HYBRID SIMULATION FOR EARTHQUAKE RESPONSE OF MULTI-STOREY BUILDINGS

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Keywords: hybrid testing; multi-storey structures; reinforced concrete; heavy timber; multi-hazards

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Recently, a centre for multi-hazard infrastructure resilience research has been established at Carleton University. This centre aims to study the effects of multiple natural hazards (e.g. earthquake, blast, fire, and wind) on civil engineering infrastructure. A major focus of this research centre is on hybrid simulation and its ability to capture the performance of large-scale civil engineering structures under different load effects. Two ongoing studies currently underway at Carleton are focused on the use of hybrid simulation to capture the earthquake response of multi-storey structures. The two prototype structures are a 3-storey reinforced concrete (RC) shear wall building and a 7-storey heavy timber building located in Victoria, British Columbia.

In the RC structure, the shear walls are designed as moderately ductile shear walls, with sufficient shear reinforcement and confinement of the boundary elements to prevent premature shear failure and promote a ductile response. Figure 1a shows a typical three-storey shear wall under consideration in this study. The goal of the study is to use hybrid simulation to capture the local failure mechanisms of the first storey shear wall while also understanding the global seismic response of the structure. In addition, the study also focuses on the challenges associated with using hybrid testing to capture the response of stiff structural elements, such as a RC shear wall and ways that we can overcome these challenges in the future.

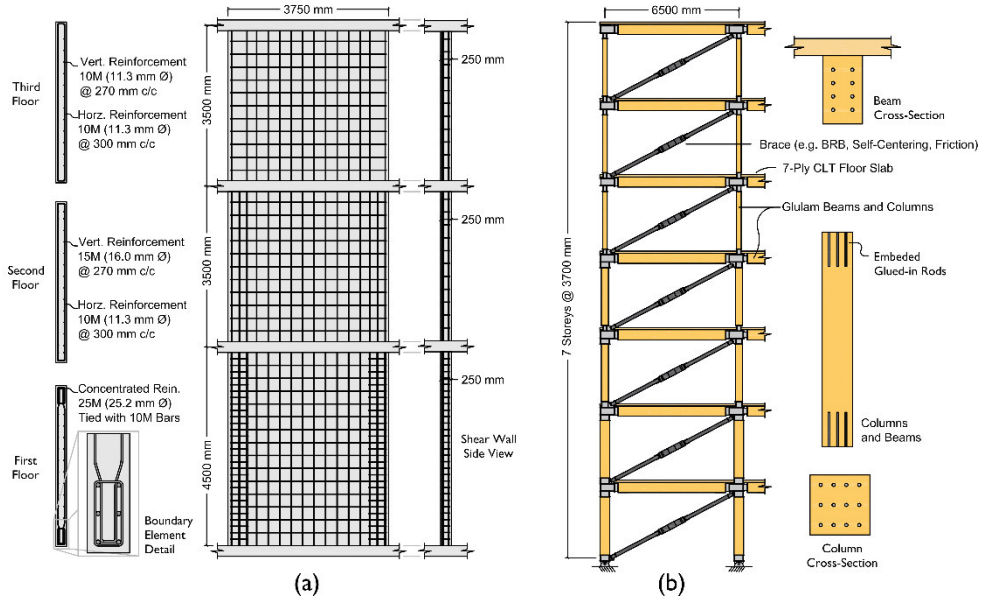

Figure 1: (a) RC structure: typical shear wall detail; (b) Heavy timber structure: typical braced frame detail.

The prototype heavy timber building is a seven-storey four-bay braced frame that uses an innovative connection detail to form a hybrid timber-steel lateral load resisting system. This newly developed structural system is aimed at meeting the growing demand for taller wood structures around the world while at the same time addressing the need for adequate earthquake resistance. The structural system combines traditional glue-laminated (glulam) heavy timber beams and columns with small, selective amounts of steel at critical beam-column connections. To fasten the glulam and steel components together, a glued-in steel rod connection is used (Fig. 1b). This connection is designed to transfer the forces to the timber elements in the strong parallel-to-grain direction. The goal in the design of this structural system is to incorporate advanced bracing systems such as buckling restrained braces (BRBs) or self-centering braces into heavy timber braced frames. The timber-steel connection design forms a stronger connection and allows the beam-column connections to transfer the high forces associated with these types of advanced bracing systems. The goal of the study is to further investigate the seismic performance of the newly proposed timber-steel structural system, including the local behaviour of the steel-timber connection detail and the global seismic response of the braced frame.

Figure 2 shows the physical and analytical substructures for the hybrid simulation of both prototype structures. In the RC shear wall structure, the first storey shear wall is selected as the physical substructure, such that the exact nonlinear response of the plastic hinge region can be determined, including local failure mechanisms that are difficult to capture without a very detailed finite element model. The remaining two storeys of the shear wall are modelled numerically using multi-layered shell elements in OpenSees, forming the analytical substructure. This substructuring approach assumes that the response of the upper storeys will remain at or near elastic, such that their response can be accurately captured in the finite element model. In contrast to the RC shear wall structure, which is designed to dissipate seismic energy through the formation of a plastic hinge, the innovative heavy-timber structure uses a friction bracing system. The friction brace is designed to dissipate energy during a major earthquake while the surrounding heavy timber elements and steel connections are designed to remain elastic. In the hybrid simulation, the first strorey braced-bay is experimentally tested in the lab, forming the physical substructure while the remaining six storeys are modelled numerically in OpenSees. Elastic beam column elements are used to model the heavy timber beams and columns and nonlinear two-node links are used to model the friction braces. The first storey braced frame is selected as the physical substructure because the connections in the first storey are under a larger demand compared with those located in the upper stories of the structure, and thus are assumed to have a larger impact on the global seismic response of the SFRS. At this time, the hybrid simulation experiments are in progress, as the establishment and procurement of equipment in Carleton's new multi-hazard research facility is ongoing.

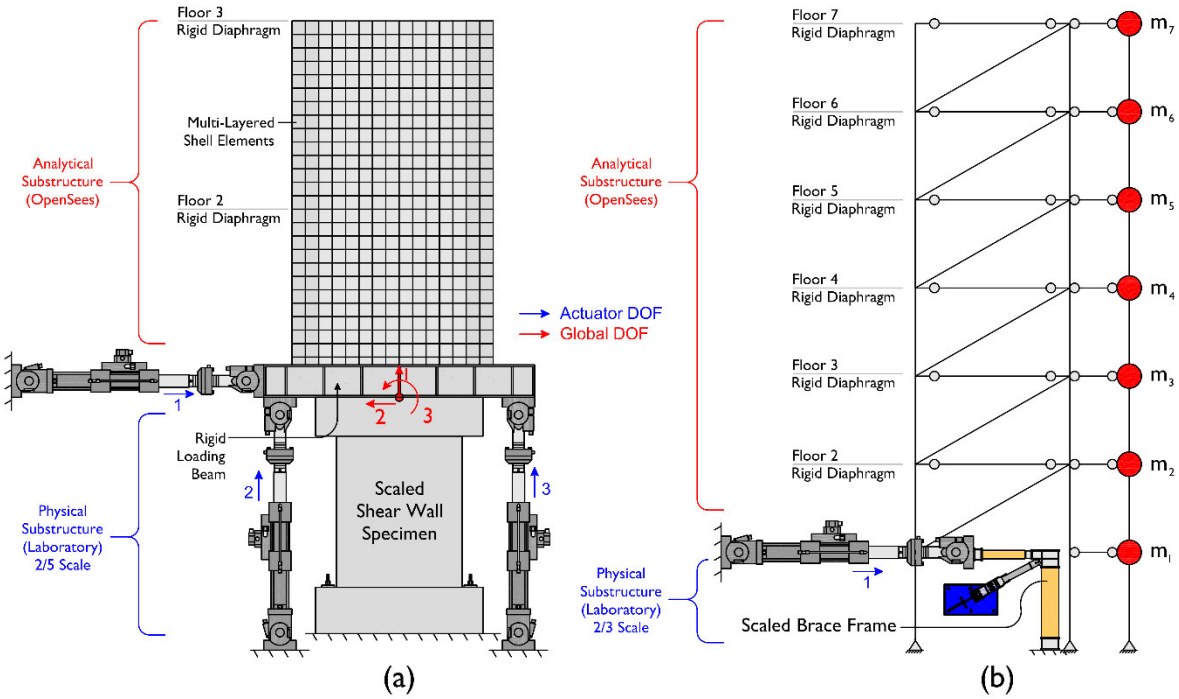

Figure 2: Substructured finite element models: (a) RC shear wall; (b) Heavy timber braced frame.

A TWO LOOP CONTROL METHOD FOR SHAKE TABLE TESTS COMBINING MRAC AND TVC

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Keywords: Shake table test; Model reference adaptive control; Lyapunov stability; Three-variable control

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Shake table test is the most direct experimental methods to evaluate structural performance in earthquake engineering. The purpose of the control systems in shake table is to reproduce reference accelerations recorded during earthquake. In this study, a two loop control method, consists of an inner-loop three-variable control (TVC) controller and an outer-loop model reference adaptive control (MRAC) controller based on Lyapunov stability theorem, is proposed to improve the acceleration performance of shake table system and enhance the robustness of the system against the control structure interaction (CSI) effects and the uncertainties of specimen. The inner-loop TVC controller can not only improve acceleration tracking performance but deal with the initial transient problem of adaptive algorithm, and the outer-loop MRAC controller can online adaptively adjust the control parameters to obtain desired output and avoid causing premature damages to the specimen.

The scheme of two loop control method is shown in Fig. 1, $u_m(t)$ is the input of reference model which is commonly the earthquake acceleration time-history record, $u_s(t)$ is the control signal of the controlled plant including TVC controller and shake table system, $\boldsymbol{x_m}(t)$ and $\boldsymbol{x_s}(t)$ are the state vectors of controlled plant output and reference model output, respectively, $\boldsymbol{K_p}$ and $\boldsymbol{K_u}$ are the adaptive gains, and $\boldsymbol{e_x}(t)$ is the state error.

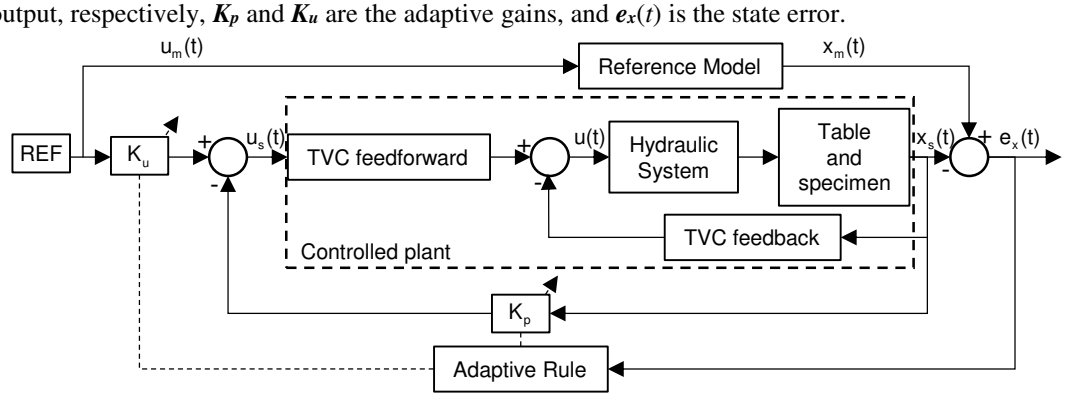

Figure1. The schematic of two loop control method

The inner-loop TVC can be separated to feedforward and feedback controllers. The feedback part can improve the control stability by feedback loops, and the feedforward part can extend acceleration frequency and improve reference tracking accuracy by feedforward gains. The outer-loop MRAC controller works on the principle of adjusting the parameters by measuring the output difference between controlled plant and reference model, and the controlled plant will follow the behavior of reference model after the adaptive parameters converge to the optimal solution. In the proposed method, the reference model is simplified, and the linear systems, e.g. the hydraulic system and the TVC controller are neglected. The MRAC algorithm does not require the controlled plant to be described accurately, making it more appropriate for shake table system under different payloads. A positive definite quadratic Lyapunov function which contains the state error and the error signal of controller parameters is used

$$V(t)=\boldsymbol{e_x}^{\mathrm{T}}(t)\boldsymbol{P}\boldsymbol{e_x}(t)+tr\{\boldsymbol{K_p}^{\mathrm{T}}[\boldsymbol{e_x}(t),t]\boldsymbol{\Gamma_p}^{-1}\boldsymbol{K_p}[\boldsymbol{e_x}(t),t]\}+tr\{\boldsymbol{K_u}^{\mathrm{T}}[\boldsymbol{e_x}(t),t]\boldsymbol{\Gamma_u}^{-1}\boldsymbol{K_u}[\boldsymbol{e_x}(t),t]\} \tag{1}$$

where, $\boldsymbol{P}$ is a symmetrical positive definite matrix, and $\boldsymbol{\Gamma_p}^{-1}$ and $\boldsymbol{\Gamma_u}^{-1}$ are symmetrical positive definite constant matrices with appropriate dimension. Because Lyapunov function is positive definite and the derivative of Lyapunov function is negative definite, the Lyapunov stability theorem guarantees that the state error will approach 0 asymptotically and the tracking error will also asymptotically vanish. And the MRAC controller parameters can be obtained as

$$\boldsymbol{K}_p[\boldsymbol{e}_x(t),t]=-\int_0^t \boldsymbol{\Gamma}_p \boldsymbol{B}_s^{\mathrm{T}} \boldsymbol{P} \boldsymbol{e}_x(\delta) \boldsymbol{x}_s^{\mathrm{T}}(\delta) d\delta + \boldsymbol{K}_p(0),\ \boldsymbol{K}_u[\boldsymbol{e}_x(t),t]=-\int_0^t \boldsymbol{\Gamma}_u \boldsymbol{B}_s^{\mathrm{T}} \boldsymbol{P} \boldsymbol{e}_x(\delta) u_m^{\mathrm{T}}(\delta) d\delta + \boldsymbol{K}_u(0) \quad (2)$$

where, $\boldsymbol{B}_s$ is input matrix of the controlled plant. Numerical simulation of a small-scale shake table, consists of a 6000 kg rigid table and a single degree of freedom specimen, was performed in MATLAB/Simulink to verify the effectiveness, and a conventional control method combining PID and TVC controllers is also implemented for comparison. The specimen was assumed linear elastic and the mass of specimen for reference model of MRAC is designed as 6 kg, which is 1/1000 table mass, to minimize the interaction caused by dynamics of the specimen. The parameters of PID controller and the initial value of MRAC controller are optimized by Genetic algorithm. For the optimization, the bare table case subjected to a synthesis ground motion NAcc1 is adopted. Note that the parameters will keep unchanged for PID control, but will only serve as initial value and automatically adjust for MRAC. Simulations for the five cases, in which the mass of the specimen are zero, 600 kg, 2500 kg, 7500 kg, and 10000 kg, were carried out using ten ground motions including Hachinohe, Kobe, Northridge, El Centro, Taft and another five synthesis ground motions, NAcc1 to NAcc5. To generalize the conclusion, Table 1 compares the median and standard deviation of the root mean square (RMS) between the conventional control and the proposed method for the five cases in both time and frequency domains, and the RMS is normalized against the maximum absolute value of reference acceleration. From Table 1, it can be found that both median value and standard deviation of the proposed method are smaller than those of the conventional method in all cases. In addition, comparing the RMS of bare table case with that of the case with maximum payload, it increases about 15% for the PID controller, while the MRAC only increases about 7%. The results show that the proposed controller has much better performances than the conventional PID controller, and it not only improve the accuracy of shake table system but provides good robustness against the CSI effects and the uncertainties of specimen. Fig. 2 shows the adjustment of adaptive parameters for two loop control method. The mass of specimen is considered as 7500 kg, and the ground motion recorded in Northridge is taken as reference signal. From Fig. 2, it can be observed that the values of adaptive parameters vary with time during the simulation process, and gradually become stable when the difference of output between controlled plant and reference model becomes smaller. The adaptive algorithm will achieve high accuracy performance after the parameters converge to the optimal solution, but the initial parameters variation may exhibit poor response. In this study, the TVC controller is used as an inner-loop controller to deal with the initial transient problem, and the simulation results show that the tracking error of proposed method is smaller than MRAC controller, and only uses half of time to convergence.

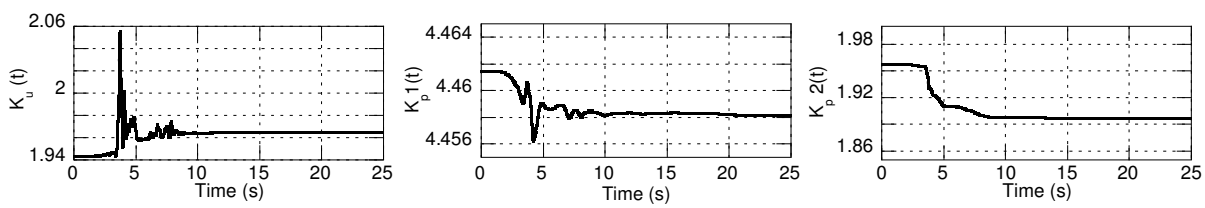

Figure 2. The adjustment of the adaptive parameters for the Northridge earthquake.

Table 1. The median and standard deviation of RMS for acceleration tracking error.

Specimen mass (kg)		Time domain RMS (g)		Frequency domain RMS (g^2/Hz)	
		PID+TVC	MRAC+TVC	PID+TVC	MRAC+TVC
Bare table	MED.	5.708	1.847	2.739	0.862
	STD.	1.439	1.022	1.593	0.508
600	MED.	5.793	1.829	2.819	0.855
	STD.	2.163	0.982	1.644	0.506
2500	MED.	5.926	1.985	2.590	0.864
	STD.	1.553	1.222	1.588	0.495
7500	MED.	5.976	2.219	2.639	0.950
	STD.	1.652	1.253	1.575	0.466
10000	MED.	6.004	2.262	3.059	0.973
	STD.	1.872	1.471	1.681	0.460

An innovative two loop control method consists of an inner-loop TVC controller and an outer-loop MRAC controller based on Lyapunov stability theory is presented in this study. The proposed method can adaptively adjust the parameters during the test, and the controlled plant will follow desired reference signal without causing premature damages to the specimen. The numerical simulation results show that the two loop control method outperforms the fixed-gain conventional controller for acceleration control in both time and frequency domains, has good robustness against the uncertainties of specimen and the CSI effects in different payloads, and achieves high accuracy performance more quickly than MRAC controller.

EXPERIMENTAL EVALUATION OF THE STABILITY RESPONSE OF STEEL BRACED FRAME COLUMNS USING HYBRID SIMULATION

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Keywords: Large-scale testing; Multi-tiered steel braced frame; Column buckling; Pseudo dynamic hybrid simulation.

Objectives

Hybrid simulation is an economical structural testing technique in which the critical part of the structure expected to respond in the inelastic range is tested physically whereas the rest of the structure is modelled numerically using a finite element analysis program. This study describes the application of hybrid simulation for steel I-shaped columns in Multi-Tiered Braced Frame (MT-BFs) structures. Specifically, the buckling response of MT-BF columns under severe seismic loading was investigated. A two-tiered concentrically braced frame part of an industrial building located in coastal California was selected. The frame was designed in accordance with the 2010 Seismic Provisions in the U.S. A full-scale W250x101 column part of the two-tiered concentrically braced frame was physically tested while the rest of the frame was numerically analysed using the *OpenSees* finite element program. Physical testing was carried out using an advanced multi-directional hybrid testing system (MDHTS) at Polytechnique Montreal. The MDHTS is an advanced structural testing system which is capable of applying complex loading and boundary conditions along six degrees of freedom to the test specimens. The features and capabilities of the MDHTS were first described. The development of the hybrid simulation was then presented. Finally, the main findings of the hybrid simulation of MT-BF structures were discussed.

Results

Schematic of the hybrid simulation loop used for the pseudo-dynamic hybrid simulation of the MT-BF structure is shown in Fig. 1a. It includes two main portions: the computational driver, or the finite element model, and the physical test portion that includes the FlexTest controller and experimental equipment. In the hybrid simulation, physical testing was performed on the first-tier column segment of the structure. The remaining portion of the frame was reproduced in the computer model built in the *OpenSees* environment. The *OpenFresco* program was used as a middleware in this test. The hybrid simulation was performed using the MTS CSI system, which links the middleware and MTS Flextest controller. At every analysis step of the simulation, the relative displacements between the two column ends, as predicted by the *OpenSees* analysis, are sent to the controller in the laboratory so that the actuators of the MDHTS can impose them to the test specimen by means of the upper platen. The measured forces from the actuators, as calculated at the system control point, are then fed back to the controller and sent to the *OpenSees* numerical model to determine the structure displacements in the subsequent step.

The hybrid simulation started with the application of the gravity loads at top of the two braced frame columns as a dynamic analysis. The portion of the gravity load resisted by the test specimen was simultaneously applied to the column in the laboratory. The nonlinear response history analysis was then performed under the 1971 San Fernando LA - Hollywood Storage record, which was scalded to match the MCE level earthquake, by controlling the three translational DOFs at the control point of the test specimen. The rotational DOFs except torsion were controlled by load and set to zero to create a pinned connection at the top end of the specimen, which represents the base of the braced frame column. A continuous testing approach with a ramp time of 2.0 s was employed to provide a smooth movement of the actuators, compensate for possible delays, allow the numerical model to complete the numerical integration step, and allow the test controller to perform data communication between the physical and numerical substructures. Large out-of-plane deformations were observed at 16.4 s of the ground motion, which was accompanied by a loss of the axial load-carrying capacity of the column. Thus, column buckling (Fig. 1b) occurred as a result of combined axial compression load and large in-plane displacement demands.

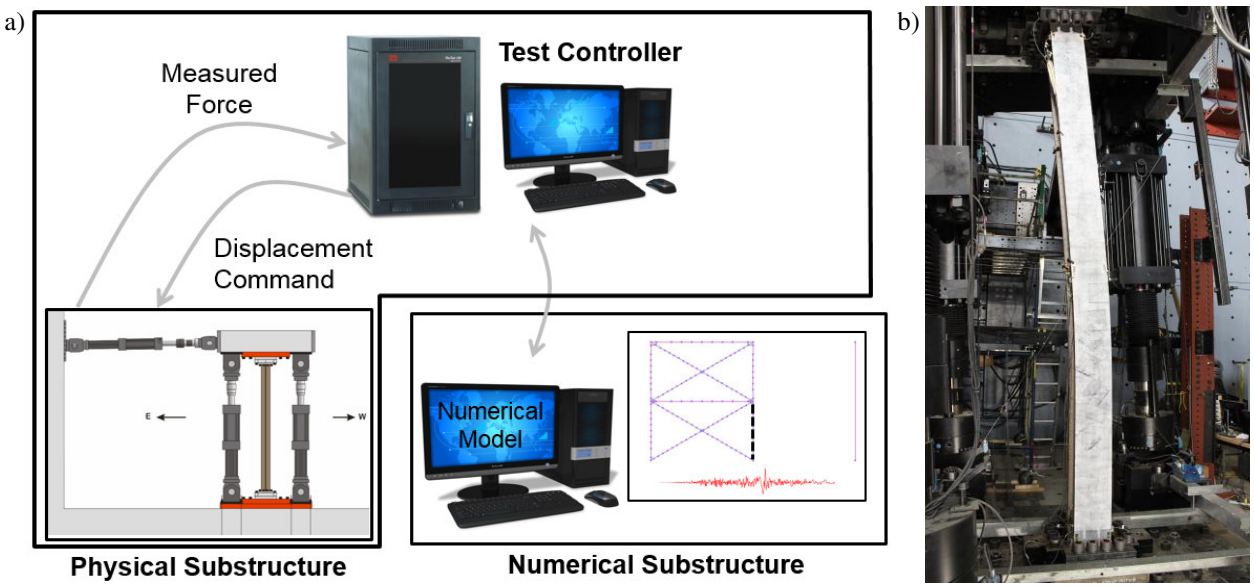

Fig. 1: a) Hybrid simulation loop; b) Column deformed shape at the initiation of buckling.

Conclusions

The test results show that the pseudo-dynamic hybrid simulation is a cost-effective solution for the large-scale testing of steel braced frame columns that are expected to fail by inelastic buckling due to complex loading and boundary conditions that are imposed as a result of the nonlinear seismic response of the structure. Furthermore, the hybrid testing technique is an effective experimental tool to generate reliable data on column stability limit states. Finally, the results from the hybrid simulation confirmed the findings of previous numerical simulations to assess the seismic response of columns in steel multi-tiered braced frames.

Additional work is needed to further improve the efficiency of hybrid simulations for the study of complex limit states such as column inelastic buckling in structures subjected to highly nonlinear seismic response such as steel braced frames and moment-resisting frames.

EXPERIMENTAL INVESTIGATION ON SEISMIC BEHAVIOR OF PVA-STEEL HYBRID FIBER REINFORCED CEMENTITIOUS COMPOSITE BEAM-COLUMN JOINTS

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Keywords: seismic performance; beam-column joint; fiber reinforced cementitious composite; reverse cyclic load

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Joints in the frame structure are subject to the combination effect of axial, flexure and shear forces, which makes them the most vulnerable parts of the frame structure. The brittle nature of concrete makes it hardly to restrain the shear crack formation and the slip of the longitudinal reinforcement embedded in the concrete. One conventional way to enhance the seismic performance of the joints is to increase the transverse reinforcement in the joint region, which is sometimes not feasible in construction. As an another way to fix this problem, mixing fibers in concrete enhances the tensile strain capacity and improve the brittleness of the concrete by the bridging of fibers, which makes it possible in restraining the development of shear crack effectively in the joint region. However, the formation of cracks is a continuous development process with the deformation of joints. Mixing just single type of fiber can only effectively control the development of cracks which correspond to the fiber dimension. Based on the different stages of the crack formations, the whole process of the crack formation is controlled by the combination of different dimensional fibers.

In order to understand the advantage the hybrid fiber reinforced cementitious composite (HyFRCC), one conventional reinforced concrete beam-column joint specimen and five HyFRCC joint specimens with different mix designs were cast and reverse cyclic tests were conducted to investigate the failure characteristics, hysteresis behavior and ductility of all specimens. The displacement ductility indices of specimens are shown in Figure.1.The skeleton curves of specimens are shown in Figure.2. The cumulative energy dissipation curves of specimens are shown in Figure.3.

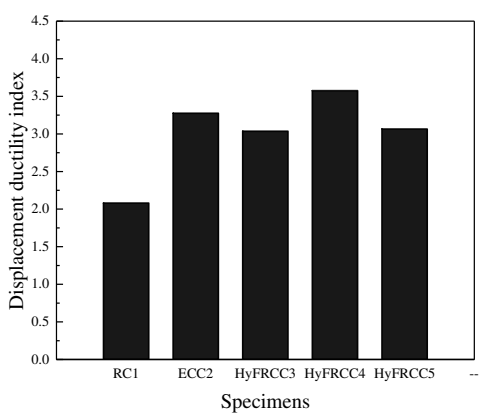

Figure 1. Specimens displacement ductility indices

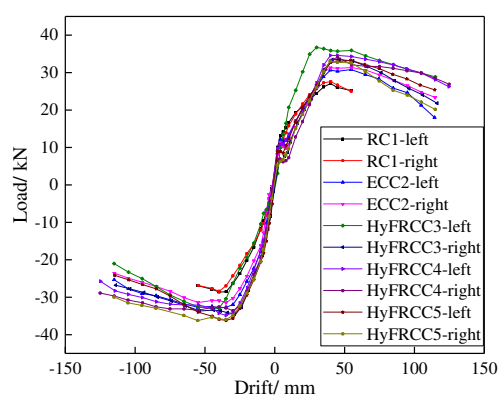

Figure 2. Backbone curves of the specimens

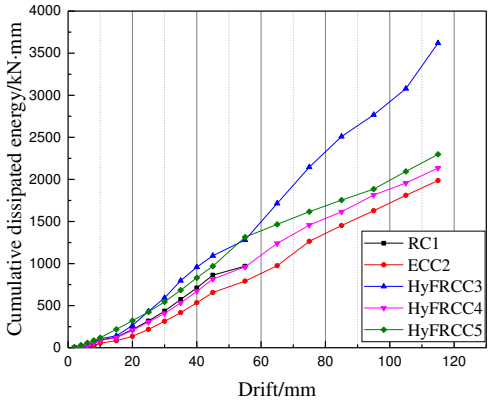

Figure 3. Cumulative energy dissipation curves of specimens

Experimental results show that the addition of fibers in concrete can significantly enhance the compressive strain energy at the prior and post peak loading. The strain energy of the specimen with only PVA fiber and with hybrid PVA and steel fibers is respectively 1.46 and 1.42 times of the strain energy of the ordinary concrete specimen at the prior peak loading, 6.58 and 8.02 times at the post peak loading, respectively. The ductility of the specimen with only PVA fiber and with hybrid PVA and steel fibers is 1.57 and 1.55 times of the ductility of the ordinary concrete specimen, respectively. The experimental results of hybrid PVA-steel fiber reinforced cementitious composite specimens indicate that the ductility decreases with the increase of the steel fiber content while the total fiber content is constant. The ductility of the specimen decreases with the increase of the total fiber content, and the addition with steel fiber can effectively improve the strain energy of the matrix after the post peak loading in compression. Mixing steel fiber into PVA fiber reinforced cementitious composite can effectively restraining the development of larger scale cracks.

SHAKE TABLE STUDY ON THE SEISMIC RESPONSE OF EQUIPMENT ON WHEELS IN BASE-ISOLATED HOSPITALS

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Keywords: Nonstructural components; Medical equipment; Wheel and Casters; Base isolation; Shake table tests

About one-third of equipment and contents in a typical hospital are supported on wheels/casters. The concern with such equipment during earthquakes is that they might exhibit large movements, which could tear off or disconnect the equipment's electric plugs or connections to piped hospital oxygen, medical air, and nitrous oxide. This could lead to loss of functionality of the equipment and possible death. Moreover, large displacement may result in collision with medical personnel or other equipment and objects. In the case of heavy equipment on wheels, a collision with people in the vicinity of the equipment may result in injury.

Seismic isolation has become the preferred choice for protecting hospitals and other critical facilities against earthquakes. However, although isolation decreases floor accelerations, it increases the fundamental period of the structure. Since equipment on wheels/casters provide very low resistance to motion, they are likely more sensitive to floor displacements than to floor accelerations. This presentation will summarize the findings of a shake table study investigating the seismic response of medical equipment on wheels/casters, housed in (a) a conventional braced-frame hospital building, (b) a hospital building isolated by Lead Rubber Bearings (LRB), and (c) a hospital building isolated by a Triple Friction Pendulum (TFP) system. Two test specimens were used: an ultrasound machine weighting 272 kg which represents a typical heavy piece of medical equipment, supported on two wheels (rear) and two casters (front), and a cart loaded with typical light medical equipment (all together 23 kg), supported on four casters. The tested ultrasound featured a brake mechanism acting on the front casters only. The light hospital cart was supported on four twin wheel casters, the type typically installed on the majority of light-weight office and laboratory items. None of the casters of this particular cart had a brake mechanism, although similar casters with brake are also common.

A hypothetical four-story hospital building located in Los Angeles was designed according to the loading requirements of ASCE 7-05 for Site Class C. The fixed-base design featured a steel Special-Concentrically-Braced-Frame (SCBF) lateral load resisting system (Risk Category IV, and importance factor of 1.5) was designed according to the requirements of IBC2006, AISC360-05, and ASCE 7-05. The SCBF was designed with a response modification factor, over-strength factor, and drift ratio limit of 6, 2, and 1.5%, respectively. The isolated design for the hospital was based on a design with effective period of 2.5 s and damping ratio of 15% at the MCE level. This resulted in 49% reduction in the design base-shear. An Ordinary-Concentrically-Braced-Frame (OCBF) was used as the lateral force resisting system for the superstructure. The OCBF as designed to remain elastic.

A cascading analyses approach was followed in this study. First nonlinear time history analyses of elaborate nonlinear structural models of the three hospital designs were conducted in OpenSees for a suite of ground motions. These analyses produced floor acceleration histories which were in turn used as input for the shake table tests. The shake table tests were conducted at the Applied Dynamics Laboratory, McMaster University.

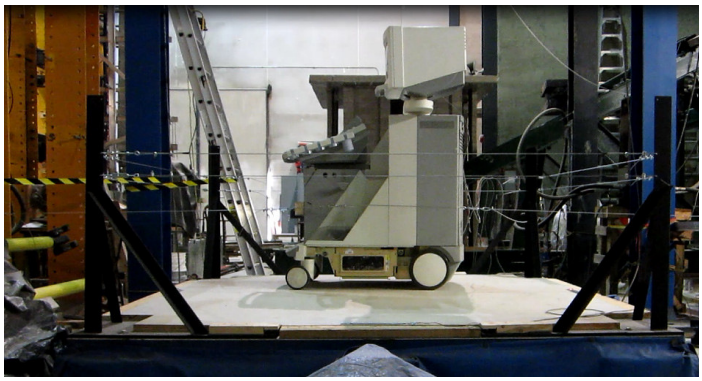

Figure 1. Ultrasound machine on simulated hospital floor surface built atop the shake table at Applied Dynamics Laboratory, McMaster University.

The equipment was placed directly on a simulated hospital floor surface constructed on the shake table (see Figure 1). The shake table tests were carried out under unidirectional excitation. The ultrasound was tested under two conditions: with locked and with unlocked casters. The casters of the hospital cart were not lockable, so it was tested only in the unlocked condition. Tests were performed with the ultrasound's wheels in the parallel, oblique, and perpendicular orientation with respect to the direction of excitation. In lieu of conventional contact sensors, a vision-based measurement system was used, where a video camera with a 2.7K resolution at a 60 fps rate was used to track the motion of LED lights affixed on the equipment.

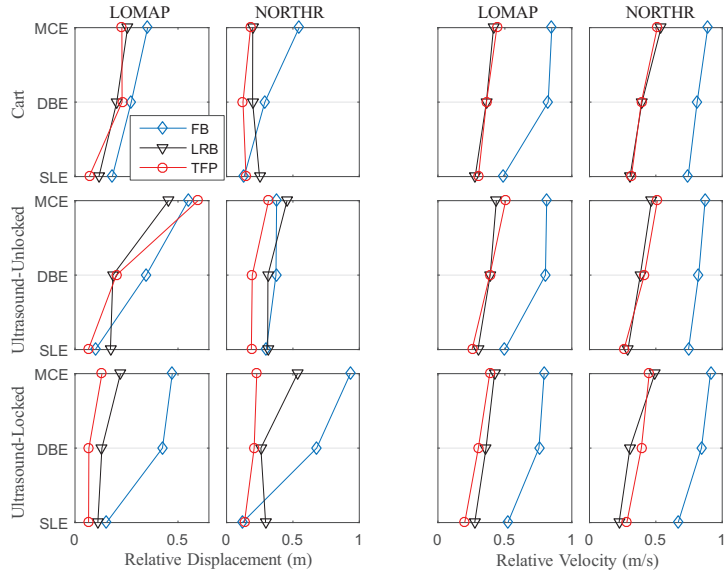

Figure 2. Comparison of peak displacement and velocity responses of the equipment on the 3rd floor.

The seismic response of the equipment placed at the 3rd floor, evaluated through shake-table tests will be reported in this presentation. Although the electronic functionality of the equipment was not assessed before/after the shake table test, there was no physical damage to the equipment (detachment of components or failure of any sort) as a result of the shaking. Furthermore, there was no notable rocking, and the main mode of response was rolling of the wheels and casters.

Figure 2 compares the peak responses under two earthquake motions. The left two columns plot the relative displacement and the right two columns show the relative velocity responses. It appears that base isolation in most cases, but not always, reduces the displacement response of the hospital cart and unlocked-ultrasound, as in many cases the equipment experienced larger displacements in the base-isolated condition than the fixed-base condition. In contrast, the reduction in the displacement response of the locked-ultrasound is evident in base-isolated building. Therefore, locking the casters is recommended for equipment and contents in base-isolated buildings. Based on the figure, the TFP system, on average, resulted in slightly smaller relative displacement response of the equipment. Considering the relative velocity plots, in all the cases base isolation greatly reduced the response of all the equipment items. The velocity responses of equipment are very close for the LRB and TFP isolation systems.

The presentation will also touch upon fragility analysis for medical equipment on wheels and casters in fixed-base and base-isolated hospitals. Figure 3 shows fragility curves associated with the different systems for relative displacement (top row) and relative velocity (bottom row) demands of equipment on unlocked casters. The PGA adopted for scaling the ground motions is considered as the intensity measure in generating the fragility curves. The first row plots correspond to the curves for 0.25 m, 0.5 m, and 1.0 m relative displacement thresholds. Based on these plots, isolating the hospital resulted in smaller probability of exceeding the capacities, with the TFP system exhibiting a slightly superior performance over the LRB system in reducing demands. Considering the relative velocity curves on the second row plots, again, base isolation very effectively reduced the probability of exceeding the velocity thresholds. In this case, the curves are very close for both isolation systems with a slightly better performance for the LRB system.

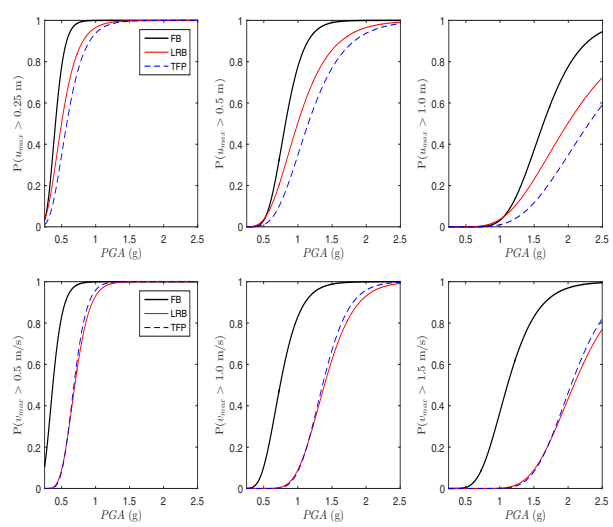

Figure 3. Fragility curves comparing the different systems.

EXPERIMENTAL STUDY OF EXPOSED COLUMN BASE

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Keywords: Exposed column base; hysteretic curves; quasi-static test; resistance mechanism; anchor rods

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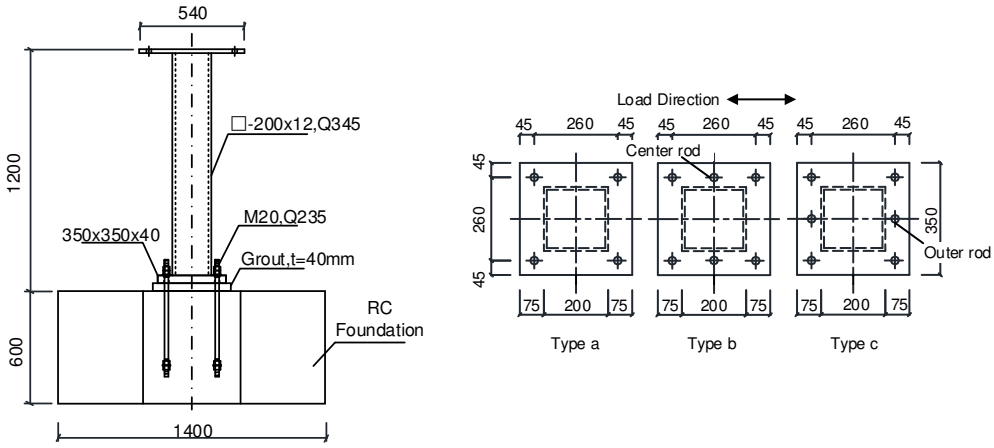
Objectives

In low and mid-rise steel structures in the seismic regions, exposed column base connections are commonly used to transfer axial forces, shears and moments from the entire structure into the foundation. Exposed column base connections comprise several components including the column, base plate, anchor rods, grout, and the concrete foundation. The strength and stiffness of these connections was controlled by interactions between these components. Various experimental and analytical studies have been conducted. Most of the study adopted in US focused on the seismic behavior of exposed column base with W-section columns and four-anchor rods configuration. While, experimental studies in Japan focused on the seismic behavior of exposed column base with hollow steel section (HSS) column. The strength and stiffness evaluation for exposed column base with regular four anchor rods configuration could be evaluated using the current steel connection design guideline in the world, but the hysteretic curves and deformation capacity of such exposed column base connections is unclear. The objectives of this study are to characterize the seismic response, i.e., strength, deformation, and hysteretic characteristics, of HSS column base connections by considering the anchor rod material characteristics, anchor rod configuration, and axial force level. Especially, the seismic behavior of exposed column base connection under tension axial load was studied. Based on the experimental results, the design methods of exposed column base will be revised by considering the anchor rod configuration and axial force level.



(a) Geometry of specimen (b) Anchor rod configuration

Fig. 1 Dimensions of test specimens (unit:mm)

Five quasi-static tests on exposed column base connection with HSS column were conducted. As shown in Fig. 1(a), the specimen comprises a steel column and a reinforced concrete beam. The anchor rod configuration is shown in Fig. 1(b). The distance between anchor rods is 260mm in both directions for "Type a". As shown in Fig. 1(b), for the other two type configuration, one more anchor rod is added either in the sides along loading direction (named as center anchor rod, "Type b") or the sides perpendicular to the loading direction (named as outer anchor rod, "Type c"). Specimen 4RM was designed as prototype. Specimen 4RMT was loaded under tensile axial force (axial force ratio is -0.1) and Specimen 4LM, 4RM, 6RCM, and 6REM were loaded under compressive axial force (axial force ratio is

0.2). Specimen 4LM were designed to investigate the effect of anchor rod material property, and Specimen 6RCM and 6REM were designed to investigate the effect of the number and configuration of anchor rod.

Results

The specimens were loaded till either the anchor rod fracture or the maximum stoke capacity of the jack. According to the strain gage attached on the column, the column was not yield in the loading. No obvious cracks were observed in the concrete beam. All the failure were concentrated on the anchor rod and grout. Specimen 4RMT failed by anchor rod fracture at 0.02 rad story drift. Specimen 4LM failed by anchor rod fracture at 0.04 rad story drift. The other specimens were loaded till the maximum stoke capacity of jack (around 0.15 rad) and no fracture of anchor rod was observed.

The hysteresis curves of moment and rotation curves of the specimens were shown in Fig. 2. And the yield rotation and moment, maximum rotation and moment, and ductility ratio in both loading directions are listed in Table 1. It is noted that Specimen 4RMT showed the smallest moment resistance and rotation capacity. Since the failure mode of Specimen 4MRT is different from the other specimens, the ductility ratio is not compared with the others. As shown in Fig. 2, Specimen 4RM, 6RCM, and 6REM shows good ductility. And the maximum moment was increased as the number of anchor rod increased.

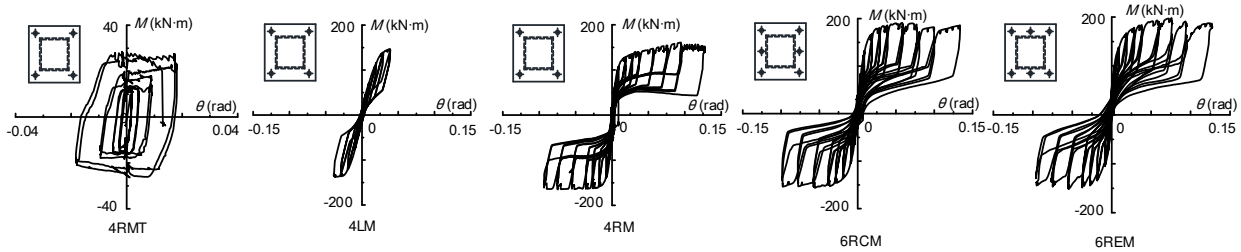


Fig. 2 Moment-rotation relationships of specimens

Table1 Test Results

Spec.	K_0	Yield strength				Ultimate strength				μ_θ^+	μ_θ^-
		θ_y^+ (rad)	M_y^+ (kNm)	θ_y^- (rad)	M_y^- (kNm)	θ_u^+ (rad)	M_u^+ (kNm)	θ_u^- (rad)	M_u^- (kNm)		
4RMT	6018.10	0.002	12.04	-0.002	-12.62	0.018	28.41	-0.02	-26.39	--	--
4LM	6110.73	0.019	116.10	-0.024	-116.53	0.046	146.76	-0.054	-138.10	2.42	2.25
4RM	7475.97	0.017	127.09	-0.023	-129.54	0.074	160.77	-0.095	-165.02	4.35	4.13
6RCM	9049.25	0.014	126.69	-0.019	-146.53	0.058	176.53	-0.081	-172.42	4.14	4.26
6REM	7587.42	0.016	121.40	-0.015	-123.34	0.074	185.86	-0.055	-151.52	4.62	3.67

Conclusions

1. Exposed column base with cold-formed anchor rods failed by fracture of anchor rod. The ductility of exposed column base was significantly reduced by using cold-formed anchor rods. Compared with the exposed column base connection using hot-rolled anchor rods, the ductility ratio was reduced by 72%.

2. Specimen 4RMT failed by the anchor rod fracture at the story drift of 0.02rad. The maximum resistant moment of specimen 4RMT was reduced by 80% by comparing with the specimen 4RM, which the axial force ratio is 0.2 in compression. The baseplate of specimen 4RMT was uplifted due to the tensile axial load. The slippage of specimen 4RMT was obivious.

3. The maximum strength, initial stiffness, energy dissipation, and ductility were increased as the number of anchor rods. However, the contributions of outer rod and center rod were different. The additional set of anchor rods will be more efficient to increase the strength and stiffness when they were arranged as the outer rods.

4. According to the strain gage data on the bolt, the force transferred by the anchor rods are proportional to the distance from the baseplate rotation point. The baseplate could be considered as rigid plate when the plate thickness is larger than 40mm.

EXPERIMENTAL STUDY OF A ROCKING TRUSS WITH BRBS AT BASE

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A high performance lateral resistant structural system with high ductility and damaged elements replaceable characteristic is constructed using a vertical truss hinged in its base and buckling-restrained braces (BRBs) vertically installed in its two sides of the base. The vertical loads and transverse shear force is carried by the hinge in the base of the truss, and the bending moment is balanced by the BRBs in its two sides. The BRBs yield axially under the lateral load, so that the structural assembly behaves excellent hysteretic performance. The pseudo dynamic experiment of such a structure is conducted, in which the model is excited by three ground motions with different seismic intensity. The structure exhibits strong stiffness under minor earthquake because the BRBs stay in elastic, while it behaves wonderful ductility and high low-cycle fatigue capacity due to the excellent hysteretic performance of the BRBs when it is excited by strong or rare earthquake. The other parts of the structure remain in elastic because they are protected by the prior yielding of the BRBs, and the damages are limited in the BRBs. The residual deformation can be overcome by force to restore the performance of the structure when the BRBs experience minor damage, while as they are seriously damaged, the structure can be renewed by replacing the BRBs easily.