17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

HYBRID SIMULATION OF THE EARTHQUAKE RESPONSE OF A MULTI-STOREY RC SHEAR WALL THROUGH COLLAPSE

J. Woods[(1)], D.T. Lau[(2)], J. Erochko[(3)]

[(1)] *Assistant Professor, Queen's University, joshua.woods@queensu.ca*
[(2)] *Professor, Carleton University, david.lau@carleton.ca*
[(3)] *Associate Professor, Carleton University, jeffrey.erochko@carleton.ca*

Abstract

This paper presents the results of an investigation into the use of hybrid simulation to capture the system-level earthquake response of a multi-storey reinforced concrete (RC) shear wall. Over the past decade, hybrid simulation has emerged as an accurate and economically efficient test method for understanding the seismic response of large-scale civil structures. Despite these advances, there have been relatively few studies on the use of hybrid simulation to investigate the earthquake response of RC shear wall buildings. This is likely because of the inherently stiff nature of RC shear walls, which makes accurate hydraulic control a challenge in the experimental part of the hybrid simulation. With a stiff physical substructure, a small error in the applied displacement results in a large force error, meaning that target displacements must be accurately imposed to keep experimental errors to a minimum. The goal of this study is to address some of the challenges surrounding the use of hybrid simulation with stiff physical substructures.

Previous hybrid simulation studies on stiff structures have employed mixed force and displacement control algorithms. This study evaluates the feasibility of an alternative approach based on a displacement-based hybrid simulation formulation to study the earthquake response of a multi-storey shear wall building. The approach uses high-precision and high-resolution displacement transducers to accurately externally control the hybrid simulation. The first-storey of a three-storey RC shear wall is experimentally tested in the laboratory while the rest of the wall is simulated in a computer model. This substructuring approach capitalizes on the benefits of hybrid simulation as a test method by physically testing the portion of the wall that is expected to behave in a highly nonlinear manner, while the response of the rest of the wall, which is expected to remain at or near elastic, is captured in the finite element model. The wall is modelled using shell elements in OpenSees to realistically capture the interaction of flexure and shear. The experimental test setup is designed to impose lateral load, overturning moment, and vertical gravity forces on the top of the shear wall in the laboratory using three hydraulic actuators. To study the seismic response of the wall over a range of earthquake hazard levels up to collapse, it is subjected to a series of earthquakes at increasing intensity.

The results of the study demonstrate that it is feasible to use a displacement-based hybrid simulation formulation to study the earthquake response of a stiff RC shear wall if accurate displacement sensors are used to control the hybrid simulation, ensuring that the command displacements are precisely imposed and measured. Overall, hybrid simulation is shown to be an effective tool to study the earthquake response of a full-scale RC shear wall through collapse.

Keywords: reinforced concrete, shear wall, hybrid simulation, numerical analysis, collapse

1. Introduction and Literature Review

Hybrid simulation combines the strengths of experimental testing and analytical modelling to analyze the response of a complete structural system. Using strategic substructuring, hybrid simulation is able to capture the exact nonlinear behaviour of complex structural components or subassemblies through testing while at the same time supplementing it with simulation of the rest of the structure through computer modelling to capture the global response of an entire structural system. Compared with traditional component-level seismic testing, hybrid simulation is able to include the effects of mass and damping at the system level, resulting in a more realistic representation of the loading conditions and thus determination of the system structural response during an earthquake. When compared with large-scale shaking table tests, hybrid simulation provides a more efficient and economical test method that does not require a comparatively large investment in terms of time and money for the test specimen and test facility.

Despite considerable interest in the development and implementation of hybrid simulation as a test method, there have been relatively few studies on its use to study the behaviour of reinforced concrete (RC) structures. One early application of hybrid simulation to RC structures is a study by Negro et al. [1], which used hybrid simulation to investigate the earthquake response of a full-scale 3-storey RC frame. The RC frame was physically tested in the laboratory while the mass and damping for the structure were modelled numerically. Results of the study demonstrated the capabilities of hybrid simulation to study the response of the RC frame under realistic seismic demand, including the effects of damping at the system-level. More recently, Whyte and Stojadinovic [2] studied the response of two squat RC shear walls representative of the type of walls commonly found in industrial nuclear facilities. A single storey squat RC shear wall was experimentally tested under in-plane loading without the effects of axial load. The mass and damping of the single degree-of-freedom (SDOF) system were modelled numerically in OpenSees. Because the shear wall specimen was very stiff, a high-precision and high-resolution digital encoder was used to measure the command and feedback displacements from the analytical substructure. Results of the study found that the use of an encoder to measure the command and feedback displacements was effective for the stiff RC shear wall. While the studies by [1,2] demonstrated that hybrid simulation can be an effective tool to investigate the earthquake response of RC structures under realistic seismic demands, they were substructured such that the full-scale structure was physically tested in the laboratory and only the mass and damping were modelled numerically. This substructuring approach does not take full advantage of the benefits of hybrid testing and its unique ability to separate critical structural elements from those that can be easily modelled numerically.

Both studies by [1,2] used a displacement-based hybrid simulation formulation, in which the hybrid simulation was controlled using command and feedback displacements between the physical and analytical substructures. Although this technique is effective for flexible structural systems because the command displacements are large enough to be accurately controlled and measured, while the command displacements for a stiff structural system are small and any error in the application of this displacement will translate into a large increment in force and result in an error in the hybrid simulation. To overcome this challenge, some researchers have proposed force-based or mixed-mode hybrid simulation formulations for stiff structural systems. One such application of a mixed-mode control approach for hybrid simulation was proposed by Charlet [3], who conducted a hybrid simulation on an RC column. Because of the comparatively high axial stiffness of the RC column, an iterative algorithm was developed to generate continuous force commands for the axial degree-of-freedom (DOF) based on the displacement command from the analytical substructure. More recently, Nakata et al. [4] and Yang et al. [5] have both proposed purely force-based hybrid simulation formulations for stiff structural systems. However, force-based hybrid simulation presents some unique challenges of its own, including softening of the physical substructure in the laboratory, which requires that the hybrid control mode be switch to a displacement-based formulation to ensure that the system does not become unstable. Consequently, the force-based hybrid simulation methods proposed by [4-5] use a mixed-mode or switch-based algorithm. The technique proposed by Nakata et al. [4] uses a purely force-based approach to control the hybrid simulation until a change in stiffness of the structure is detected, at which point the method switches to a displacement-based hybrid simulation approach. Alternatively, the method proposed by Yang et al. [5] uses a displacement-based formulation for the flexible DOFs and a force-based approach for the stiff DOFs (typically axial). The technique switches the force control mode to displacement control once softening of the system is detected by comparing the tangent stiffness of the physical substructure to its initial stiffness. Both of these algorithms have been applied to simple structural systems, such as a single-storey steel frame, but have not been applied to multi-degree-of-freedom structural systems and have not been implemented in common hybrid simulation middlewares (e.g. OpenFresco).

The primary objective of this study is to determine the feasibility of using a displacement-based hybrid simulation formulation to study the earthquake response of a multi-storey RC shear wall. A multi-storey RC shear wall is substructured into physical and analytical components, which are experimentally tested in a laboratory and numerically modeled in a computer software, respectively. The experimental test setup is designed to impost lateral load, overturning moment, and vertical gravity forces on the top of the shear wall in the laboratory using three hydraulic actuators. High-precision and high-resolution displacement encoders are used to externally control the hybrid simulation. The multi-storey RC shear wall is subjected to a series of earthquakes over a range of hazard levels up to collapse. The results of the study demonstrate that it is feasible to use a displacement-based hybrid simulation formulation to study the earthquake response of a stiff RC shear wall if accurate displacement sensors are used to control the hybrid simulation, ensuring that the command displacements are precisely imposed and measured. Overall, hybrid simulation is shown to be an effective tool to study the earthquake response of a full-scale RC shear wall through collapse.

2. Hybrid Simulation Program

2.1 Prototype Shear Wall Building

The prototype structure for the hybrid simulation in this study is a three-storey RC shear wall building designed for a site in Victoria, British Columbia. Figure 2 shows a plan view of the building and a typical shear wall detail. The structure has a flat plate slab and columns to support the gravity loads. The building has a first storey height of 4.5m while the remaining stories measure 3.5m resulting in an overall building height of 11.5m. In plan, the structure measures 30m×50m, which includes four 7.5m bays in the N-S direction and four 12.5m bays in the E-W directions. The principle seismic force resisting structural system includes perimeter shear walls around a centrally located concrete core to create a torsionally stable configuration. The structure is design using the equivalent static force procedure from the National Building Code of Canada (NBCC) and response spectrum analysis [6]. The walls are designed as moderately ductile RC shear walls (R_d=2.0) according to CSA A23.3 and detailed to form a plastic hinge at their base [7]. Additional details on the design of the prototype structure are available in Woods [8].

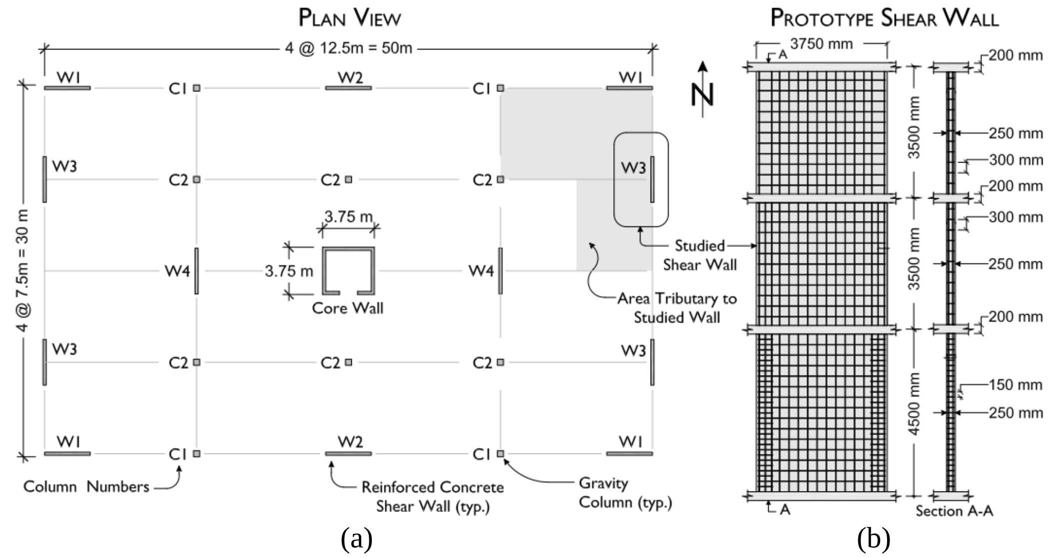


Fig. 1 – Three-storey prototype shear wall building: (a) floor plan; (b) typical shear wall detail

2.2 Hybrid Simulation Substructuring Approach

Ideally, the hybrid simulation conducted in this study would be based on a computer model of the complete three-dimensional (3D) RC shear wall building shown in Fig. 1. However, because of the long computational time associated with a finite element model of the complete 3D building, which would result in comparably long hybrid simulation times, a single three-storey RC shear wall from the prototype structure, which is highlighted in Fig. 1, was used as a basis for the hybrid simulation. During the earthquake response of a multi-storey RC shear wall, most of the damage is expected to be concentrated in the first-storey RC wall, which are typically designed to form a plastic hinge at their base. An accurate understanding of the wall behaviour in this region is critical to predicting the earthquake response of the wall. Consequently, the physical substructure in this study is the first-storey of the three-storey shear wall, such that its nonlinear response could be accurately captured in the laboratory. Figure 2 shows the substructuring approach for the multi-storey shear wall in this study. The analytical substructure is the upper two stories of the wall, which are expected to remain at or near elastic during a moderate to large earthquake. To maintain compatibility between the analytical and physical substructures, the wall is tested in the laboratory under the in-plane lateral and axial displacements and rotation at the interface between the first and second stories of the wall. This hybrid simulation substructuring approach combines the accuracy of an experimental test with the efficiency of a numerical model to study the overall system-level response of a full-scale multi-storey RC shear wall without the need to experimentally test the full-scale structure in a laboratory.

2.2.1 Physical Substructure

To accommodate for space limitations in the structures laboratory at Carleton University, the first-storey of the three-storey RC shear wall is scaled to 2/5 of its original size. Figure 3 shows the dimensions and reinforcement details for the shear wall specimen in this study. Scaling results in a wall specimen that measures 1500mm×1800mm×100mm ($l_w \times h_w \times t_w$) and has a height-to-length aspect ratio (h_w/l_w) of 1.2. The wall has horizontal and vertical steel reinforcement ratios of 0.4% and 0.28%, respectively. Table 1 summarizes the material properties for the concrete and steel reinforcement for the wall.

Figure 3 shows the experimental test setup for the physical substructure in the laboratory. Three hydraulic actuators are used to control the 3 degree-of-freedom at the interface node between the physical and analytical substructures (shown in Fig. 2)., which are the in-plane displacement, axial displacement, and rotation at the top of the shear wall. A rigid steel loading beam is used to connect the hydraulic actuators to the heavily reinforced cap beam of the wall. The foundation of the wall is fixed to the laboratory strong floor and an additional supporting block is placed adjacent to the wall to prevent any sliding/rotation of the wall during testing. A steel support is used to prevent any out-of-plane displacement or rotation of the wall during the hybrid simulations and ensure that it is loaded in-plane. Figure 3 also shows the positions of the three encoders, mounted directly to the shear wall, which are used to externally control the hybrid simulation

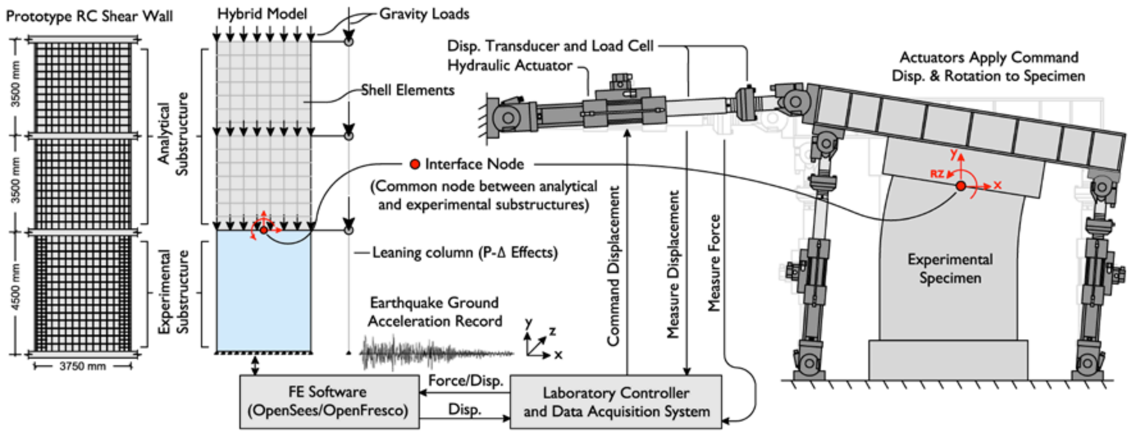
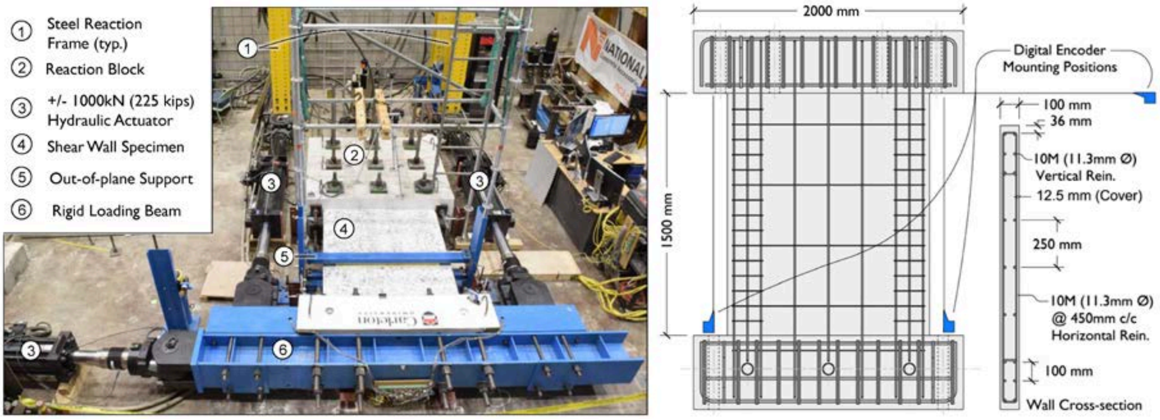


Fig. 2 – Hybrid simulation substructuring approach for multi-storey RC shear wall



(a) (b)

Fig. 3 – (a) Physically tested shear wall; (b) experimental test setup and encoder placement

Table 1 – Average material properties for the steel reinforcement and concrete from physical wall

Vertical Steel Reinforcement		Horizontal Steel Reinforcement		Concrete	
f_y (MPa)	455	f_y (MPa)	468	$f'c$ (mm/mm)	31.6
E_s (GPa)	193	E_s (GPa)	190	E_c (mm/mm)	27.9
ε_y (mm/mm)	0.0022	ε_y (mm/mm)	0.0028	ε'_c (mm/mm)	0.0011
ε_u (mm/mm)	0.273	ε_u (mm/mm)	0.292	ε'_u (mm/mm)	0.012

2.2.2 Analytical Substructure

The analytical substructure is a finite element model of the second and third stories of the three-storey RC shear wall shown in Fig. 1. The analytical substructure is modeled in OpenSees [9]. OpenSees is used to model the analytical substructure because of its ability to seamlessly incorporate the functions and features of OpenFresco, which is used to connect the analytical and physical substructures together for the hybrid simulation [10]. The shear wall is modeled using four node elastic shell elements. The shell elements are two-dimensional plane-stress shell elements defined using the *Quad* function in OpenSees. The elastic elements are assigned a modulus of elasticity of 16000 MPa, corresponding to 50% of the uncracked elastic modulus to account for cracking and softening of the upper stories of the RC shear wall. The use of elastic shell elements allowed this study to focus strictly on the performance of the hybrid testing system, physical experimental test setup in the laboratory, and functionality of the middleware prior to introducing additional complexities associated with a nonlinear finite element model (e.g. convergences problems, model accuracy longer analysis times) into the hybrid simulation.

In the analytical substructure, the tributary mass for the prototype shear wall is lumped at each storey level. A leaning column with lumped masses representing the mass of the rest of the structure is also included to account for P-delta effects. Damping is assumed to be 5% of critical and is assigned to the first and third modes. The finite element model included gravity and earthquake loading phases. First, gravity loads of 260kN, 400kN, and 400kN are applied to the third, second, and first storey levels of the full-scale wall in the model, respectively. To maintain similitude between analytical and physical substructures (because the physical substructure is 2/5 of full-scale), the command displacements and feedback forces are scaled during the hybrid simulation. For the scaling, the elastic modulus of the material is assumed to be constant (S_E=1.0), the scale factors for length (S_L) is 0.4, which results in a scale factor for force (S_F) of 0.16 ($S_F=S_E S_L^2=1.0\times 0.4^2=0.16$) between the analytical and physical substructures. This scaling procedure results in a gravity load of 169.6kN applied to the physical substructure in the laboratory (1060kN$\times$0.16=169.6 kN), which is equivalent to a 1.13MPa axial stress or approximately 4% axial load ratio ($P/A_g f_c'$).

Following application of the gravity load, the earthquake time-history analysis is conducted with a fixed time-step of 0.01s. The *NewmarkHSFixedNumIter* numerical integration scheme developed by Schellenberg et al. [10] is used in conjunction with Newton solution algorithm and 10 iterations for each time-step. These analysis parameters were determined using a sensitivity analysis of a purely analytical finite element model of the shear wall. The total model analysis time for each earthquake ground motion record is 27s (2s for the gravity loading + 25s for the earthquake loading), however, the tests in this study were pseudo-dynamic and not conducted in real-time. Each time-step took approximately 7.5s to execute, which results in a total test time of approximately 5.63 hours for each hybrid simulation in this study based on an analysis time-step of 0.01s (27s ÷ 0.01s/step = 2700steps × 7.5s = 5.63 hrs).

2.3 Hybrid Simulation Architecture

The primary objectives of this study is to investigate the feasibility of using a displacement-based hybrid simulation formulation to study the earthquake response of a multi-storey RC shear wall. Using a displacement-based hybrid simulation for a stiff structural element, such as a RC shear wall, introduces a number of challenges to the hybrid simulation test method. Two of the major challenges that must be accounted for are the stiffness of the experimental test setup and the accuracy of hydraulic control used to apply the command and feedback displacements to the physical substructure. Ideally, the stiffness of the experimental test setup would significantly exceed the stiffness of the physical substructure to ensure that the feedback displacement measured by the displacement transducers controlling the hybrid simulation is the deformation of the physical substructure and not the deformation of the experimental test setup. However, when the physical substructure is very stiff, it may not be economically feasible to achieve a sufficiently stiff experimental setup. Furthermore, because an RC shear wall is very stiff, particularly in the axial direction, the command displacements sent to the physical substructure in the laboratory are small, and any discrepancy between the command displacement and the displacement applied to the physical substructure (feedback) will correspond to a large increment in force. Consequently, to produce accurate results, the command displacements need to be very accurately imposed and very precise hydraulic control is required.

To overcome these challenges in this study, high-precision and high-resolution digital encoders are used to externally control the hybrid simulation. By mounting the encoders directly to the physical specimen (shown in Fig. 3) in the laboratory, this effectively bypasses any deformation occurring in the experimental test setup and directly measures the deformation of the physical substructure. When this external control approach is combined with high-precision and high-resolution displacement transducers that are capable of very accurately controlling the hydraulic actuators and measuring the feedback displacements, it makes a displacement-based hybrid simulation possible for a stiff physical substructure. The displacement transducers used in this study are Sick AFS/AFM60 SSI absolute encoders, which have a displacement resolution of approximately 0.0025mm. This resolution was found to be sufficient for the wall tested in this study, but an encoder with higher resolution could be used if additional precision is required.

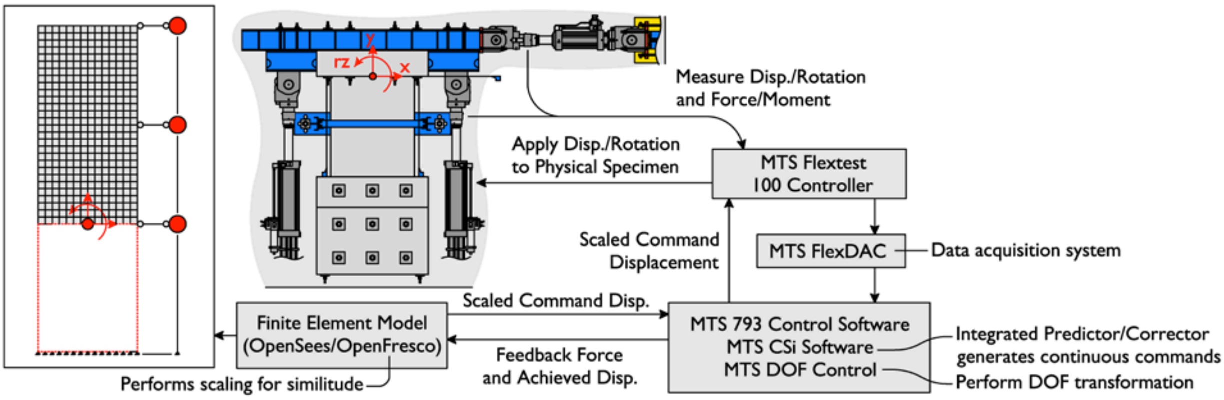


Fig. 4 – Hybrid test architecture

Because there are three DOFs to be controlled at the interface node between the analytical and physical substructures, three displacement transducers are required to simultaneously control the lateral and axial displacements and rotation at the top of the shear wall. While externally mounting the digital encoders in this configuration is effective in bypassing any deformations in the experimental test setup, it introduces another challenge because the displacement transducers used to send and receive the command and feedback signals are mounted in different locations compared to the force transducers used to measure the feedback restoring forces and overturning moment. Consequently, two different coordinate transformations are required: (1) for the displacement and rotation command/feedback and (2) for force and moment feedback. The ability to separate transformation for displacement and force is not currently available in the OpenFresco framework and instead was implemented in this study through the use of the MTS DOF control software. MTS DOF control software has traditionally been used to perform coordinate transformation for multi-actuator shake tables and provides the ability to define multiple coordinate transformations for any number of sensors or actuators. Transformation (1) uses the geometric position of the encoders to convert the command axial displacement, lateral displacement and rotation of the interface node at the top of the shear wall to displacements of the three encoders. Transformation (2) uses the geometric positions of the actuators and force measurements from their load cells to calculate the shear force, axial force and overturning moment at the interface node, which is sent back to the analytical substructure during the hybrid simulation. These two transformations work simultaneously throughout the hybrid simulation to send and receive command displacements and rotation as well as send feedback forces and moment.

Based on the proposed displacement-based hybrid simulation formulation a hybrid test architecture was developed. Figure 4 shows the hybrid test architecture used in this study. For each time-step throughout the hybrid simulation, the following steps are executed:

1. OpenSees solves the equations of motion and obtains the lateral displacement, axial displacement and rotation at the interface node at the top of the first storey shear wall (identified in Fig. 2).
2. OpenFresco scales the displacements (S_L) and rotation (S_R) according to similitude (S_L=0.4 & S_R=1.0).
3. The scaled displacements and rotation are sent to the control equipment in the laboratory and are received by the controller through the MTS computer simulation interface (MTS Csi) software. MTS Csi has a predictor-corrector algorithm that enables continuous hybrid testing and maps the appropriate control channel to the corresponding displacements or rotation command from OpenFresco.
4. The control software sends the appropriate command signal to each hydraulic actuator using transformation (1) to achieve the command displacements and rotation at the top of the wall.
5. The force from the load cell on each actuator is converted to a lateral force, axial force, and overturning moment at the top of the wall based on the geometry of the actuators defined in transformation (2).
6. The displacements, rotation, forces and moment are sent back to OpenFresco and scaled back to full-scale prior to being used to solve the equations of motion for the next time-step in OpenSees. The scale factors for response quantities converted back to full-scale are 2.5 and 1.0 for displacement and rotation, respectively, while the feedback forces and moment are scaled by factors of 6.25 ($1/S_F$=1/0.16=6.25) and 15.625 [$(1/S_F S_L)$ = 1/(0.16×0.4) = 15.625], respectively.

2.4 Earthquake Sequence

To test the response of the multi-storey shear wall over a range of earthquake hazard levels, the three-storey RC shear wall was subjected to an increasing intensity earthquake sequence. The ground motion record used for the earthquake sequence was from the 1994 Northridge earthquake recorded at Canoga Park Station. The record was applied at intensities of 20%, 50%, 100%, 200%, and 300%. Figure 5 shows the earthquake sequence and corresponding response spectra for each record. At the 100% intensity level, the response spectra of the record matches approximately the uniform hazard spectra for the building design site. At the 200% and 300% intensity levels, these ground motion records represent very large earthquakes, which are expected to cause significant damage to the multi-storey shear wall and could lead to structural collapse.

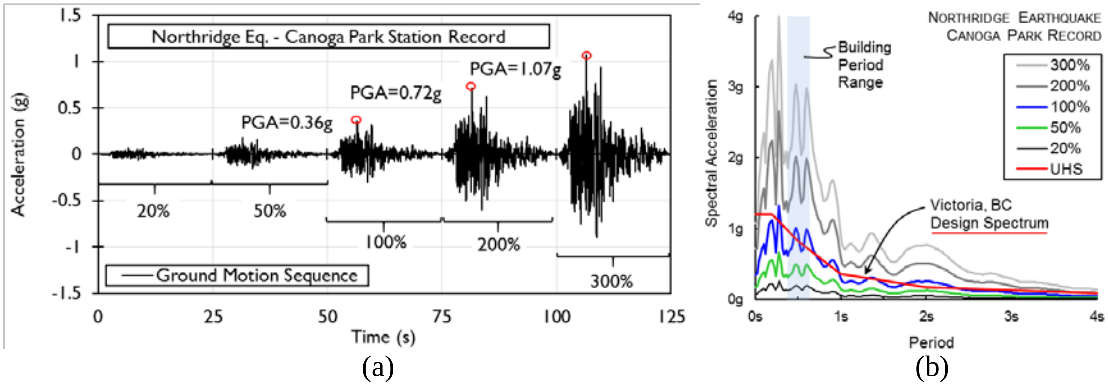


Fig. 5 – (a) Hybrid simulation earthquake sequence; (b) response spectra for the earthquake record set

3. Hybrid Simulation Results

3.1 Local Hybrid Simulation Results

Table 2 shows key structural response parameters for the physical wall for each ground motion intensity. Following the first test (Northridge earthquake at 20% intensity), the performance of the hybrid model and hybrid test setup were assessed, including the achieved target and feedback displacement time histories and a comparison with a purely analytical finite element model. Figure 6 shows the in-plane displacement and rotation time histories compared with a fully elastic analytical model and the measured errors between the command and feedback displacement and rotation. The results show that the results from the purely numerical model match reasonably with the hybrid simulation results, especially considering the small displacement magnitude. The error between the command displacement and rotation throughout the test (Fig. 6b) are less than 0.05mm and 0.00005rad on average, demonstrating the control performance capabilities of the digital encoders. With respect to the observed behaviour of the physical wall in the laboratory, the wall remained elastic and did not exhibit any visible cracks, meeting the design expectation under a small earthquake at a hazard level that would be expected to occur frequently over the service life of a structure.

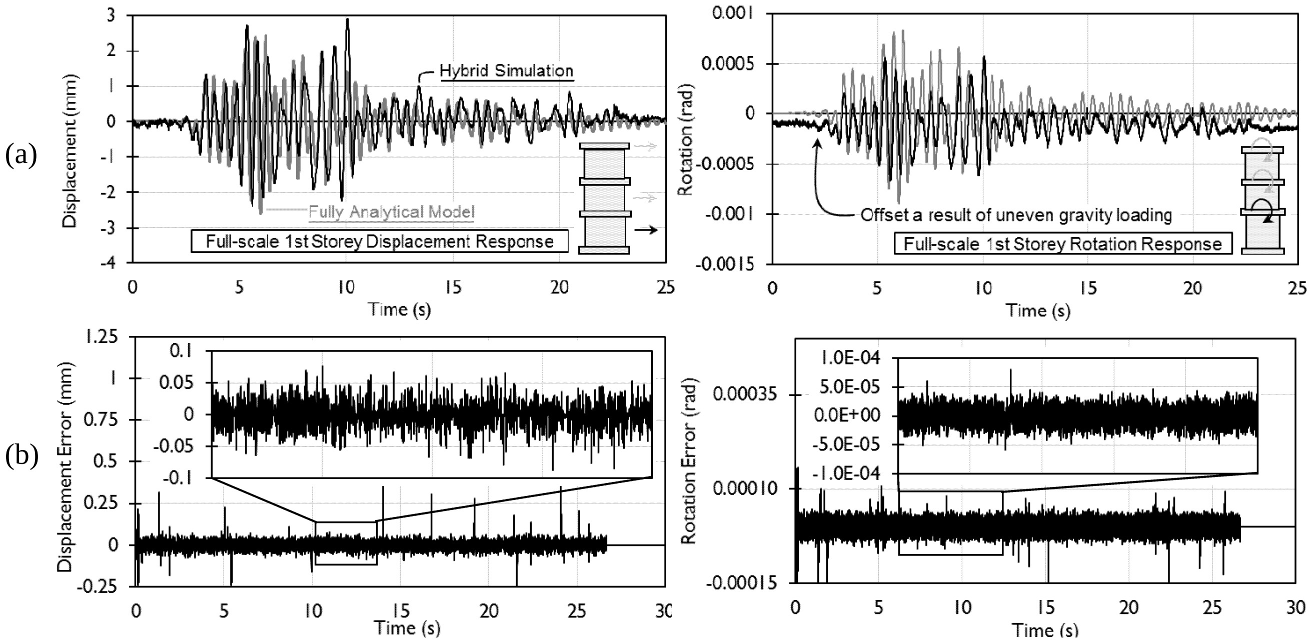


Fig. 6 – (a) Comparison of experimental and purely numerical displacement and rotation time-histories; (b) Displacement and rotation errors (difference between command and feedback for hybrid test)

Table 2 – Hybrid simulation structural response parameters

EQ Intensity	Maximum Displacement (mm)	Maximum Rotation (rad)	Maximum Shear (kN)	Maximum Base Moment (kN-m)	Residual Drift (%)	Residual Rotation (rad)
20%	1.20	0.0007	96	142	-	-
50%	2.39	0.0021	83	269	-	-
100%	5.71	0.0036	144	443	-	-
200%	16.5	0.0097	205	659	0.10	0.0011
300%	27.1	0.0159	214	670	0.98	0.0100

At the 100% intensity level, some yielding and minor cracking was observed in the wall specimen, achieving a maximum displacement of 5.71mm (0.32% drift) and rotation of 0.0036rad. At the 200% intensity level, representing a very large earthquake above the MCE hazard level, the wall exhibited significant nonlinearity in its response. Figure 7 shows the displacement-time history and moment-rotation hysteretic response behaviour for the 200% and 300% intensity earthquakes. Results from the 200% intensity earthquake show that the wall yields at an average lateral displacement of 8.35mm and rotation of 0.0044rad and achieves a maximum displacement and rotation of 16.5mm (0.92% drift) and 0.0097rad, respectively, corresponding to displacement and rotation ductilities of 1.97 and 2.20, respectively. A residual drift and rotation of 0.1% and 0.0011rad were measured following the test, acceptable performance for an earthquake at this extreme hazard level. During the 300% ground motion intensity, the wall in the finite element model collapsed. The shear wall reached a maximum displacement and rotation of 27.1mm (1.5% drift) and 0.0159rad, respectively, corresponding to ultimate displacement and rotational ductilities of 3.25 and 3.61, respectively, exceeding the target ductility (R_d) of 2.0 for a moderately ductile RC wall according to CSA A23.3. Ultimately, the wall failed in diagonal compression after significant yielding of the vertical steel reinforcement along the base of the wall. Significant crushing of the concrete in the bottom corner of the wall and extensive diagonal cracking (maximum width > 2.0mm) were also observed following the test.

3.3 Global Hybrid Simulation Results

In addition to detailed information pertaining to the local response of the first storey of the three-storey RC shear wall, the hybrid simulation results also provide detailed information related to its global response. Figure 9 shows the displacement, inter-storey drift, and overturning moment for the full-scale RC shear wall for increasing ground motion intensity. The results show that as expected the displacements increase along the height of the shear wall and the inter-storey drifts are approximately uniformly distributed. The shear and overturning moment distributions clearly show the effect of nonlinearity in the first storey shear wall, which limits the demand on the wall specimen. These results demonstrate how hybrid simulation can also provide detailed information related to the system-level performance of a full-scale structure during an earthquake.

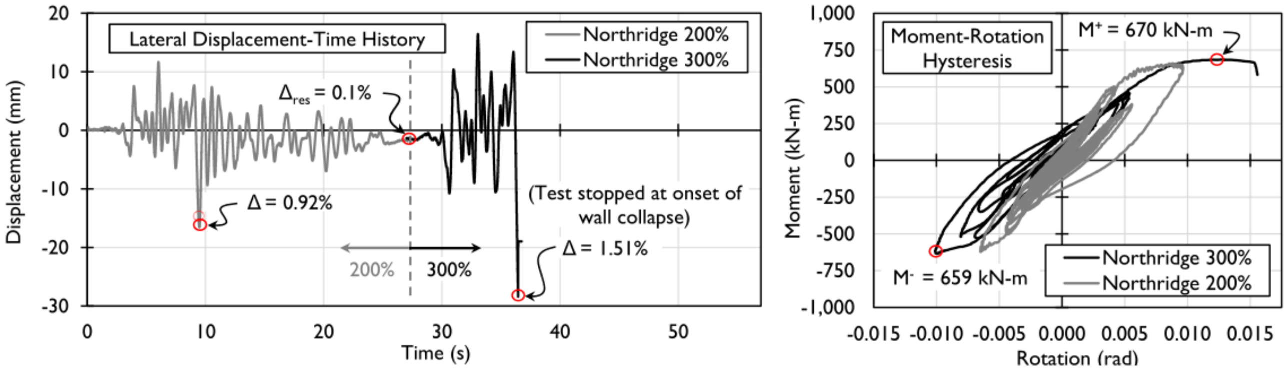


Fig. 7 – Displacement-time history and moment-rotation response for Northridge 200% and 300%

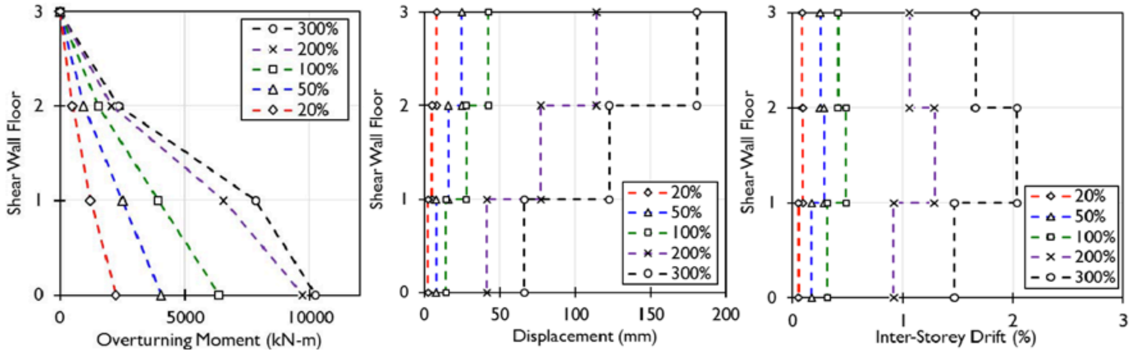


Fig. 8 – Global distribution of overturning moment, lateral displacement and inter-storey drift

3.3 Comparison with Purely Numerical Analysis

In addition to the numerical model developed for the analytical substructure, a purely numerical nonlinear model of the three-storey RC shear wall is developed to provide a means for comparison with the hybrid simulation results. The nonlinear numerical model employed the same *Quad* two-dimensional plane-stress shell element utilized in the hybrid simulation but instead utilizes a nonlinear multi-layer section to capture the inelastic response of the wall. The multi-layer modeling approach, which is illustrated in Fig. 9, discretizes the different components of a RC shear wall (e.g. core concrete, cover concrete, vertical and horizontal steel reinforcement) into a series of layers of varying thickness that are assumed to be fully bonded together. Each layer of the multi-layer section is assigned a nonlinear material model. The properties of the section are defined in OpenSees through the *nDMaterial* command with the *PlasticDamageConcretePlaneStress* and *PlaneStressRebarMaterial* to define the nonlinear concrete and steel material models, respectively and the *PlaneStressLayeredMaterial* to combine the layers together.

In the *PlasticDamageConcretePlaneStress* model, the nonlinear response of the concrete is defined based on its compressive strength, tensile strength, elastic modulus, and four damage parameters: A_p, A_n, B_n, and β. Figure 9 shows the stress-strain response of the model. The tensile strength and elastic modulus were determined based on the compressive strength of the concrete and assumed to be equal to $0.1f'_c$ and $4500(f'_c)^{1/2}$, respectively. Parameter A_p governs the tensile fracture energy of the concrete and is related to the ductility of the tensile response of the concrete, which typically ranges between 0.05-0.2 for conventional strength concrete. The parameter β governs the post-yield hardening modulus and the plastic strain-rate that controls the unloading branch in the response of the element and typically ranges between 0.2 and 0.8. Parameters A_n and B_n control the softening behaviour of the concrete in compression and the ductility of the compressive response and ranges between 1-4 and 0.6-0.9, respectively. Sensitivity analysis showed that A_n had a tendency to effect the ductility of the concrete without significantly altering its peak strength. The nonlinear behaviour of the steel reinforcement is defined through the use of a Giuffre-Menegotto-Pinto material model, which is the *Steel02* material model in OpenSees. Figure 9 shows the cyclic response of the *Steel02* material model, which takes into consideration yielding, isotropic hardening, and the Bauschinger effect. Because a uniaxial material model cannot be directly assigned to an individual layer of the shell section, it must first be defined as an *nDmaterial* using the *PlaneStressRebarMaterial* for steel reinforcement in OpenSees, which also requires definition of the layer orientation. An orientation of 0° is assigned to the vertical steel reinforcement and 90° for horizontal steel reinforcement.

The parameters A_p, A_n, B_n, and β for the nonlinear concrete material model were determined by validating the modeling approach against experimental data from the testing of an RC shear wall under reversed in-plane cyclic load by Hiotakis [11]. The geometry and reinforcement details of the wall can be found in [11]. Figure 9b compares the inelastic cyclic response of the model with the experimental results from [11]. The results show that the model does a good job at predicting the strength, ductility, and energy dissipation capacity of the RC shear wall. Based on promising results, this modelling approach is utilized to study the nonlinear dynamic response of the multi-storey RC shear wall in this study.

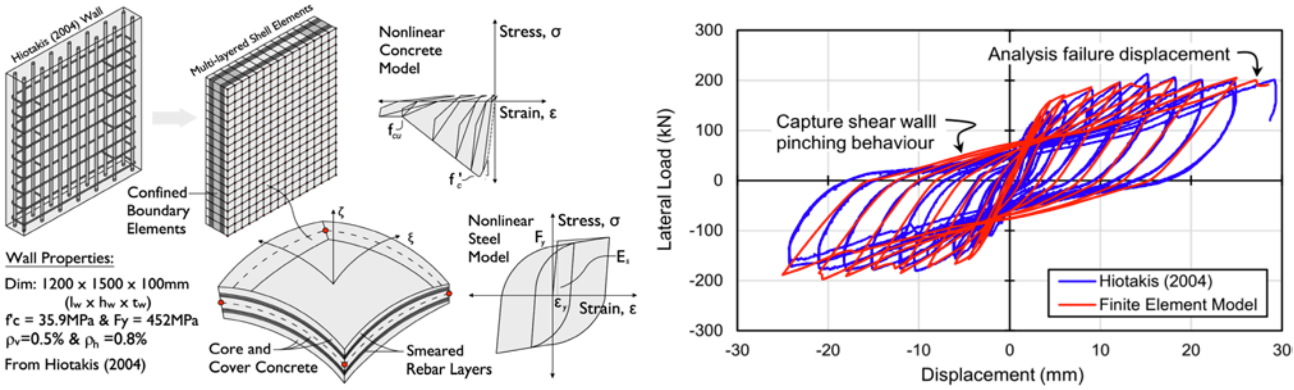


Fig. 9 – (a) Nonlinear multi-layer shell element; (b) Force-displacement hysteretic response comparison of nonlinear shear wall model with experimental results from Hiotakis (2004) [11]

Figure 10 compares the results from the hybrid simulation with the purely numerical nonlinear model subjected to the Northridge earthquake at the 200% and 300% intensity levels. The results show that the model results are generally in good agreement with the hybrid simulation results. The model accurately predicts the inelastic response of the wall and the onset of collapse, reaching a maximum drift of 1.5% at the first storey level. The model also accurately captures the displacement time-history of the wall in the stiff axial direction. These results suggest that the encoders have sufficient resolution to accurately capture the axial displacement time-history of the wall. The results also show that the model is able to capture the cumulative damage effect and softening of the wall under repeated earthquakes but is not able to capture the permanent residual drift following the Northridge 200% ground motion.

4. Conclusions

This study addressed some of the challenges surrounding the use of a displacement-based hybrid simulation formulation for stiff RC structures and assessed the feasibility of using hybrid simulation to study the earthquake response of a multi-storey RC shear wall. Conclusions of the study include:

- It is feasible to use a displacement-based hybrid simulation formulation to study the earthquake response of a stiff RC shear wall if appropriate considerations are made during design of the test setup to ensure that command displacements can be accurately imposed and deformation of the experimental test setup does not negatively influence the hybrid simulation results;
- High-precision and high-resolution digital encoders can be very effective in externally controlling the hybrid simulation and keeping execution errors to a minimum;

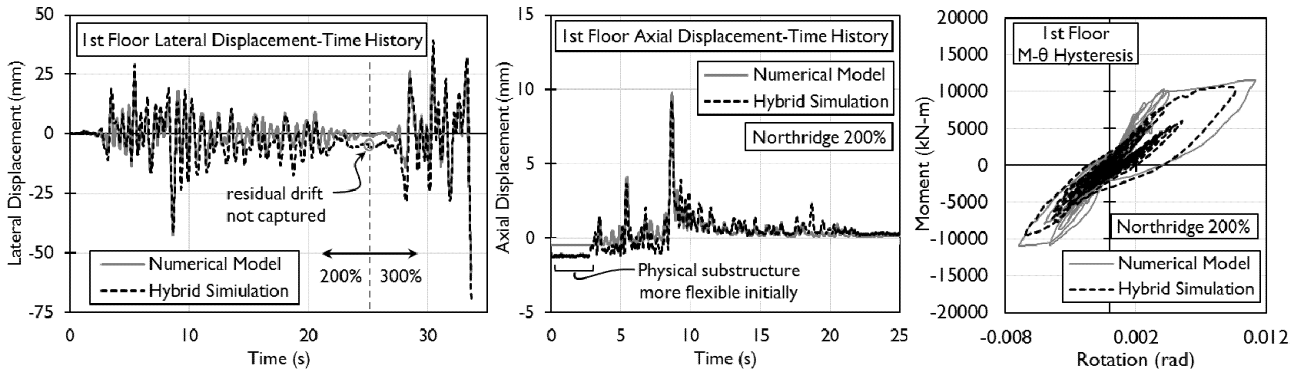


Fig. 10 – Comparison between hybrid simulation and purely numerical results for Northridge 200/300%

- The use of two different coordinate transformations dedicated to displacement command and feedback and force feedback were found to be very effective in permitting the external control strategy;
- Hybrid simulation can provide detailed information about the local seismic response of a physical substructure under a very realistic demand, including its nonlinear hysteretic response behaviour and failure mechanisms, while at the same time capturing the global system-level response of the full-scale structure; and
- The hybrid simulation results were in good agreement with the purely numerical model, validating that the hybrid simulation produced realistic results, specifically with respect to the axial degree-of-freedom.

Future studies should compare results from the proposed displacement-based hybrid simulation formulation with shaking table tests conducted on a multi-storey RC shear wall to assess the potential of using hybrid simulation to replace expensive and time-consuming full-scale shake table testing.

5. Acknowledgements

The authors would like to acknowledge the Canada Foundation for Innovation who provided funding for the Carleton Multi-hazard Research Testing Facility. Technical support from Mr. Martin Leclerc at Polytechnique Montreal and Dr. Shawn Gao at MTS are gratefully acknowledged. Student funding from the Natural Science and Engineering Research Council of Canada (NSERC) is also acknowledged.

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