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Earthquake Response of a Multi-Storey RC Shear Wall using Hybrid Simulation

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ABSTRACT

Hybrid simulation is an innovative testing technique that provides an effective and economical means to study the full-scale response of civil engineering structures without the need to test an entire structure in a laboratory by combining analytical modelling and experimental testing. While hybrid simulation has been used in the past to study the seismic response of flexible structural systems, its application to stiff structures, such as reinforced concrete (RC) shear wall structures, has been limited because of the unique challenges stiff structural systems present to the hybrid simulation test method. This study examines these challenges and presents the results of a study on the feasibility of using hybrid simulation to capture the earthquake response of a multi-storey RC shear wall structure. The physical substructure tested in the laboratory is a 2/5-scale representation of the first storey of a three-storey moderately ductile RC shear wall. The second and third storeys of the shear wall are modelled numerically using OpenSees, which forms the analytical substructure for the hybrid simulation. To maintain compatibility between these substructures, three hydraulic actuators are used to control the in-plane displacements and rotation at the top of the first storey shear wall. Because of the high stiffness of the physical substructure in the laboratory, high precision and high-resolution digital encoders are used to externally control the hybrid simulation. Results of the study demonstrate that hybrid simulation is a feasible alternative to traditional test methods used to study the earthquake response of full-scale RC shear wall structures. The use of high precision externally mounted encoders for the displacement and rotation feedback proved to be an effective control strategy, minimizing command errors and providing accurate command and feedback displacements and rotations during the hybrid simulations.

Keywords: hybrid simulation, reinforced concrete, shear wall, OpenSees, multi-storey structure

INTRODUCTION

Hybrid simulation combines the strengths of experimental testing and analytical modelling to analyze the response of a complete structural system. In this approach, 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 the use of hybrid simulation 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. In this study, the full-scale 3-storey 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. 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 and the hybrid simulation results showed similar local behaviour and failure mechanisms when compared with identical wall specimens test under quasi-static in-plane reversed cyclic loading.

While the studies by [1-2] demonstrated that hybrid simulation can be an effective tool to study 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. In this approach, only the critical highly nonlinear elements in the structure are physically tested in a laboratory while the remaining elements that remain at or near elastic are modelled in a finite element software. When combined together, this substructuring approach produces a complete full-scale structural response without the need to experimentally test the full-scale structure in a laboratory, providing an effective and efficient full-scale test method that has the potential to replace full-scale shake table tests, which are costly and time consuming. Past studies by Chang et al., Charlet, and Saouma et al. [3-5] have applied more effective substructuring approaches to RC frames and bridge structures, but these approaches have not been applied to RC shear walls in the past.

This study expands on previous research and examines the feasibility of using hybrid simulation to study the earthquake response of a full-scale multi-storey RC shear wall structure. Figure 1 shows a conceptual representation of the hybrid simulation substructuring approach used in this study. The hybrid model consists of an analytical substructure, representing the upper stories of the shear wall modelled using discrete shell elements and a physical substructure consisting of the first storey shear wall. In this substructuring approach, the highly nonlinear response of the first storey shear wall is captured in the laboratory while the global response of the second and third storeys are captured in the finite element model. To maintain compatibility between the numerical and physical substructures, three actuators are used to apply the in-plane lateral and axial displacements and rotation to the top of the first-storey shear wall. This hybrid simulation substructuring approach provides an effective balance between the accuracy of an experimental test and the efficiency of numerical model to capture the overall system level response without the need for full-scale experimental testing.

HYBRID SIMULATION PROGRAM

Prototype Structure

The prototype structure for the hybrid simulation in this study is a three-storey RC shear wall structure 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 conforms to a FEMA type C2 concrete shear wall building assessed in FEMA 440 [6]. The structure has a flat plate slab and columns to support the gravity loads. The building has a first storey height of 4.5 m while the remaining storeys measure 3.5 m resulting in an overall building height of 11.5 m. In plan, the structure measures 30 m x 50 m, which includes four 7.5 m bays in the N-S direction and four 12.5 m bays in the E-W directions. The principle seismic force resisting structural system includes perimeter shear walls around a centrally located concrete core. The structure is design using the equivalent static force procedure from the National Building Code of Canada (NBCC) and response spectrum analysis [8]. The walls are designed as moderately ductile RC shear walls ($R_d = 2.0$, $R_o = 1.4$) according to CSA A23.3, detailed to form a plastic hinge at their base [7]. The shear walls are oriented to create a torsionally stable configuration. Additional details on the design of the prototype structure are available in Woods [9].

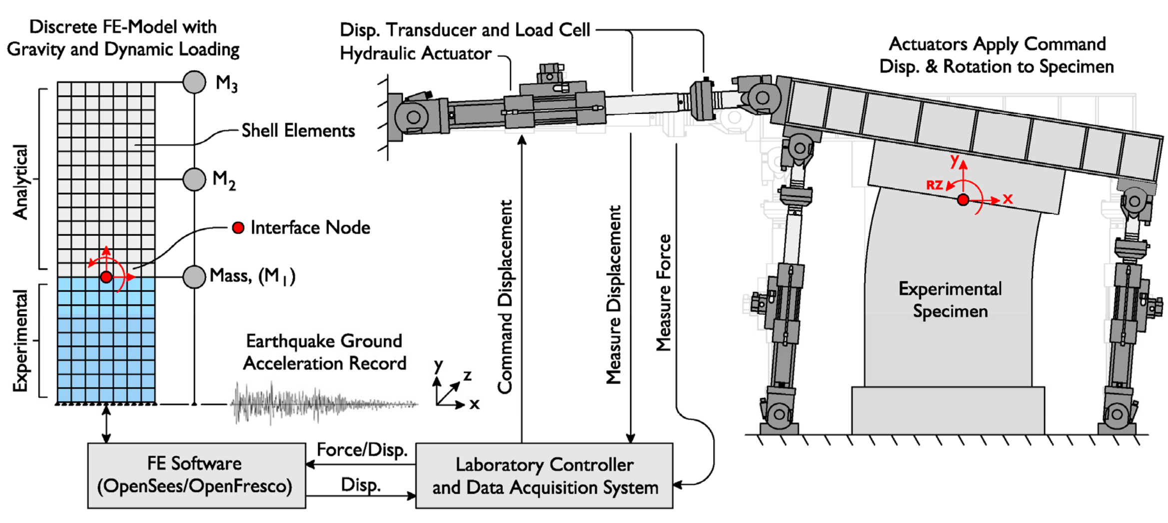

Figure 1. Hybrid test concept for a multi-storey RC shear wall structure.

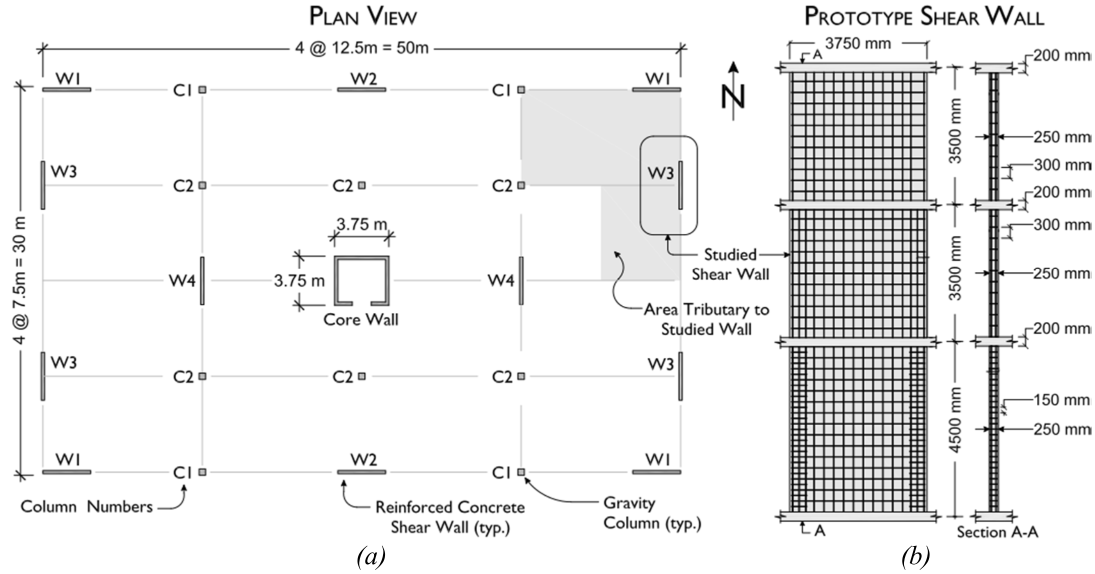

Figure 2. Prototype RC shear wall structure: (a) plan view, (b) typical shear wall detail.

Analytical Substructure

The analytical substructure is a finite element model of the second and third storey of the three-storey RC shear wall modelled in the OpenSees finite element software [10]. OpenSees is used to model the analytical substructure because of its ability to seamlessly incorporate the functions and features of the Open Framework for Experimental Setup and Control software (OpenFresco), which is used to connect the analytical and physical substructures together for the hybrid simulation [11]. The shear wall is modelled using four node elastic shell elements. The shell elements are two-dimensional plane-stress shell elements defined using the *Quad* element 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 storeys of the RC shear wall ($0.5 * 4500\sqrt{f_c'}$). The use of elastic elements for the analytical substructure allowed the study to focus strictly on the performance of the hybrid testing system, physical experimental test setup in the laboratory, and functionality of the communication link between the finite element model and the laboratory equipment prior to introducing additional complexities associated with a nonlinear finite element model (convergences problems, model accuracy etc…) into the hybrid simulation. Future studies will focus on the use of a nonlinear finite element model for the upper stories of the RC shear wall.

The tributary mass for the prototype shear wall is lumped at each storey level in the analytical substructure. A leaning column with lumped masses representing the mass of the rest of the structure is also included in the analytical substructure 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 260 kN, 400 kN, and 400 kN are applied to the third, second, and first storey levels, respectively. This corresponds to a total gravity load of 1060 kN on the full-scale first storey shear wall. To maintain similitude laws, the command displacements and feedback forces are scaled between the analytical and physical substructures in the laboratory, which is at 2/5 scale. 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 169.6 kN applied to the physical substructure in the laboratory, 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 in the finite element model, the earthquake time-history analysis is conducted with a fixed time-step of 0.005s. The *NewmarkHSFixedNumIter* numerical integration scheme developed by Schellenberg et al. [11] is used in conjunction with *Newton* solution algorithm and 50 fixed iterations for each time-step. These analysis parameters were determined using a sensitivity analysis of a purely analytical finite element mode of the shear wall.

To interface between the physical specimen in the laboratory and the numerical model in OpenSees, the open-source middleware OpenFresco is employed [11]. In OpenFresco, a *Generic* experimental element is used to represent the shear wall specimen in the analytical substructure. A *Generic* element is capable of representing an element at any number of nodes with any number of degrees-of-freedom (DOFs). The element is defined at the control node, shown in Fig. 1, at the top of the first storey shear wall and has three primary control DOFs (in-plane lateral and axial displacements and rotation). The initial stiffness matrix, K_{initial}, is defined according to the basic coordinate system for the generic elemental element shown in Fig. 1. Generally, it is considered good practice to over-estimate the initial stiffness of the experimental element to ensure the initial command displacement sent to the experimental element is not too large, which could result in instability in the hybrid simulation or accidentally damage the physical substructure. Because an alternative software is used in this study to transform between global DOFs and actuator DOFs, a *NoTransformation* experimental setup is employed in OpenFresco. This experimental setup command sends the displacements and rotations to the hydraulic control equipment to the lab without transforming between model and actuator coordinate systems. The only transformations to the model response quantities (e.g. displacement, rotation, force, and moment) to account for similitude laws. As discussed previously, based on a scale factor of 40% between substructures, this results in command displacement and rotation scale factors of 0.4 and 1.0, respectively, and feedback displacement, rotation, force, and moment scale factors of 2.5, 1.0, 6.5, and 15.625, respectively. Additional details on the development of the hybrid model are available in [9].

Physical Substructure

To accommodate for space limitations in the laboratory at Carleton University, the first-storey of the three-storey RC shear wall is scaled to 2/5 of its original size. Figure 3a shows the dimensions and reinforcement details for the shear wall specimen in this study. Scaling results in a wall specimen that measures 1500 mm x 1800 mm x 100 mm (l_w x h_w x t_w) and has a height-to-length aspect ratio (h_w/l_w) of 1.2. The wall specimen has horizontal and vertical steel reinforcement ratios of 0.4% and 0.28%, respectively. The concrete used in the shear wall specimen had an average 28-day compressive strength of 31.6 MPa and a compressive strength on the day of the tests of 32.5 MPa. The 10M horizontal and vertical steel reinforcement had average yield strengths and strains of 468 MPa and 455 MPa and 0.0028 and 0.0022, respectively.

Figure 3b shows the experimental test setup for the physical substructure in the laboratory. Three hydraulic actuators are used to apply the in-plane displacement, axial displacement, and rotation at the top of the shear wall specimen. A rigid steel loading beam is used to connect the hydraulic actuators to the heavily reinforced cap beam of the wall specimen. The foundation of the shear wall specimen is fixed to the laboratory strong floor and a supporting block is used to provide additional support to prevent any sliding/rotation of the wall specimen during testing. A steel support is used to prevent any out-of-plane displacement or rotation of the wall specimen during the hybrid simulations.

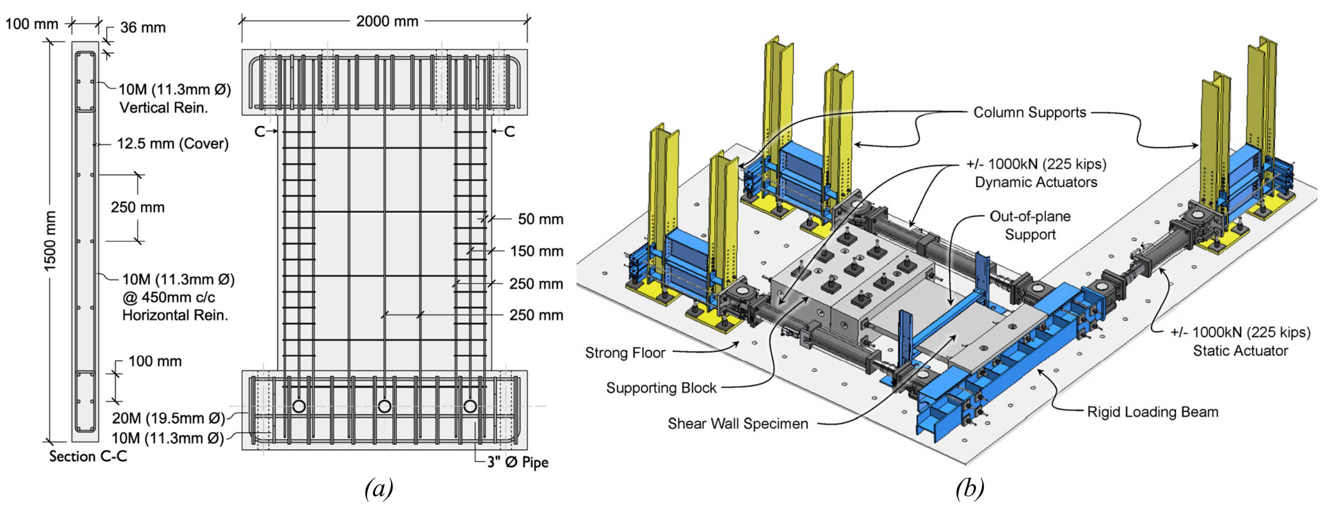

Figure 3. (a) Geometry and steel reinforcement details for the scaled shear wall test specimen. (b) Experimental test setup

Challenges in Hybrid Testing of Stiff Structures

One of the major challenges surrounding hybrid testing of stiff structural components is the application and measurement of the target displacement command sent to the physical substructure and the measured displacement response that is sent back to the finite element model. Because of the large stiffness of the RC shear wall specimen, this can result in deformation to the experimental test setup if it is not sufficiently stiffer than the physical substructure. In addition, the command displacement sent to the physical substructure is often very small (<0.1 mm), making it difficult for actuators with conventional displacement transducers to control. One approach researchers have proposed to conduct hybrid simulation on stiff structures is the use of force-based hybrid simulation approaches [12-13]. One of the major challenges surrounding force-based hybrid simulation formulations is softening of the physical substructure in the laboratory. This behaviour would cause the hybrid simulation to become unstable under force control. To overcome this challenge, Yang et al. [13] has recently proposed a switch-based hybrid simulation that switches from force control to displacement control after softening of the structure is detected. Although the approach has proven to be effective in small-scale testing, it is not readily available in the OpenFresco framework and would require the actuators used in the hybrid simulation to switch control modes, which is not possible with the equipment used in this study. Alternatively, the approach proposed by Whyte and Stojadinovic [2], which uses externally mounted high-precision encoders and a displacement-based formulation to control the hybrid simulation is employed in this study to effectively bypass any deformations in the experimental test setup while at the same time providing superior accuracy when compared with conventional displacement transducers.

Figure 4 shows some of the potential deformation mechanisms for the experimental test setup in this study. During the design of the experimental test setup, it became evident that designing the components of the experimental test setup to resist these deformation mechanisms would be uneconomical and impractical. Consequently, external displacement transducers mounted directly on the wall specimen are used to control the hybrid simulation. Figure 4 shows the locations of the three encoders mounted on the shear wall specimen. To improve the accuracy and resolution of the displacement feedback, high-precision digital encoders were incorporated into the control loop. Three Sick AFM60 digital rotary encoders mounted to wire-draw mechanisms provided measurement resolution up to 0.0025 mm, which proved to be sufficient for these hybrid tests.

While the use of externally mounted encoders bypassed deformations in the experimental test setup, it also introduced an additional challenge because the displacement transducers used for displacement/rotation feedback and the force transducers used for force/moment feedback during the hybrid simulations were mounted in different positions. The displacement transducers were mounted directly on the shear wall specimen while the force transducers were mounted on the ends of the hydraulic actuators. To overcome this challenge, two independent coordinate transformations were used simultaneously during the hybrid simulation. The first transformation handled the command and feedback displacement loop while the second handled the force and moment feedback. This was accomplished through the use of MTS DOF control software, which is capable of transforming between actuator DOFs and global DOFs for an experimental test setup with any number of hydraulic actuators, even in over-constrained systems that have a larger number of hydraulic actuators compared with the number of DOFs. The two transformations were defined based on the geometry of the experimental test setup shown in Fig 3b.

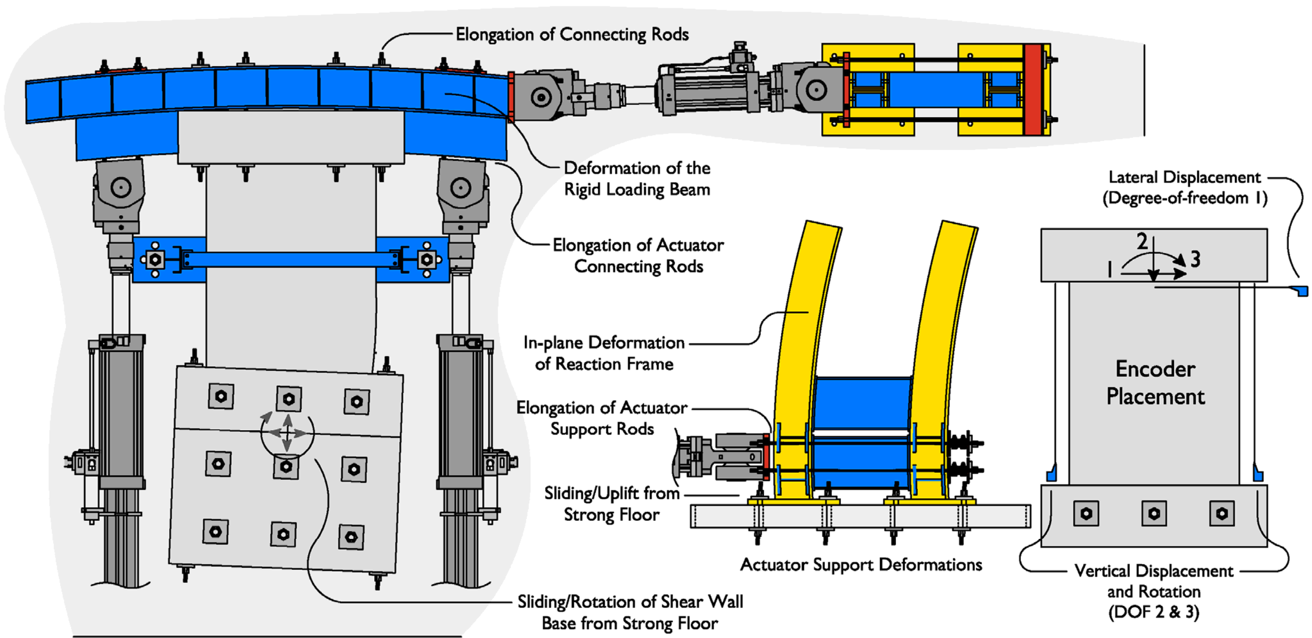

Figure 4. Potential modes of deformation for the experimental test setup and encoder mounting positions.

Earthquake Time Histories

For the hybrid simulations, the prototype shear wall is subjected to a ground acceleration record from the 1994 Northridge earthquake at increasing intensity, shown in Fig. 5a. This earthquake ground acceleration record is selected because west coast earthquake records are commonly considered suitable for structures designed in Western Canada and because its response spectra, shown in Fig. 5b, reasonably matches the response spectra for Victoria, British Columbia ([14],[8]). The Northridge earthquake record was applied to the full-scale RC shear wall at increasing intensities of 20%, 50%, 100%, 200%, and 300%, shown in Fig. 5a, to study its behaviour under a range of hazard levels. At the 20 and 50% intensity levels, the ground motion represents an OBE-level earthquake, after which a structure is expected to remain fully operational. At 100% intensity, the ground motion represents a DBE-level earthquake, during which some damage is expected, including yielding of steel reinforcement and concrete cracking. At 200% and 300% intensity, the ground motions represent MCE-level earthquakes that are expected to cause significant damage to a structure.

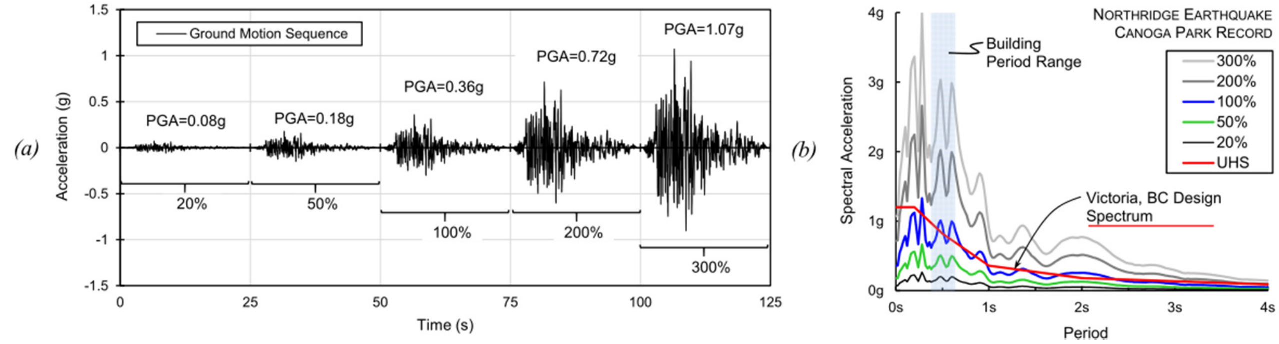

Figure 5. (a) Hybrid test earthquake sequence, (b) response spectra for the earthquake record set.

HYBRID SIMULATION RESULTS

Table 1 shows key structural response parameters for the physical wall specimen under each ground motion intensity. Following the first test under the Northridge earthquake at 20% of its unscaled 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 fully analytical finite element model. Figure 6a 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 hybrid test results agree with the fully elastic finite element model, demonstrating that the hybrid model is functioning properly and producing reasonable results. Figure 6b also shows the error between the command displacement and rotation throughout the test. The results show that the errors between the command and feedback displacements and rotations are less than 0.05 mm and 0.00005 rad on average, demonstrating the control performance capabilities of the digital encoders.

With respect to the observed behaviour of the multi-storey RC shear wall at increasing earthquake intensity, the results confirm that at the 20% and 50% intensity levels, the wall specimen remained elastic, meeting the design expectation under an OBE-level earthquake. At the 100% intensity level, some yielding and minor cracking was observed in the wall specimen, which was once again in-line with expected behaviour during a DBE level earthquake, achieving a maximum displacement of 5.72 mm (0.32% drift) and rotation of 0.0036 rad. At the 200% intensity, representing an MCE level earthquake, the wall specimen exhibited significant nonlinearity in its response. Figure 7 shows select response parameters for the wall. The results show that the wall specimen yields at an average lateral displacement of 8.35 mm and rotation of 0.0044 rad. The wall specimen achieves a maximum displacement of 16.5 mm (0.92% drift) and rotation of 0.0097 rad, corresponding to displacement and rotation ductilities of 1.97 and 2.20, respectively. The axial displacement-time history in Figure 7 is compared with the fully analytical model, and the results show that while the experimental specimen is slightly more flexible compared to the analytical model, the results are very comparable, suggesting that the control in the stiff axial direction is performing acceptably. Finally, at the 300% ground motion intensity, the wall specimen was tested to its ultimate strength and the shear wall in the finite element model collapsed. The shear wall reached a maximum displacement and rotation of 27.1 mm and 0.0159 rad, respectively, corresponding to ultimate displacement and rotational ductilities of 3.25 and 3.61, respectively. The wall specimen failed in diagonal compression shear failure, resulting in significant concrete crushing at the toe of the shear wall following excessive yielding of the vertical steel reinforcement over the length of the wall specimen.

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 8 shows select parameters for the global response of the shear wall. 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.

Table 1. Hybrid Simulation Response Parameters.

EQ Intensity	Maximum Displacement (mm)	Maximum Rotation (rad)	Maximum Drift (%)	Maximum Shear (kN)	Maximum Base Moment (kN-m)	Crack Widths (mm)	Residual Drift (%)	Residual Rotation (rad)
20%	1.20	0.0007	0.07	96	142	-	-	-
50%	2.39	0.0021	0.13	83	269	0.1-0.25	-	-
100%	5.71	0.0036	0.32	144	443	0.5-0.8	-	-
200%	16.5	0.0097	0.92	205	659	0.5-1.0	0.10	0.0011
300%	27.1	0.0159	1.5	214	670	0.8-2.0	0.98	0.010

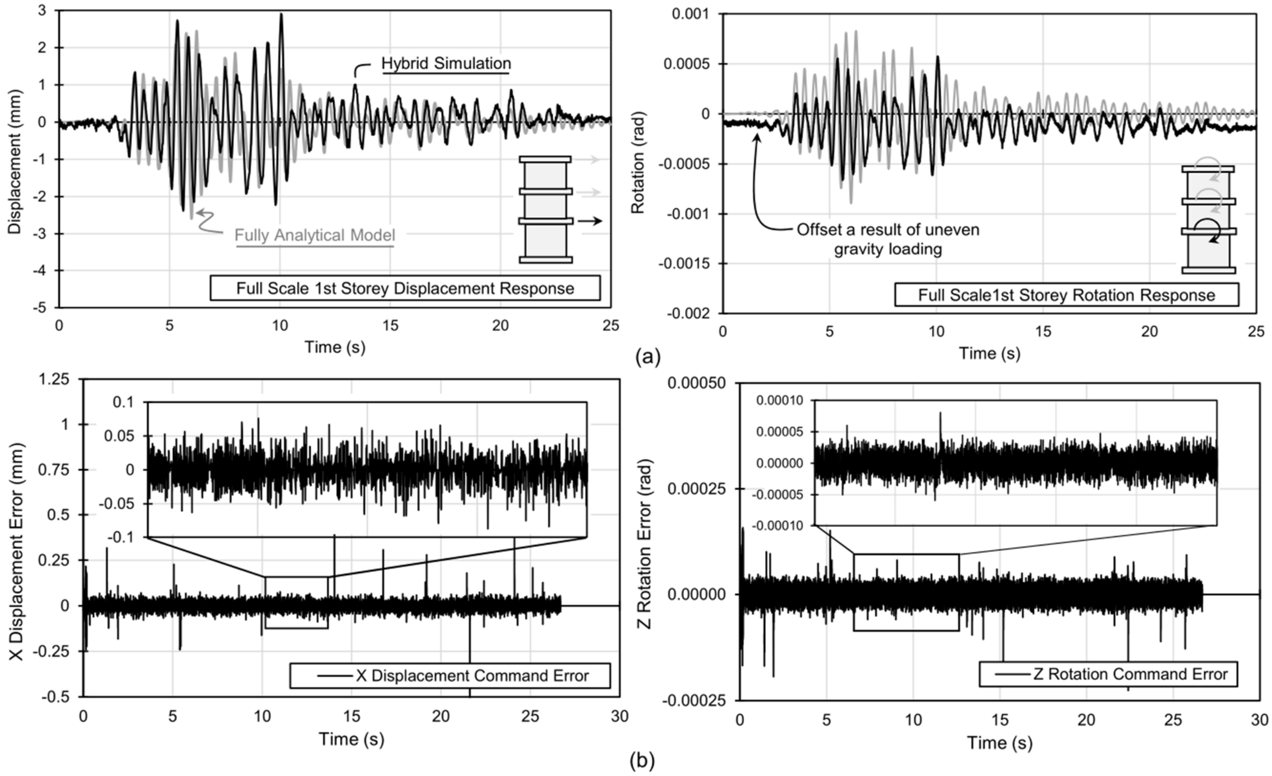

Figure 6. (a) Comparison of displacement and rotation time-histories for hybrid test and fully analytical model, (b) Displacement and rotation errors (difference between command and feedback) for hybrid test.

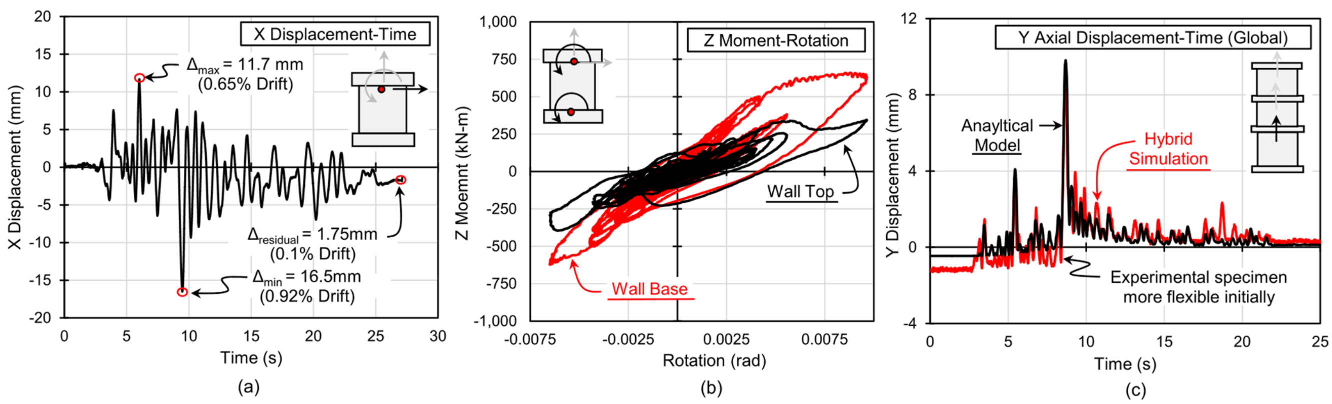

Figure 7. Hybrid simulation results – Northridge EQ 200%: (a) lateral displacement-time history (local), (b) moment-rotation hysteretic response (local) (c) axial displacement-time history (global).

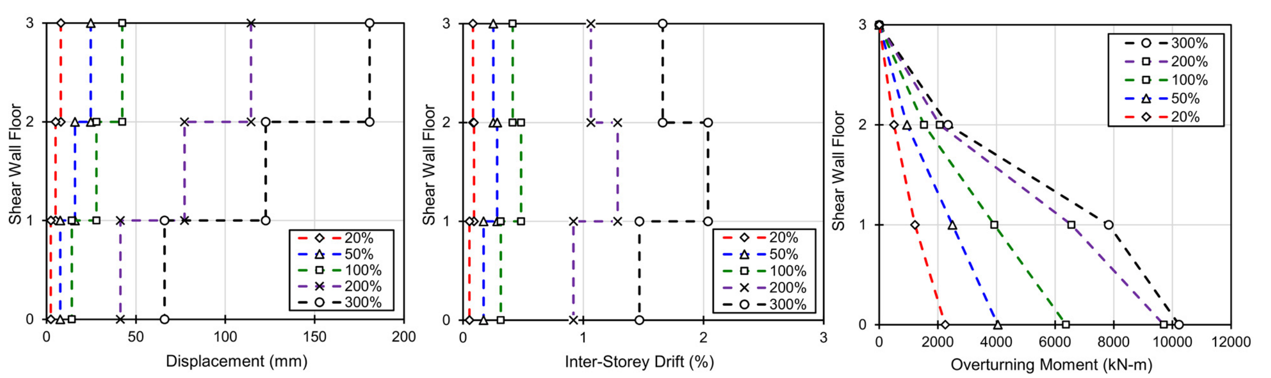

Figure 8. Hybrid simulation results – global structural response behaviour under increasing ground motion intensity.

CONCLUSIONS

The results in this paper have demonstrated how hybrid simulation can provide detailed information about the local response of a critical section of a multi-storey RC shear wall, including measuring its ductility and failure mechanisms, while at the same time capturing the global response of the complete full-scale shear wall. While hybrid simulation has been used in the past to study the seismic response of flexible structural systems, its application to stiff RC structures have been limited because of the challenges stiff structural systems present to the hybrid test method. The use of high-precision digital encoders for external control are shown to be effective control devices for stiff structural elements, even when the command and feedback displacements are very small (<0.1 mm). The error between the command and achieved displacement and rotation was found to remain on average below 0.05 mm and 0.00005 rad, respectively, which is within an acceptable margin (<2% depending on the test) when considering the maximum displacements achieved during the tests. The use of digital encoders for external control is found to be very effective in bypassing any deformations in the experimental test setup. The use of two different coordinate transformations to convert between model DOFs and experimental DOFs based on actuator and encoder coordinate systems allows for the integration of independent force and displacement feedback loops in the hybrid test. Ultimately, hybrid simulation has been shown to be a feasible alternative to traditional test methods used to study the full-scale response of multi-storey RC shear wall structures.

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