing apparatus. A newly developed multi-platform hybrid simulation framework is going to be employed in the ongoing experimental tests. It can incorporate both conventional and realistic boundary conditions into the RC shear wall tests. To accommodate the space limitation, two reduce-scaled concrete shear walls were designed and constructed according to the full-scaled reference wall. The first specimen will be tested with a conventional shear wall setup, whereas the second specimen will be tested using the hybrid simulation with realistic boundary conditions taken from the analytical models. A set of numerical substructures (for the nonlinear elements) and one experimental substructure (i.e. the reference wall) are employed. The hybrid simulation is accomplished through the UT-SIM Framework (Huang and Kwon 2018). NICON-10, an in-house developed controller and a LabVIEW-based program, is also used along with a junction box, which contains several National Instrument (NI) hardware (Mortazavi et al. 2017).

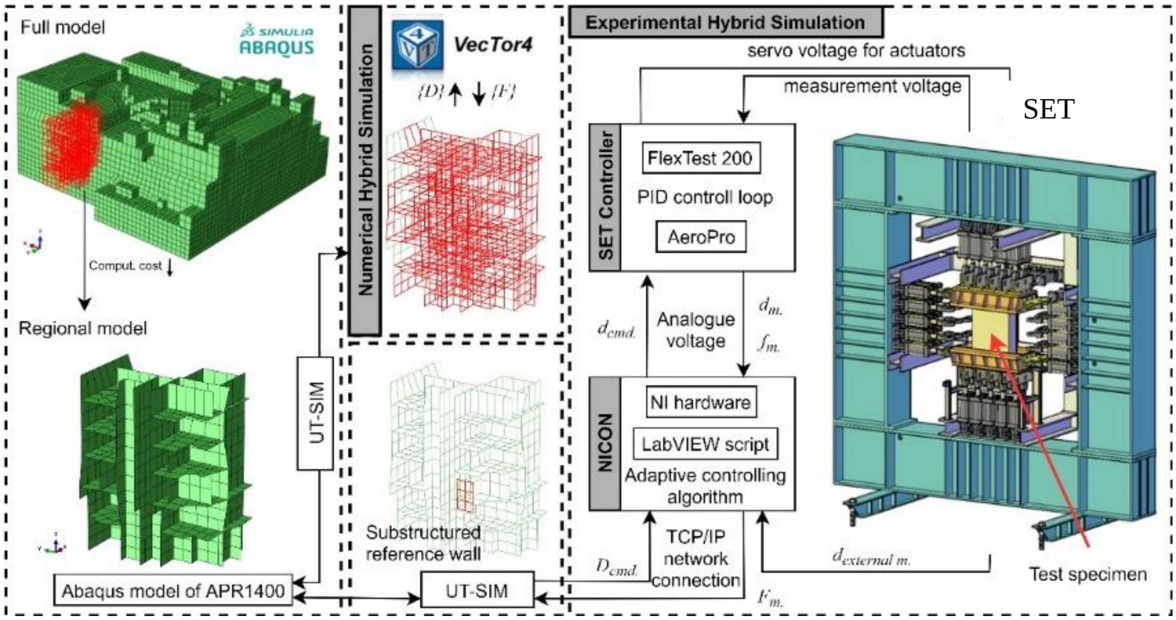


Figure 11: Overview of the proposed multi-platform multi-axial hybrid simulation

SUMMARY

In this study, the effect of the realistic boundary conditions on the behaviour of the RC shear walls in the NPP is investigated by conducting a numerical hybrid shear wall test and a conventional shear wall test. The former accounted for the system-level interaction between the testing articles and the global model, whereas the latter had predefined boundary conditions. The reference wall was selected from the auxiliary building in APR1400-type NPP. UT-SIM, a numerical multi-platform hybrid simulation framework integrated Abaqus and VecTor4 was used in the numerical hybrid test. The conventional test was performed in VecTor4. Although the crack patterns and the maximum reinforcement stress/strain were similar between the two analyses, the wall under the hybrid simulation had a higher in-plane shear carrying capacity, a smaller crack width, greater compressive stresses within the concrete, and a lower effective stiffness reduction compared to the conventional test result. Such observations can be explained by the high vertical loading variation recorded during the hybrid simulation, which was ignored completely in the conventional test. The numerical simulation results in this study demonstrated that the system-level interaction between the RC shear wall of NPP structures and the global model cannot be ignored; otherwise, the post-cracking responses of the wall can be altered. The comparison also highlighted the effect of the variable vertical loadings on the post-cracking shear wall behaviour. The observation will be verified through the ongoing experiment as the next part of the research project. The experiment will involve performing conventional tests and multi-platform multi-axial hybrid simulations on the RC wall specimens.

ACKNOWLEDGEMENTS

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