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Hybrid Simulation of a Reinforced Concrete (RC) Building Retrofitted by Shear Wall with Opening

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ABSTRACT

Over the past four decades, Taiwan has experienced numerous earthquakes that have caused numerous casualties and damage to property. In particular, the Meinong Earthquake of 2016 highlighted the vulnerability of mid-rise buildings with soft and weak stories, leading to increased awareness of the need for structural retrofitting to improve the seismic capacity of existing buildings. One popular option for resisting lateral loads in medium- and high-rise buildings is the use of shear walls. However, openings in shear walls may be necessary for remodeling or for practical reasons, such as the inclusion of stairways, windows, doors, and elevators. In this research, the seismic behavior of a half-scale 7-story reinforced concrete (RC) frame structure retrofitted by RC infilled shear wall with opening was assessed using hybrid simulation, an innovative experimental method that combines an experimental physical substructure tested in the National Center for Research on Earthquake Engineering (NCREE), Taiwan and an analytical numerical substructure modeled in Hardware-in-the-loop Hybrid Simulation Software (HSS) developed by the research team at the University of British Columbia (UBC) and the Advanced Control Testing Systems (ACTS). Hybrid simulation was implemented since it saves time and costs while providing conclusive evidence of the effectiveness of the retrofitting technology.

Keywords: hybrid simulation, reinforced concrete building, seismic retrofitting, shear wall with opening

INTRODUCTION

Over the past four decades, Taiwan has experienced numerous earthquakes that have caused numerous casualties and damage to property. In particular, the Meinong Earthquake of 2016 highlighted the vulnerability of mid-rise buildings with soft and weak stories, leading to increased awareness of the need for structural retrofitting to improve the seismic capacity of existing buildings. The main features of the collapse buildings were: (1) weak and soft first story due to the need of public and commercial activities, (2) high quantities of structural walls on the higher stories to satisfy the residential safety and privacy requirement, (3) 90-degree hooks and loose spacing of ties in the columns, and (4) beams that were stronger than columns due to the outdated strong-beam-weak-column design philosophy. Those features caused the damage and deformation concentrated on the slender columns at the first floor. The whole building therefore collapsed even with the upper portion remaining undamaged or slightly damaged. The event in 2016 indicates there is an urgent need to upgrade the seismic capacity of the existing and aged mid-rise and high-rise residential buildings in Taiwan. Furthermore, it also implies an opportunity to put the effort focusing on strengthening and stiffening the weak and soft first storey to reduce the financial cost yet retrofit the whole buildings efficiently.

One popular option for resisting lateral loads in medium- and high-rise buildings is the use of shear walls. However, openings in shear walls may be necessary for remodeling or for practical reasons, such as the inclusion of stairways, windows, doors, and elevators. To meet the functional requirements, these RC walls usually have door or window openings. Such openings often result in narrow, vertical wall segments, which are prone to shear failure during earthquakes, as observed in past reconnaissance efforts. Taylor et al. [1] conducted a study on the design of slender reinforced structural walls with openings at the base. Their findings revealed that shear plays a more significant role in the behavior of walls with openings as compared to solid walls. Therefore, it is imperative to consider the impact of shear when designing such walls to ensure structural safety and resilience in the event of seismic activity. Yeh et al. [2] tested wall specimens with special horizontal reinforcement extended through the whole vertical wall segments, i.e., wall piers, at both sides of the openings. It was observed that the shear strength of the wall can be increased due to the special horizontal reinforcement, but the damage would be more concentrated in the two vertical wall segments. Tsai et al. [3] and Hsu et al. [4] reported that, according to the observation of the experimental testing on the RC squat shear wall with openings, the main failure mechanism is the concrete crushing on the vertical wall segments. The damage concentrated on the vertical wall segments causes the wall to lose the axial force resisting capacity and collapse brittlely.

To address the issues of (1) the living requirement of the windows and doors and (2) the unfavorable failure mechanism of the vertical wall segments, this paper proposed a retrofitting technology by installing special RC shear wall with openings. The special RC wall with openings consists of the special vertical and horizontal reinforcement around the opening, which is suggested by ACI 318-19 [5] and Yeh et al. [2], and special diagonal reinforcement distributed along the vertical wall segments to strength their capacity. The experimental testing is conducted in a hybrid manner, where the retrofitted wall specimen is tested as the physical substructure, while the rest portion of the 7-storey prototype building is numerically modeled as the numerical substructure. A ground motion recorded during 2016 Meinong Earthquake with near-fault pulse-like features is selected for the hybrid simulation. The peak ground acceleration (PGA) of the selected ground motion is scaled from 50 gal to 800 gal until the physical substructure reaches its peak capacity and is severely damaged. The hybrid simulation results indicate the proposed retrofitting technology can significantly reduce the drift response of the existing aged building and prevent it from collapse in the 800-gal PGA earthquake event. Furthermore, the proposed special reinforcement detail is examined to prevent the vertical wall segments of the RC shear wall with openings from failure. The wall fails due to the diagonal shear failure on the horizontal wall segments (wall spandrels), which is similar to the behaviour of the coupling beams in the coupled wall system.

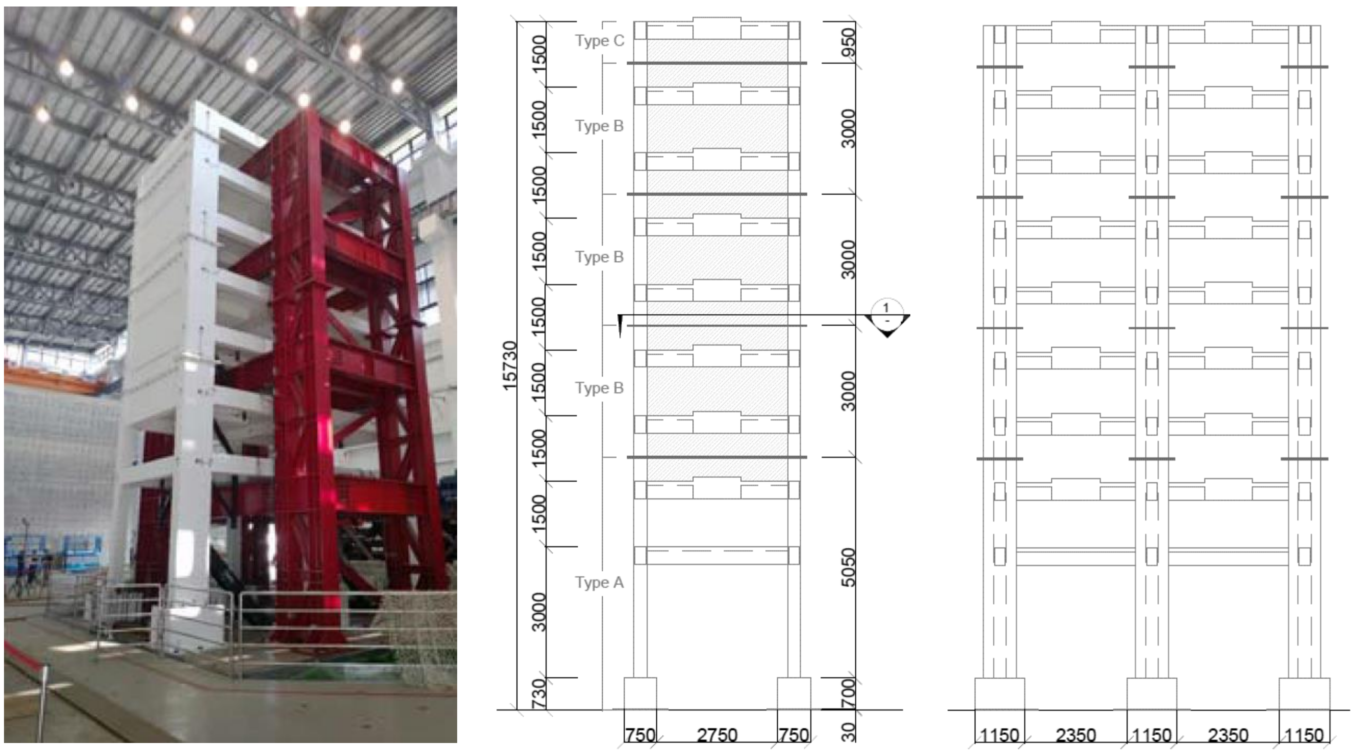
HYBRID MODEL

Prototype building

The prototype building was designed with features of (1) weak and soft first story, (2) high quantities of structural walls on the higher stories, and (3) 90-degree hooks and loose spacing of ties in the columns to represent aged existing buildings that lacks seismic resisting capacity and collapsed during the 2016 Meinong earthquake in Taiwan. The half scaled 7-Story RC frame prototype building shown in Fig 1(a) was tested dynamically on the shake table, and the RC components were tested cyclically on the reaction wall at the Tainan laboratory of the National Center of Earthquake Engineering (NCREE) on 2018 [6]. The detailed drawings and information of the experimental results are summarized in the appendix and can be accessed through the website [7]. The reference specimen was tested on a shake table under five seismic events shown on Table 1. The specimen was firstly tested under a far-field ground motion, CHY015, with the intensity of 0.10 g as the peak ground acceleration (PGA), and then tested under a near-fault ground motion, CHY063, scaled from PGA of 0.21 g to 0.84 g. The acceleration, velocity, and displacement history of the ground motion, CHY063, are shown in Fig. 2(a). CHY063 was categorized as a pulse-like near fault earthquake; hence, clear pulses can be seen on the velocity and displacement history. The response spectrums of the ground motions were shown on Fig 2(b).

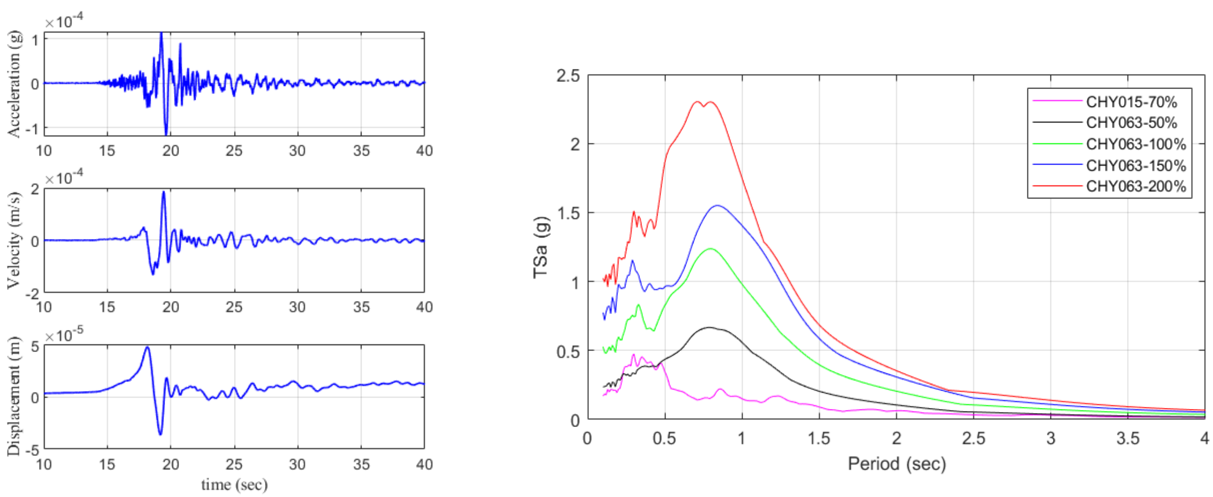
Table 1. Summary of the testing ground motions.

Category	Event	Year	Station	PGA [g]	Test ID
Far-field	Chi-Chi, Taiwan	1999	CHY015	0.10	CHY015-70%
Near-fault	Meinong, Taiwan	2016	CHY063	0.21	CHY063-50%
				0.42	CHY063-100%
				0.63	CHY063-150%
				0.84	CHY063-200%



(a) (b) (c)

Figure 1. Half-scaled 7-storey RC prototype building (a) on the shake table, (b) front view (lateral direction), and (c) side view (longitudinal direction).



(a) (b)

Figure 2. (a) Acceleration, velocity, and displacement history of CHY063 (200 gal) and (b) acceleration response spectrum of testing ground motions with 5% damping

Proposed retrofitted specimen.

A one storey single bay RC frame specimen represents the middle bay of the protype building at the first floor along the lateral direction. It consists of an RC footing mounted on the strong floor and two vertical RC columns, which are 750 mm by 300 mm rectangular column and 300 mm by 300 mm square column. Both columns have the same reinforcement detail as the one that prototype building's columns have. The details of two columns are shown in the appendix. Since the prototype building represents the existing aged RC mid-rise buildings in Taiwan. The strong-column-weak-beam capacity design principle was not required by the code in the past. The failure hierarchy is therefore governed by columns. Hence, the beam of the frame is replaced by a strong loading beam at the top frame, which is then clamped by two steel loading beams connected to two hydraulic actuators. The RC frame specimen is further retrofitted by an infilled RC shear wall with a 1000 mm by 1000 mm opening at the center. The infilled RC shear wall with opening has a thickness of 150 mm and a single layer of web reinforcement. Its web reinforcement consists of D10 reinforcing bar at a spacing of 150 mm in a two-way manner and additional D14 diagonal reinforcing bars distributed along the full height of two vertical wall segments at a spacing of 100 mm. The opening was strengthened by double D16 special reinforcing bar at a spacing of 150 mm surrounding the four edges of the opening and the special reinforcement is extended through the full heigh and length of the wall straightly without hooks at both ends. The infilled RC wall panel was bound by 260 mm D10 plating rebar which injected into the existing RC frame by 100 mm depth every 150 mm around the four edges of the wall-frame interface. D10 and D14 reinforcing bars have a yield strength of 275 MPa, and D16 reinforcing bar has a yield strength of 400 MPa. The 28-day concrete cylinder compressive strength averaged 24.3 MPa.

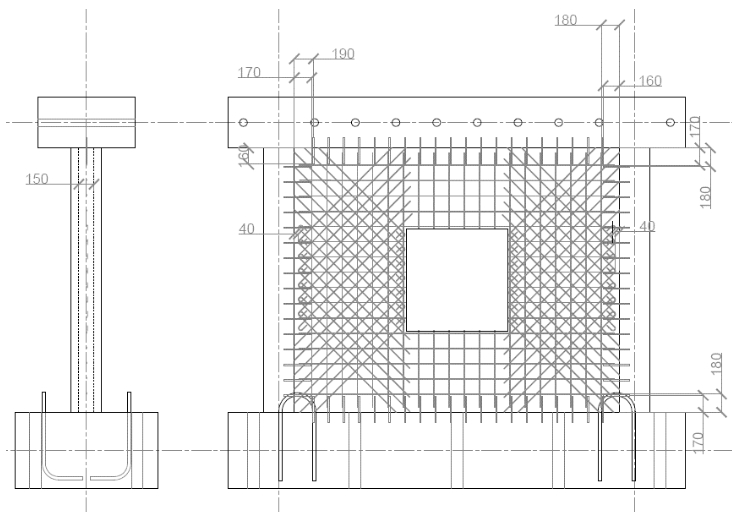


Figure 3. Force-displacement hysteresis curves of the tested substructure under the ground motion, CHY063, with PGA of (a) 50 gal, (b) 100 gal, (c) 200 gal, (d) 400 gal, (e) 600 gal, and (f) 800 gal

HYBRID SIMULATION ARCHITECTURE

The implemented hybrid simulation framework is shown in Fig 4. The experimental test setup consists of two hydraulic actuators which were controlled by the ACTS controller. The controller has two physical devices, industrial programmable controller (IPC) and data acquisition system (DAS) combined with signal processing modules (SPMs). IPC is basically a computer that can run software and programing scripts to process the signals and conduct analysis of numerical models, while the DAS and SPMs are served as I/O channels that can receive input signals from the external sensors and send output signals to control the servo-valves of the hydraulic actuators. The two devices are connected to communicate and form the control loop. The hardware can be operated by the two software, advanced low-level controller (ALC) and hardware-in-the-loop hybrid simulation software (HSS). ALC is a graphical user interface that directly shows all the signal values and does the real time signal editing such as filters and controlling algorithms. ALC is a bridge between hardware (i.e., hydraulic systems) and the numerical analysis platform, HSS to achieve the hybrid simulation testing. HSS is numerical modeling software that can be embedded with any user-defined nonlinear material models, element models, and nonlinear integration algorithms. Experimental elements that consider the geometric transformation between physical substructures and numerical substructures are developed to update the stiffness matrix and structural response (i.e., nodal forces, and nodal displacements) from the experimental setup and then send the next-step iterated simulated numerical results to the controllers as command signals to drive the hydraulic system. The displacement-based-controlling algorithms developed by Yang et al. [8] was implemented to control one of the hydraulic actuators, noted as the master actuator. The displacement feedback signal of the master actuator will be sent to the other slaving actuator as the displacement command signal to ensure the two actuators having the same displacement anytime during the whole testing to avoid out-of-plane bending and torsion.

In order to accelerate the experiment and shorten the modeling iteration calculation time, the 7-story reinforced concrete specimen was simplified into a two-dimensional lumped-mass stick model. The rigid diaphragm was assigned to each floor. The model consists of seven vertical beam-column elements and a horizontal two-force member. The beam-column elements in first storey only considered the stiffness of the four columns that were not reinforced. The beam-column element representing the second storey considered all of the six columns and the rest elements considered six columns plus two additional infilled RC shear walls.

The horizontal two-force member supported the top of the first storey to simulate the single-span shear wall of the physical substructure. The horizontal two-force member was modeled using the "Experimental Element", which was implemented in HHS analysis software to exchange signals from the corresponding physical substructure experimental setup. If the element is a two-force member, it requires a pair of force and displacement feedback signals and the corresponding tangent stiffness to construct the stiffness matrix for iterative calculation of the whole model. In HHS software, the reference displacement signal can be transmitted to the control software ALC as a reference command signal for any pre-defined PID controllers. ALC can also send the experimental force feedback signal, tangent stiffness feedback signal, and experimental error feedback signal back to the HHS analysis software.

The model assumes that all of the structural components of the existing RC protype building such as beams, columns, and wall elements are modeled as elastic beam-column elements. The retrofitted RC shear wall with opening in the middle bay of the first floor is modeled as a nonlinear experimental element. This assumption was made because the stiffness of the RC infilled shear wall is much greater than that of the other two spans of RC frames. Thus, the seismic base shear will be concentrated on the retrofitted span, and because the stiffness of the first floor increases after the retrofitting, the overall displacement response will be reduced. Columns were assumed to have better ductility than walls, which will be later examined through hybrid testing and compared the results with the previous shake table testing results. Hence, it is reasonable to assume that all beams, columns and infilled RC shear walls at the higher storeys remain elastic at smaller inter-story drift ratio.

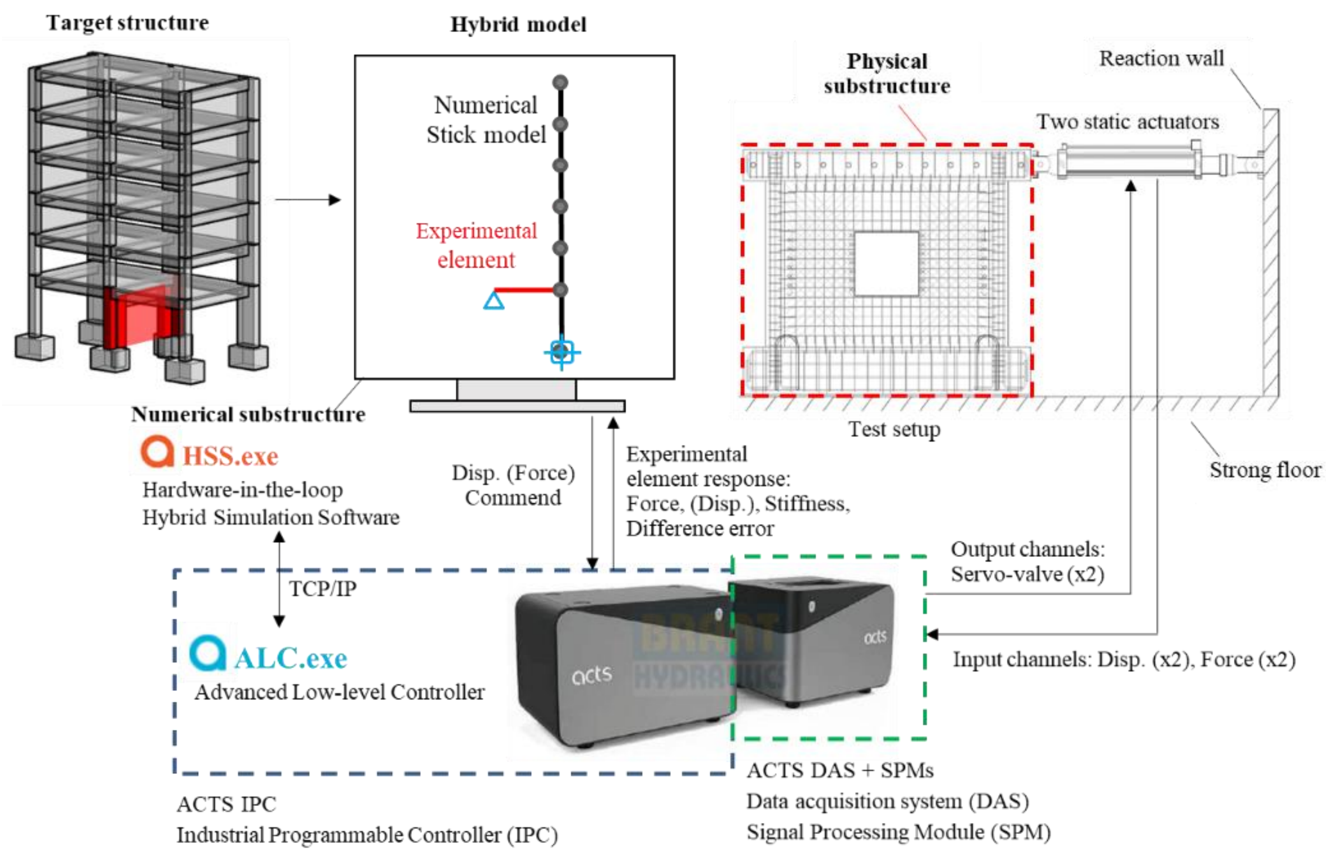


Figure 4. Hybrid simulation architecture diagram

HYBRID SIMULATION TEST SETUP

Fig 5. shows the test setup and the physical sub-structure of the retrofitted half-scaled RC frame. The physical sub-structure represents the middle bay in the first story retrofitted by infilled RC shear wall with a centered opening. The test setup has two static actuators in the horizontal direction with the maximum loading capacity of ±1000 kN have been used to provide up to 2000 kN lateral forces on the top of the physical sub-structure, the single story RC shear wall with a centered opening. Both actuators are controlled by servo-valves with the model of MOOG-072-1303 with the commend signal ± 50 mA. The LVDTs, model: BALLUFF MICROPLUSE BLT7-G110-M1050-Z-Ka02, are built within the actuators to measure feedback displacement signals. The LVDTs have the required 24 V DC excitation voltage and the feedback displacement signal is within the range of ± 10 V. Two load cells, Interface 4577CDS-1.2MN-B, are connected to the actuators respectively. The feedback force signals are amplified by 400 times and sent to the ACTS data acquisition system (ACTS DAS). The test setup for the physical sub-structure ignores the gravity load and the inter-storey moment between the first and the second floor. However, the deformation of the squat RC wall system would still be shear-dominant and have double-curvature moment distribution even when it is tested under the cantilever boundary condition [9], which is still match the assumption of rigid diaphragm.

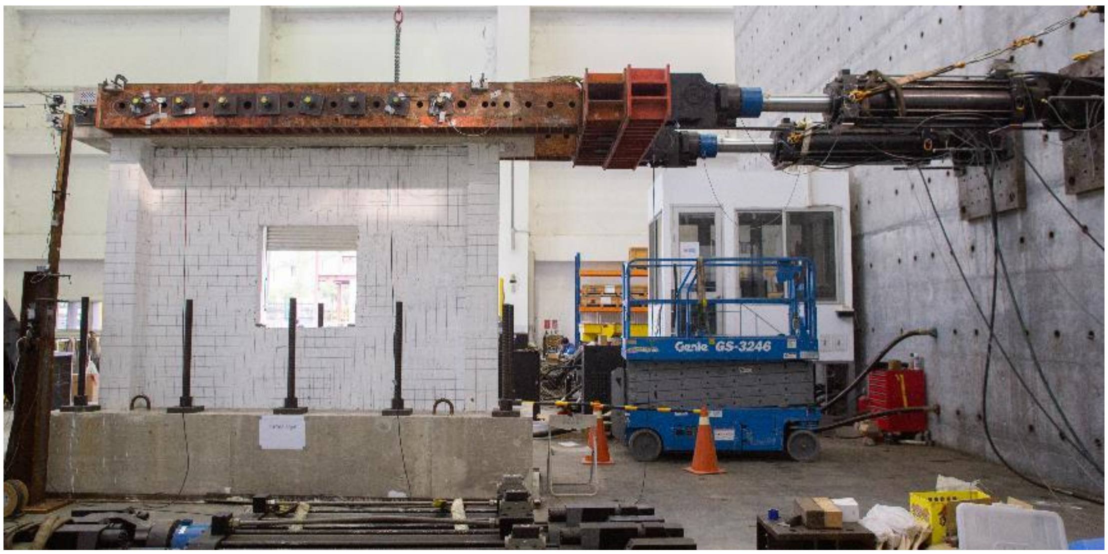


Figure 5. Test setup and the physical sub-structure of the retrofitted RC frame hybrid model

HYBRID SIMULATION OF THE SEISMIC RESPONSE OF RC FRAME RETROFITTED BY INFILLED RC SHEAR WALL WITH OPENING

The hybrid simulation experiment began with the ground motion, CHY063, with a PGA of 50 gal. Subsequent tests linearly amplified this ground motion to PGA of 100 gal, 200 gal, 400 gal, 600 gal, and 800 gal until the wall specimen suffered severe damage and the test was terminated after reaching its maximum strength. Fig 6. summarizes the force-displacement hysteresis response of the specimen under each testing ground motions. Table 2. summarizes the peak force and displacement response at both directions under each testing ground motion. In summary, during the 50 gal and 100 gal stages, only minor cracks appeared in the protective layer of the specimen, and the force and displacement hysteresis curves remained quite linear. The initial stiffness of the specimen under the 50-gal PGA ground motion was determined as 38700 kN/m, and the maximum displacement in both positive and negative directions was 1.2 mm. As the opening wall specimen fatigued and cracked due to repeated loading, the steel bars inside the shear wall began to exhibit strength. Therefore, after loading the CHY063 seismic wave with 100 gal, the stiffness of the specimen increased to 40300 kN/m (an increase of approximately 5% in initial stiffness). The stiffness increasing after cracking can be observed from the hysteresis loop shown in Fig 6(b), where slight pinching behaviour can be also observed. The maximum positive and negative displacements in this loading stage were 8.3 mm and -7.89 mm, respectively.

After the 400 gal PGA earthquake event, Fig 7(a) shows more cracks on the wall panel of the specimen, and the concrete was crushed at the upper right corner wall panel, causing diagonal shear cracks around the opening and horizontal flexural cracks at the top of the column. The maximum residual crack width of the shear crack was about 1.0 mm, appearing in the horizontal wall segment just below the opening, and the maximum residual flexural crack width of the boundary columns was 0.15 mm.

The hysteresis loop of the specimen (Fig 6(d)) showed a significant pinching effect at this stage, but there was still no apparent stiffness softening.

The specimen suffered more severe damage under the CHY063 600 gal ground motion. At this stage, a shear slip appeared at the interface between the wall panel and the loading beam and the footing, resulting narrow horizontal cracks along the edge. A slight stiffness softening was observed from the hysteresis loop shown in Figh 6(e). The experiment was finally terminated during the intensity of 800 gal PGA, and the specimen was severely damaged at the two horizontal wall segments. Although the maximum strength of the specimen (1608 kN) was reached, it did not collapse. The two boundary columns and the vertical wall segments can still provide stable resistance capacity for the axial load. The specimen still had about 90% residual strength, and the failure mode of the specimen was diagonal shear failure of the horizontal wall segments. After reaching the maximum strength, the stiffness of the specimen decreased significantly. In the subsequent aftershock loading stage, the residual stiffness of the specimen was approximately 2/3 of the initial stiffness.

COMPARISSON OF HYBRID TEST RESULTS AND SHAKE TABLE RESULTS

Fig. 8(a) shows the maximum storey displacement distribution of the simulated 7-storey RC prototype building with on one bay at the first floor retrofitted by the infilled RC shear wall with opening. The lateral deformation is concentrated in the lower stories and the maximum drift ratio shown in Fig 8(b) is not greater than 2%, which implies that the assumption of elastic columns and the elastic upper stories is valid. The proposed hybrid simulation architecture can be implemented to evaluate the seismic performance of the structure with the feature of soft and weak stories and retrofitted by relatively stiff structural components, such as RC shear wall infills. Fig 8(b) also demonstrates the comparison of the prototype building with and without retrofitting. The maximum inter-storey drift ratio can be reduced below 2% while the original storey drift ratio reached 14% can caused the instability and collapse.

CONCLUSIONS

The hybrid simulation testing using two-actuator test setup is demonstrated. The proposed simplified lump-mass stick model is validated to be sufficient for modeling the numerical substructure for the hybrid testing and the simplification assumptions are verified during the conducted hybrid simulation testing. The innovative retrofitting technology of the specially reinforced infilled RC shear wall with openings is tested to have a preferred failure mechanism which is a significant improvement compared with the conventional RC shear wall with openings. The failure hierarchy can be shifted to the horizontal wall segments, providing the similar behavour as the coupling beam. The healthy vertical wall segments and boundary columns can provide better resistance for the axial load and prevent the whole system from collapse. The hybrid simulation results is also compared with the shake table results, showing that the systematic drift profile can be significantly reduced by only strengthen and stiffen the critical soft and weak storeys. The proposed retrofitting strategy is proved to be efficient and cost-saving.

ACKNOWLEDGMENTS

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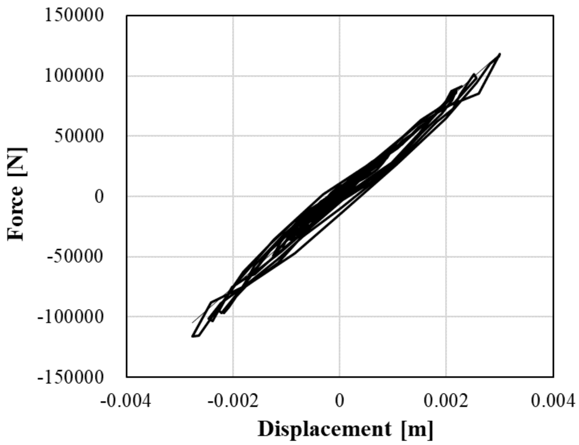
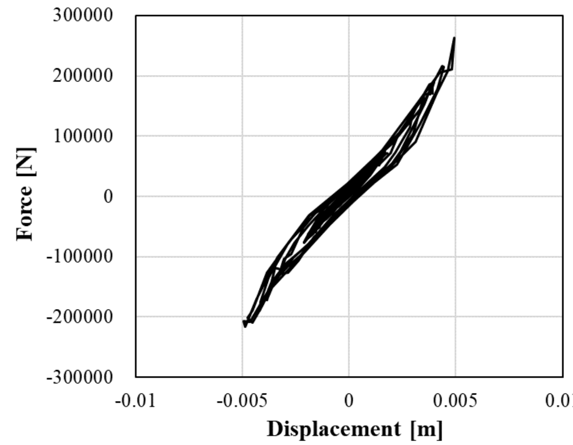
Table 2. Summary of hybrid simulation testing results of the RC shear wall with opening.

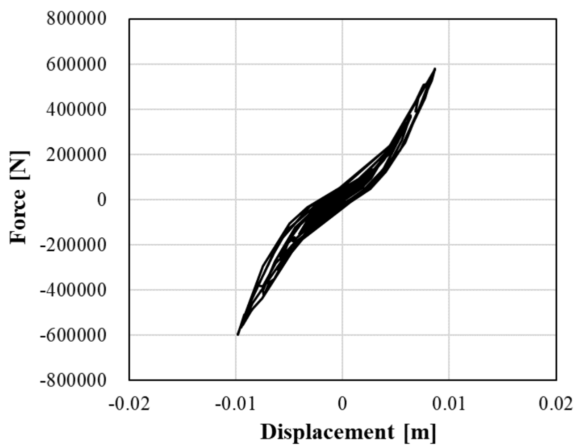
PGA [gal]	Maximum 1F displacement in positive direction	Maximum base shear in positive direction	Maximum 1F displacement in negative direction	Maximum base shear in positive direction
	$Disp.^{+}$ [mm]	$Force^{+}$ [kN]	$Disp.^{-}$ [mm]	$Force^{+}$ [kN]
50	3.0	118.3	-2.8	-116.0
100	4.9	262.6	-4.9	-259.4
200	8.7	579.8	-9.8	-596.7
400	18.2	1311.9	-20.9	-1246.4
600	30.4	1544.0	-25.7	-1537.1
800	45.7	1604.8	-31.9	-1608.8



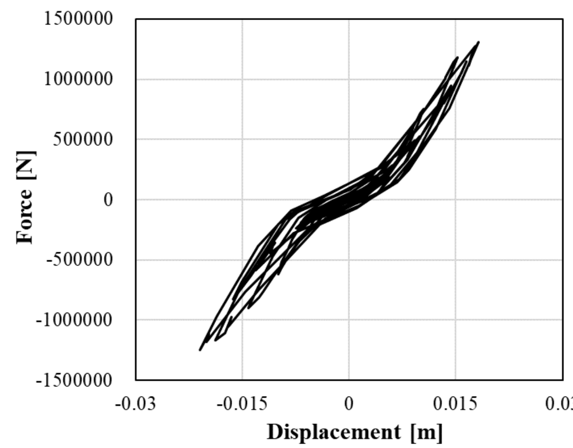
(a) CHY063-50gal



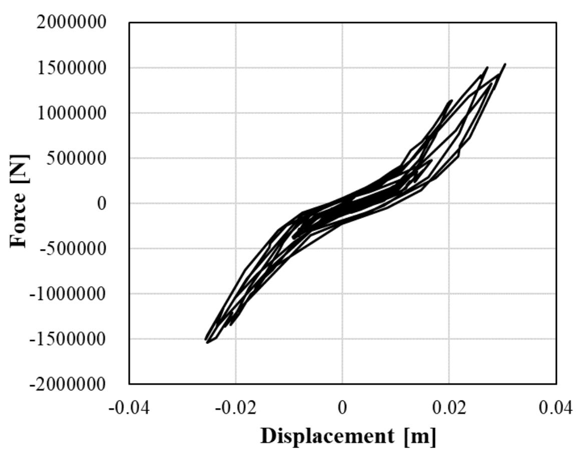
(b) CHY063-100gal



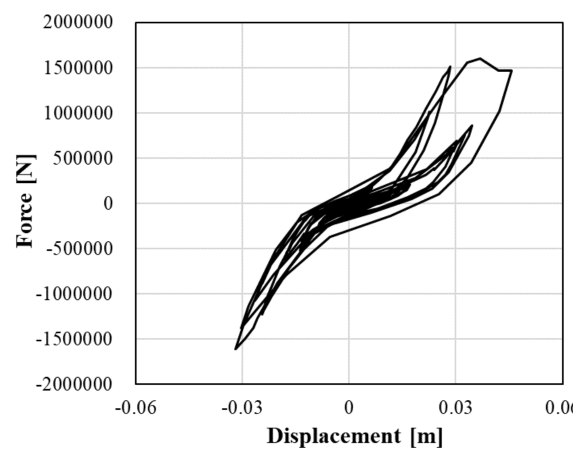
(c) CHY063-200gal



(d) CHY063-400gal



(e) CHY063-600gal



(f) CHY063-800gal

Figure 6. Force-displacement hysteresis curves of the tested substructure under the ground motion, CHY063, with PGA of (a) 50 gal, (b) 100 gal, (c) 200 gal, (d) 400 gal, (e) 600 gal, and (f) 800 gal

(a) *(b)* *(c)*

Figure 7. Crack pattern of Front view of the RC wall with opening after (a) CHY063 400 gal, (b) CHY063 600 gal, and (c) CHY063 800 gal.

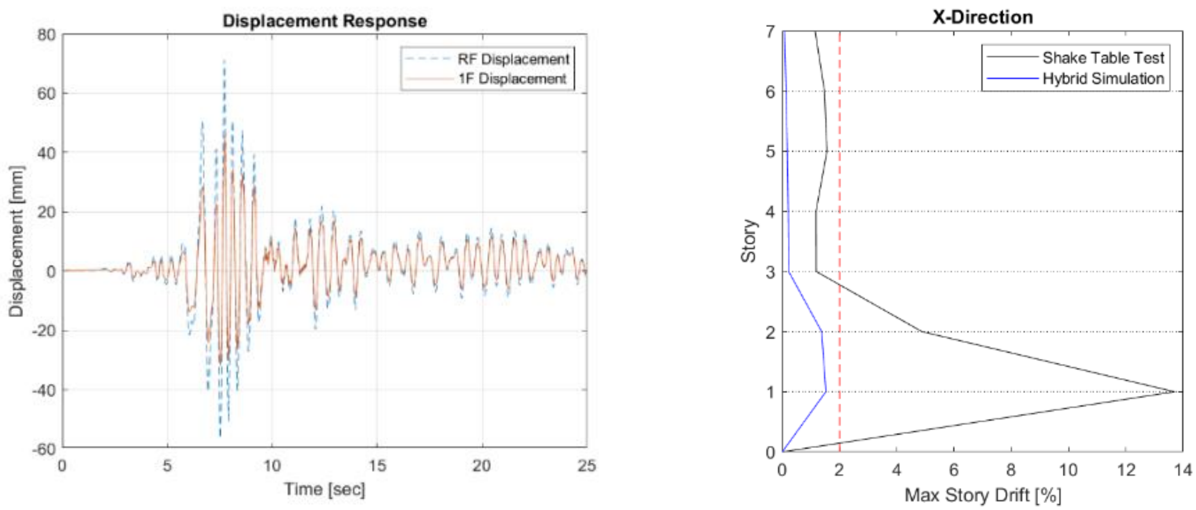


Figure 8. Testing results of the retrofitted protype RC building after CHY063 800 gal, (a) first-storey and roof displacement history, and (b) storey drift ratio of the prototype building with and without retrofitting.

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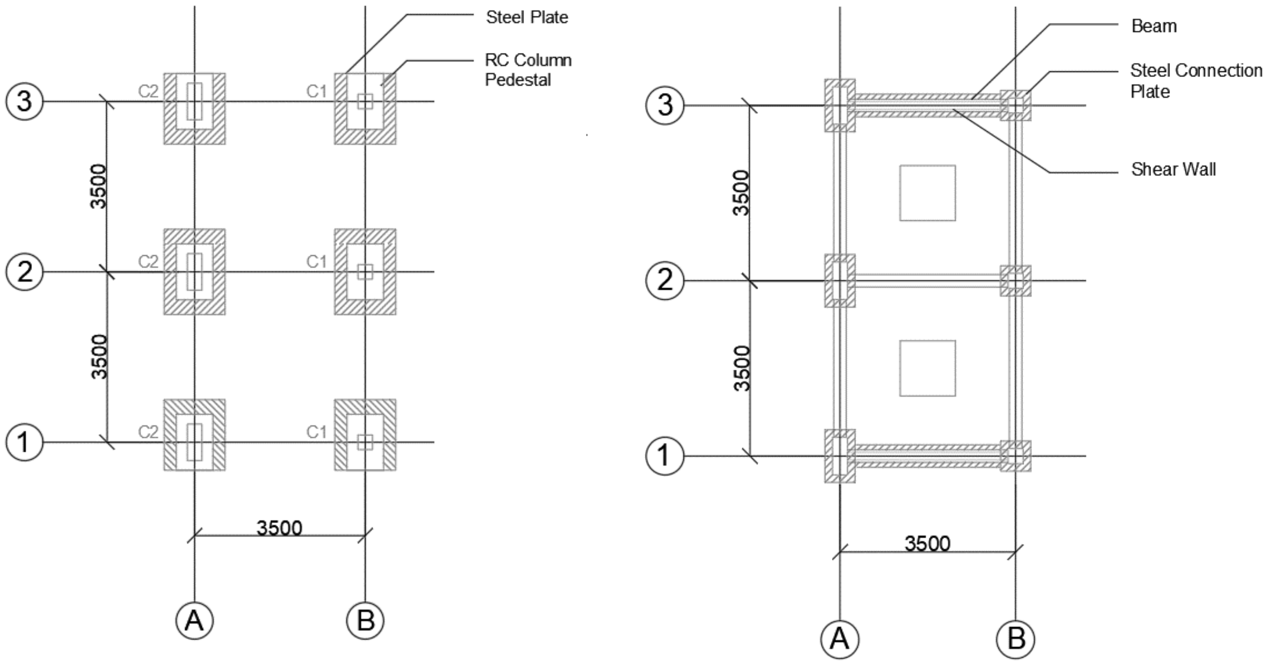
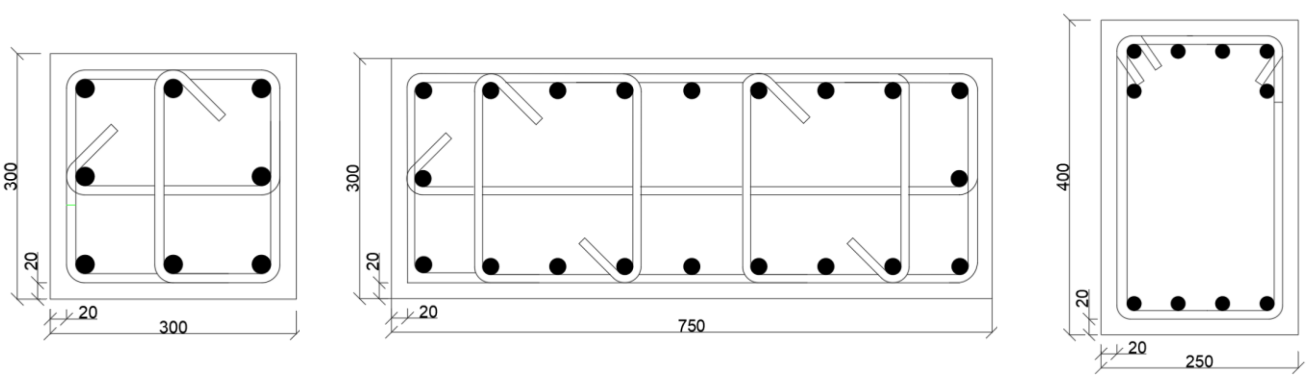
APPENDIX

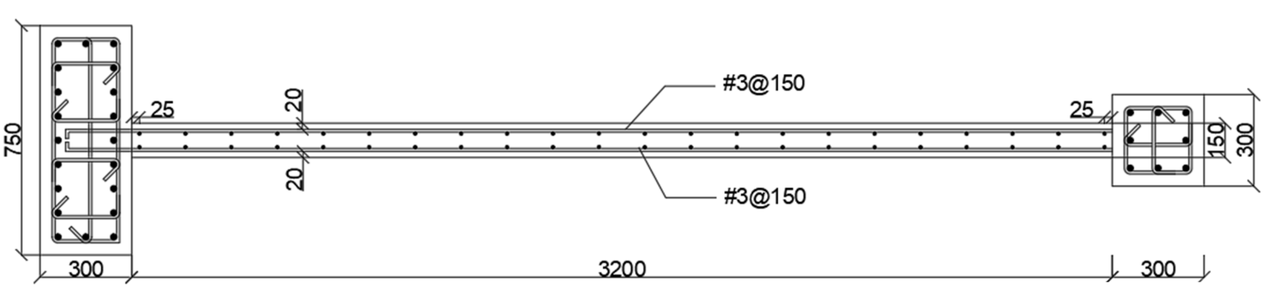


(a) (b)

Figure A1. Plan view of the 7-storey prototype building (a) the first two stories, and (b) the third to seventh stories. [unit is in mm]



(a) (b) (c)



(d)

Figure A2. Cross-sectional dimensions of (a) square columns, (b) rectangular columns, (c) beams, and (d) infilled shear walls. [unit is in mm]