EXPERIMENTAL TESTING OF LARGE SCALE STRUCTURAL MODELS AND COMPONENTS USING INNOVATIVE SHAKE TABLE, DYNAMIC, REAL-TIME HYBRID SIMULATION AND MULTI-DIRECTIONAL LOADING TECHNIQUES

Robert Tremblay[1], Pierre Léger[1], Colin Rogers[2], Najib Bouaanani[1], Bruno Massicotte[1], Amar Khaled[3], and Charles-Philippe Lamarche[4]

ABSTRACT

The paper describes seismic experimental programs that have been recently conducted in the new Hydro-Quebec Structural Engineering testing facility at Ecole Polytechnique of Montreal, Canada. A shake table test setup has been developed for multi-storey building models and testing has been completed on full-scale two-storey steel frame/wood sheathed shear wall and reduced-scale eight-storey reinforced concrete shear wall models. Seismic dynamic testing of large scale roof deck diaphragm specimens and real time dynamic sub-structuring testing of seismic dampers and isolators for bridge structures are also described. The test setup used for the multi-axis testing of rectangular bridge piers subjected to bi-directional seismic loading is discussed. Future expansion of the multi-directional testing capability of the laboratory is introduced.

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INTRODUCTION

The Structural Engineering Laboratory at Ecole Polytechnique of Montreal has been significantly extended in the 2002-05 period. The new facility includes 525 m^2 net strong floor area, a 10 m tall L-shaped reaction wall with two 12 m long wings, an uniaxial earthquake simulator, a multi-purpose tension/compression 12 MN load frame with 3 m wide x 8 m tall test space, a series of high performance actuators, and a real time hybrid control system. Several test programs have now been undertaken and completed in the laboratory on various large-scale structural systems. A majority of these experimental studies have been performed to examine the seismic behaviour of different seismic force resisting systems for building or bridge structures. The tests also aimed at validating numerical simulation tools that are used to assess the seismic performance and inelastic response of these systems.

In several of these experimental studies, the seismic induced loading was applied dynamically to take into account possible strain rate dependencies or investigate the dynamic response of the structural systems studied. The real-time sub-structuring testing technique has been implemented and used in some of these tests. In other tests, multiple actuators were used to reproduce the multi-directional force and displacement demand from earthquakes. This paper outlines techniques that have been used in selected past test programs, with focus on an innovative shake table test setup that has been developed for multi-storey building models. Seismic dynamic testing, real-time hybrid simulation, and multi-axis testing applications are also briefly described,

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[1] *Group for Research in Structural Engineering, Dept. of Civil Geological and Mining Engineering, École Polytechnique; Montreal, QC, Canada*
[2] *Dept. of Applied Mech. and Civil Engineering, McGill Univ.; Montreal, QC, Canada*
[3] *Dept. of Construction Engineering, École de Technologie Supérieure; Montreal, QC, Canada*
[4] *Dept. of Civil Engineering, Université de Sherbrooke; Sherbrooke, QC, Canada*

and an overview of a new multi-directional structural component hybrid testing system to be implemented in the near future is given.

SHAKE TABLE TEST SETUP FOR MULTI-STOREY BUILDINGS

The uniaxial earthquake simulator has a payload capacity of 15 tons and 3.4 m x 3.4 m plan dimensions. The multi-cellular shake table box is mounted on four frictionless linear hydrostatic bearings. The bearings are designed with high vertical capacity resulting in a large overturning moment capacity for the table. The system features a fully digital MTS 469 three-variable control system with delta pressure stabilization, amplitude phase control, online iteration, and adaptive inverse control capabilities. The actuator is powered by a hydraulic power supply with a total flow capacity of 1400 l/min. The frequency range is 0-50 Hz and the system can achieve peak displacements of ± 125 mm, peak velocities of 1.0 m/s and peak accelerations ranging between 3.0 g (table empty) and 1.0 g (at full payload capacity). The earthquake simulator is serviced by a 15 ton overhead crane and the vertical clearance between the test platform and the crane hook is 11 m. The large overturning moment capacity and test height clearance of this facility represents very suitable conditions for testing tall two-dimensional structural systems such as braced frame or shear wall systems.

Tremblay et al. (2005) presented a preliminary study on the design of test setup for the shake table testing of seismic force resisting systems used in multi-storey building structures. The system was originally designed with a 10 m height to accommodate reduced scale models of structures up to 10 storeys in height. It includes a lumped mass system that simulates the tributary seismic floor weights at every level of the structural system studied. The masses are vertically supported by columns that are independent of the test structure, simulating the gravity load frame typically found in actual buildings and allowing P-Δ effects to be taken into account in tests. The number of floors and storey heights can be easily modified to reproduce the prototype building geometry. Final design and fabrication of the setup has since been completed and, at the time of writing, the system has been used for tests on a scaled model of an 8-storey reinforced concrete shear wall and full-scale tests of single- and two-storey steel frame/wood sheathed shear wall specimens. Details of the experimental setup are presented for the 8-storey shear wall tests and the modified configuration used for the 2-storey shear wall is then presented.

Testing of Reinforced Concrete Shear Walls

A research project has been undertaken to better characterizing the contribution of the higher modes of vibration on the bending moment and shear force demand on cantilevered reinforced concrete shear walls. The work focuses on slender walls located in eastern North America, where earthquakes are expected to develop ground motions richer in high frequencies, a situation where higher mode effects can be significant and induce flexural plastic hinges in the upper levels as well as excessive shear force demand. Shake table testing was incorporated in the project to validate the numerical solutions obtained from various predictive models (Ghorbanirenani et al. 2008). An 8-storey prototype residential building located on a class C site in Montreal, Quebec, was selected for this experimental study. The total height of the building is 20.97 m (8 storeys x 2.621 m) and a 9 m tall wall specimen with a length scaling factor l_r = 0.429 was designed for the tests. The artificial mass simulation procedure was used to develop the similitude requirements. The method was modified to introduce a scaling factor on acceleration, a_r = 2.65, such that the entire tributary seismic weight of the wall studied could be included in the test setup. This resulted in scaling factor on time, t_r = 0.403. Further information on the design and numerical simulations of the test specimen can be found in Tremblay et al. (2008).

Figure 1a shows a schematic of the test specimen mounted on the shake table. The wall has a rectangular cross section with uniform thickness of 80 mm and a change in width at the 6th level. The wall specimen was constructed in the vertical position, with one-storey lifts that were poured in sequence to replicate actual construction practice. The storey height in the model is 1125 mm and the total weight of the wall, W_w = 52 kN, including the weight of the base footing (11 kN). At each level, the seismic weight tributary to the wall studied is simulated by rectangular steel plates that are supported on steel columns. This seismic weight system also reproduces the gravity load carrying system that is laterally braced the shear wall. In order to free up the capacity of the linear bearings supporting the shake table to maximise the overturning moment demand on the test specimen, the seismic weight/gravity load system is constructed on the laboratory strong floor, beside the shake table. This configuration allows seismic weight much larger than the 15 ton (145 kN) payload capacity of the table: the steel plates weigh approximately 62 kN per floor, resulting in a total gravity load W_g = 500 kN for the 8 floors.

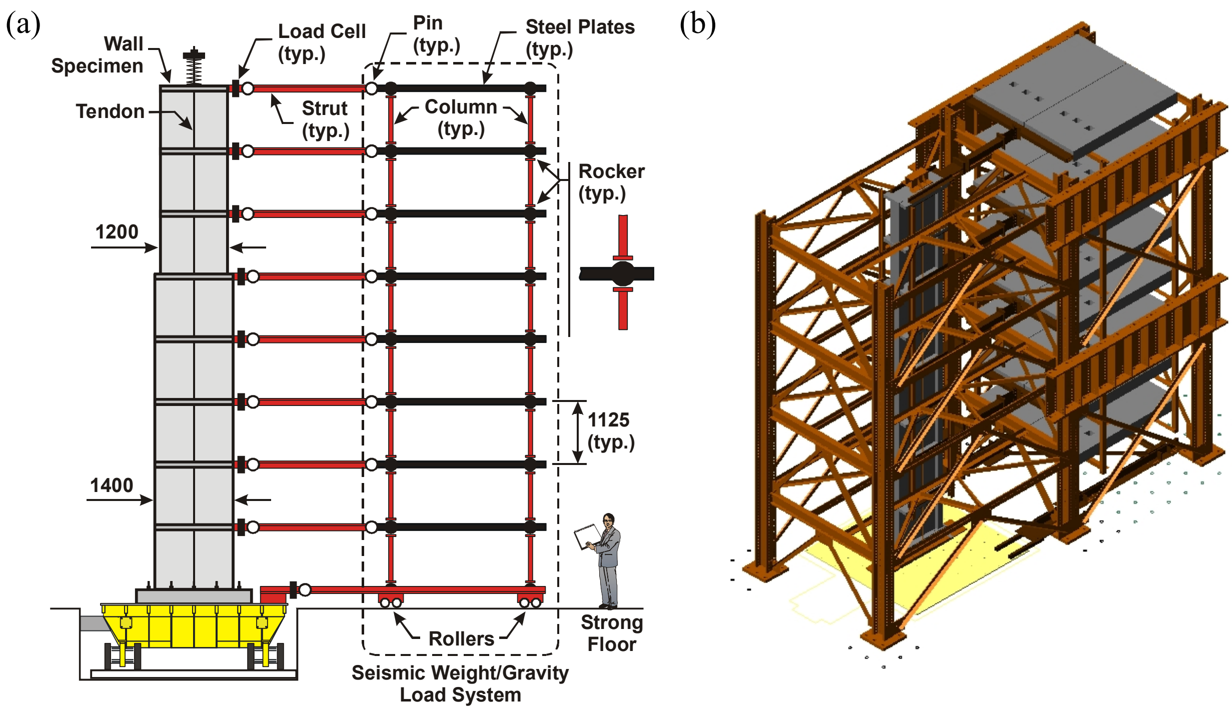
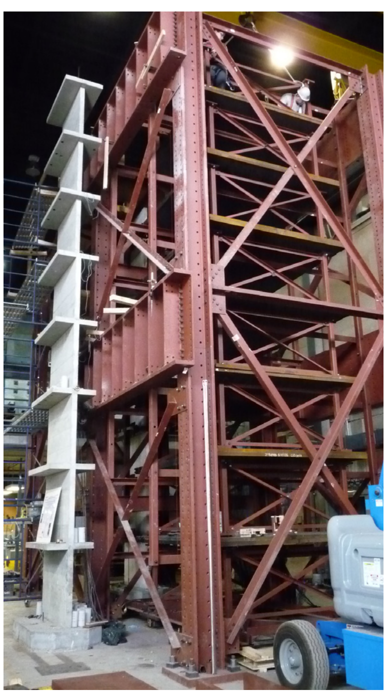


Fig. 1. (a) Test specimen and seismic weight/gravity load system; (b) Complete test setup with stabilizing steel frame.

The four steel column segments supporting the seismic weight steel plates between each floor are built with carefully machined cap plates at their upper and lower ends. Cylindrical rockers are inserted between the seismic weight steel plates and the columns ends such that the gravity load system has no lateral strength and stiffness and lateral loads and P-Δ effects are entirely resisted by the test specimen. In the transverse direction, diagonal bracing is inserted between the columns to ensure out-of-plane stability. At all floors, horizontal steel struts with high axial stiffness link the floor masses to the test specimen. The struts are connected to 300 mm wide x 80 mm thick slab extensions cast on each side of the wall to mimic the horizontal shear transfer mechanism that prevails between the floor diaphragms and the wall in actual constructions. Load cells were introduced between the struts and the test specimen to monitor the floor inertia forces developing during the tests. At the base of the gravity load system, the steel columns are pin-supported to longitudinal horizontal steel members that extend up to the earthquake simulator to which they are connected. Those members are vertically mounted on frictionless roller bearings that roll on polished and levelled high strength steel plates placed on the laboratory strong floor. Hence, the base of the gravity system experiences the same horizontal displacement as the earthquake simulator and the test specimen is subjected to P-Δ forces induced by the lateral displacements of the specimen relative to the ground, as is the case in actual buildings. The weight of the movable horizontal base frame W_b = 11 kN. The total weight carried by the four roller bearing units was therefore equal to 511 kN. An axial load P_0 corresponding to 1.5% of $A_c f'_c$ was applied to the wall by means of pre-tensioned tendons. A coil spring system was used to anchor the tendons at the wall top to minimize variation of the axial load during the tests.

The test specimen and seismic weight/gravity system are enclosed in a braced steel frame that provides for the out-of-plane stability of the test specimen and prevents collapse of the whole test assembly in case of failure of the test specimen. Figures 1b and 2a show the entire test setup including the stabilizing steel frame. In Figure 2a, a second shear wall test specimen is being prepared next to the steel frame. The floor slab segments cast on each side of the wall can be seen in this figure. Out-of-plane lateral support of the test specimen is provided by four vertical steel shapes that are mounted on the steel frame and carefully aligned next to edges of the specimen floor slabs. Teflon material was placed between these steel shapes and the slab edges to minimize friction during the tests. The steel frame also includes working platforms that ease access to the test specimen for the instrumentation and observation during the tests.

(a)



(b)

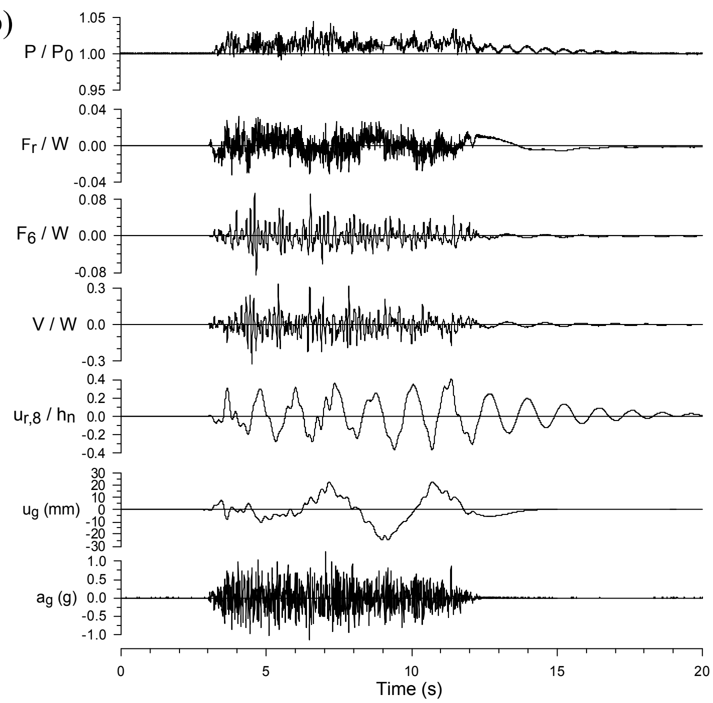


Fig. 2. (a) Shake table test setup upon assembling the seismic weight at the 8th level (a second test specimen is placed next to the test setup); (b) Time history response under the design base ground motion (model scale).

The structure was subjected to a simulated seismic time history corresponding to an **M**7.0 event at 70 km in Montreal. The signal was modified to match the elastic code design spectrum used in the design of the specimen. Several tests were performed by increasing each time the amplitude of the motion. Figure 2b shows the applied ground motion acceleration and displacement time histories, a_g and u_g, as well as selected response parameters for the test performed under the design base earthquake level: the relative displacement at the 8th level normalized to the specimen height, $u_{r,8}/h_n$, the base shear V normalized to the total seismic weight W = 541 kN, the inertia load at the 6th floor, F_6, the total horizontal friction force at the base of the roller bearings, F_r, as normalized with respect to the total weight supported (511 kN), and the axial load in the wall, P, normalized to the value applied at the beginning of the test, P_0. The periods of the wall specimen in the first three modes of vibration, as measured prior to this test, are 0.76, 0.18, and 0.093 s. The fundamental mode of vibration dominated the top horizontal displacement response, although second mode effects can be observed in the figure. Elongation of the first mode period can also be noticed in the large amplitude cycles (T_1 becomes longer than 1.0 s). Conversely, shear and inertia forces were governed by higher mode response and plastic hinges were observed at the wall base as well at the 6th level, as predicted by analysis. During the test, the friction force F_r remained very small, less than 3% of the total supported weight, indicating that a very small portion of the actuator load was lost in friction. The tendon/coil spring assembly also proved very effective in maintaining the axial load constant during the test.

Testing of Cold-Formed Steel Frame/Wood Sheathed Shear Walls

A research program that aims at developing appropriate detailing and proven seismic design methods for strap braced walls wood as well as steel sheathed shear walls constructed with cold-formed steel members has been undertaken at McGill University. Testing of single-storey specimens under monotonic and reversed cyclic loading has been performed in previous stages to propose shear resistance and stiffness values and tentative seismic force modification factors (Branston et al. 2006; Boudreault et al. 2007). Nonlinear time history dynamic analyses were performed to validate the proposed seismic design procedure for multi-storey applications.

(a) (b)

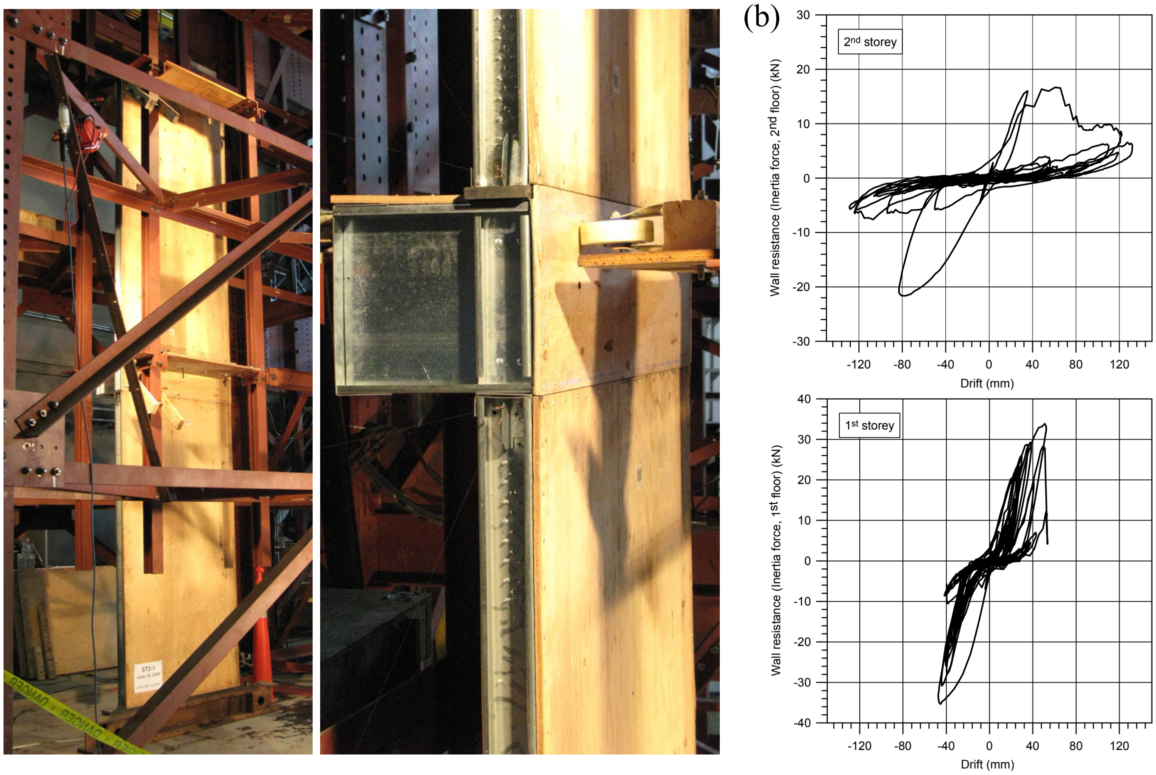


Fig. 3. Shake table testing of cold-formed steel frame/wood sheathed shear walls: (a) Two-storey specimen in the test setup; (b) Measured storey hysteretic responses under strong ground motion.

Shake table testing of one- and two-storey shear walls made of plywood sheeting screwed to cold-formed steel stud and track assemblies has been initiated to validate and improve the numerical predictions and verify the overall inelastic performance under seismic base excitation; especially to identify whether the multi-storey wall systems are physically capable of resisting earthquake loads without significant soft storey effects. Information on the periods of vibration was also needed for these cold-formed steel framed lateral systems. A variant of the seismic weight/gravity load system described earlier was used in these shake table tests. In particular, the wall height was increased to 2.44 m with an additional 0.3 m thick floor structure. The seismic weight was reduced to 30 kN per floor to represent the force level associated with this type of lateral framing system. Figure 3a shows a two-storey shear wall specimen (1.22 x 2.44 m wall segments) in the test setup. Figure 3b compares the storey shear-storey drift hysteretic response recorded at each level under strong ground shaking. The graphs show the complex pinched and degrading inelastic behaviour exhibited by these wall assemblies. The tendency for concentration of the inelastic demand in the top floor, due to a more sparse sheathing connection pattern compared with the ground floor wall, can also be clearly observed in this particular test.

Future Shake Table Test Programs

The performance of repair and strengthening schemes for reinforced concrete shear walls will be examined in future shake table tests. Shake table experiments on cold-formed steel shear walls (with either wood or steel sheathing) and braced frames will continue with tests performed on full-scale three storey buildings. It is also planned to use the shake table test setup for the study of innovative braced steel frame systems including dual systems incorporating elastic framing components that are specifically designed to minimize inelastic demand concentration over the structure height or systems that feature rocking or self-centring capabilities.

DYNAMIC TESTING OF STEEL ROOF DIAPHRAGMS

Dynamic seismic testing was completed on large size diaphragms built with corrugated steel deck panels as used in the roof of single-storey steel buildings. Figure 4a shows a schematic of the 21 m x 7.3 m rectangular test specimen: the steel deck sheets are installed on a horizontal steel beam and joist assembly replicating typical roof structural framework. The steel deck sheets are fastened to each other along their edges as well as to the supporting steel structure to develop diaphragm behaviour. The test frame was mounted horizontally on rockers seating on the laboratory strong floor and in-plane loading was dynamically applied using two 1000 kN high performance actuators acting in phase at either end of the test specimen.

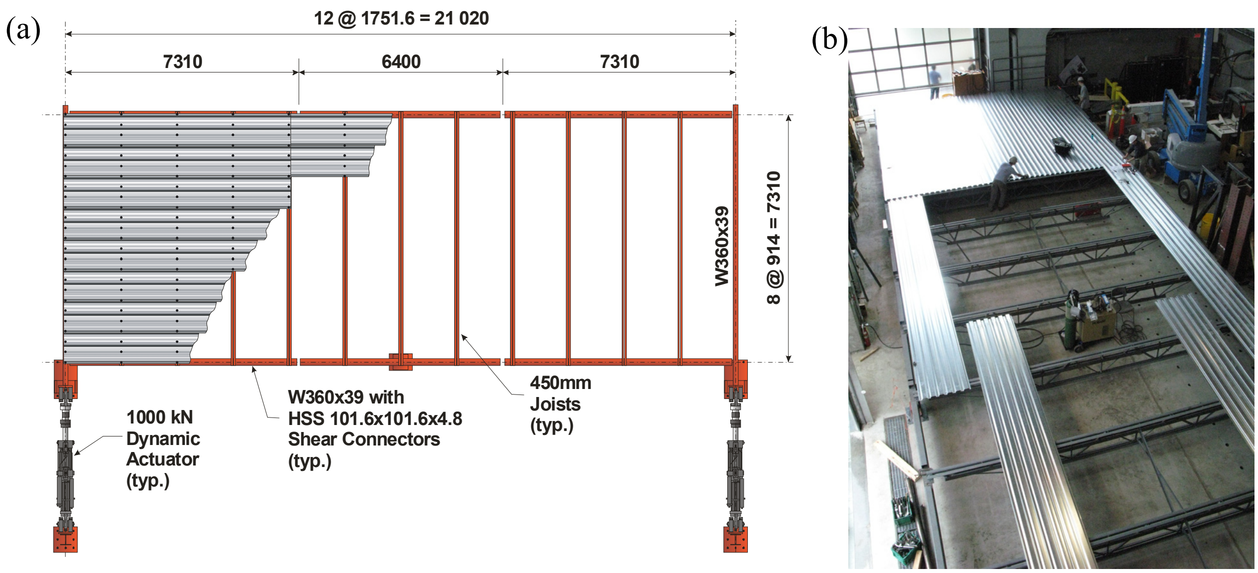


Fig. 4. Dynamic seismic testing of steel deck roof diaphragms: (a) Test setup (deck sheets perpendicular to in-plane loading shown); (b) Construction of a test specimen.

This loading system reproduced the ground motion effects as transmitted at the roof level by the vertical framing elements in actual building structures. Several specimens were tested to examine the influence of the deck sheet thickness and fastener type and spacing. The effect of varying the amplitude of loading on the in-plane diaphragm shear stiffness and periods of vibration was also investigated. Inelastic response under strong seismic ground motions typically developed in the connectors and by tearing or local buckling of the sheet material in the vicinity of the connectors. The large dimensions of the test specimens permitted to study the distribution and amplitude of this inelastic demand over the diaphragm. The impact on elastic and inelastic diaphragm responses of the end lap joints that exist between deck sheets could also be studied in the test program.

REAL-TIME DYNAMIC SUB-STRUCTURING TESTING

The MTS 469 digital controller of the shake table has been upgraded to include the capability of performing either seismic testing or real-time structural hybrid testing. When used for hybrid testing, the system is capable of running up to five structural actuators simultaneously under a common single test configuration, including the 12 MN load frame. The system includes three computers to allow real time execution between Matlab/Simulink® models and the MTS servo-controller: one computer where Simulink models are developed and hosted, one computer used as a secondary target computer where Simulink programs are efficiently run using the MathWorks xPC Target operating software, and one computer used for the MTS controller. Shared memory via Systran's ScramNet® capabilities are used to pass command and feedback signals simultaneously to all computer nodes. A schematic of the control configuration is illustrated in Fig. 4a for hybrid testing of a structure equipped with seismic dampers.

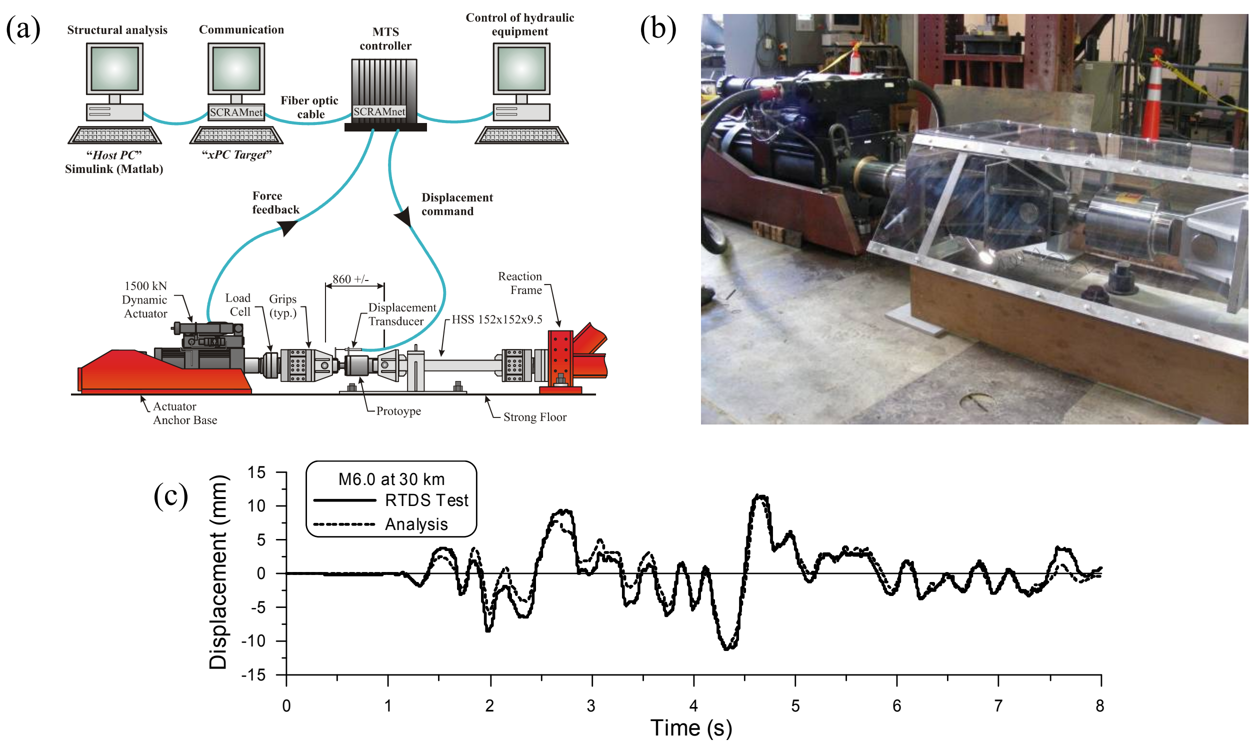


Fig. 5. Hybrid simulation of an isolated bridge structure: (a) Test configuration; (b) Damper physically tested in the laboratory; (c) Comparison of the bridge response under M6.0 at 30 km ground motion from RTDS and numerical simulations.

In the last two years, efforts have been directed towards the development of a Rosenbrock-W semi-implicit integration scheme that can be used in real time dynamic sub-structuring (RTDS) and pseudo-dynamic (PSD) testing applications (Lamarche et al. 2009). The algorithm has been implemented and validated by comparing against shake table tests conducted on a two-storey steel frame model (Lamarche et al. 2008). The system has been recently used with success for the full-scale testing of various strain rate dependant seismic isolators and dampers for bridge structures. The main objective of that project was to assess the capacity to predict the response of bridge structures using commercially available computer programs. Real time hybrid simulations have been carried with the dampers physically tested in the laboratory. Figure 5b illustrates such a physical test being carried out using a 1500 kN dynamic actuator. Figure 5c compares the response determined from a purely numerical simulation to that obtained from the hybrid test for a bridge equipped with nonlinear viscous dampers. In that particular case, the test confirmed that the analysis software could be used efficiently to assess the seismic displacement demand imposed on the bridge.

MULTI-AXIS TESTING

Multi-Axial Testing of Reinforced Concrete Bridge Columns

Multi-directional loading has been performed on half-scale bridge columns with rectangular cross-section using the 10 m tall, L-shaped reaction wall of the laboratory and five high performance structural actuators, as illustrated in Fig. 6. The objective of the test program was to validate seismic design requirements for bi-directional seismic loading, with special interest in the difference in the demand anticipated from earthquakes expected in eastern and western regions of North America (Khaled et al. 2006).

In the test setup, constant gravity load was applied using a transverse horizontal beam and two vertical 1000 kN actuators symmetrically located on either side of the test specimen. One of these two actuators was controlled in the displacement mode to maintain the position of the beam whereas the other one was load controlled to impose the required axial compression load in the column. The target displacement time histories along the three horizontal degrees of freedom at the column top were imposed by means of three horizontal actuators. In that particular test program, in-plane torsional rotation was kept equal to zero such that the response under the combination of the bending moments about both principal directions as determined from previous time history analysis could be examined.

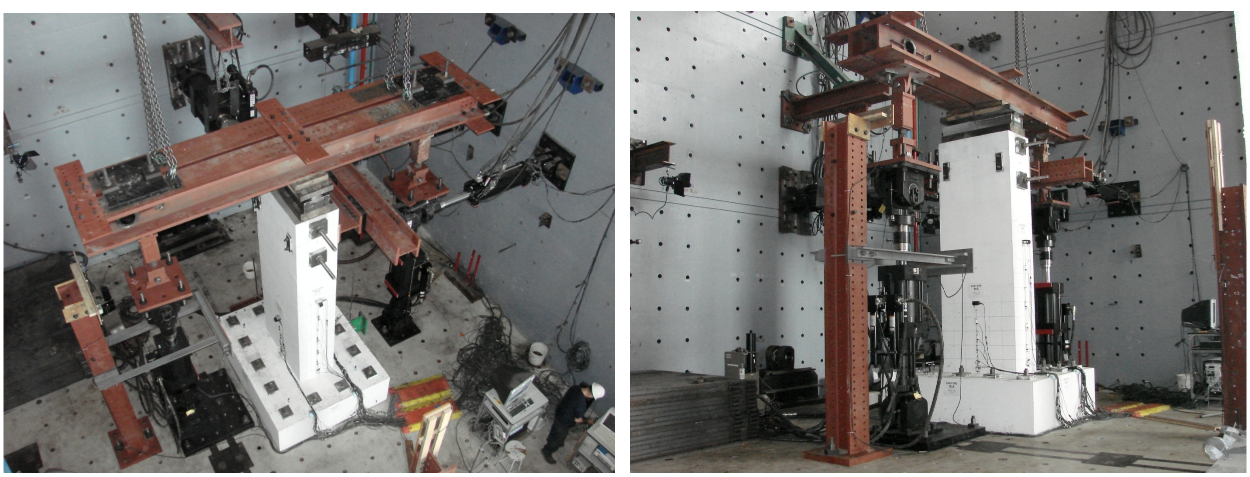


Fig. 6. Testing of a 1:0.5 rectangular bridge column under bi-directional seismic loading.

New Multi-Directional Hybrid Testing System

Ecole Polytechnique of Montreal has recently been awarded a major equipment grant for the acquisition of a high performance multi-directional structural component hybrid testing system that will be used in combination with the existing L-shaped reaction wall. The system is designed to apply any combination of forces or deformations along 6 degrees of freedom at the top end of the test specimen, resulting in a combination of axial load, torsional moment, bi-axial bending moments and bi-axial shear forces applied to the specimen. As shown in Fig. 7a, a total of eight structural actuators are used in combination with one moment platen. The base of the test specimen is anchored to the strong floor of the structural laboratory and the upper part is secured to the underside of the moment platen. The system has also been designed to be mounted within the existing 12 MN load frame to take advantage of the large axial load capacity of the test frame (Fig. 7b). In this configuration, 4 vertical actuators are used in combination with 2 moment platens such that any combination of end bi-axial moments can be applied together with high axial compression force. Free rotation of the upper platen relative to the load frame cross-head is achieved by means of a pressure balanced bearing unit. Reaction frames will be used to prevent the horizontal displacements and torsional movements of the upper moment platen (not shown in the figure). The project also includes an upgrade of the existing shake table actuator to enhance the capacity of the test setup described earlier.

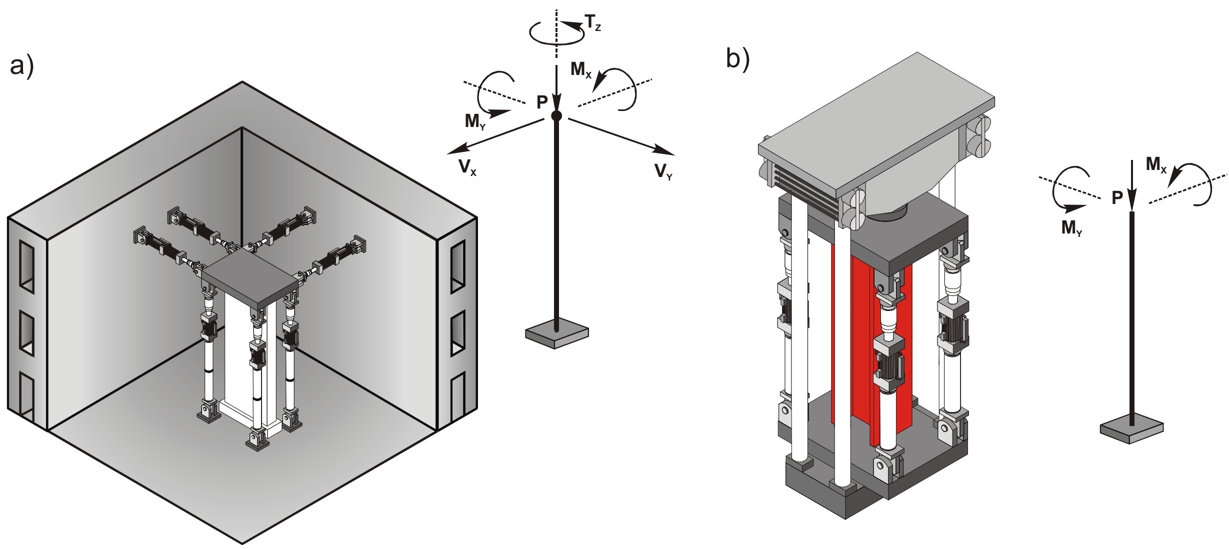


Fig. 7. Proposed multi-directional hybrid system configurations: (a) With the L-shaped reaction wall; (b) Within the 12 MN load frame (lateral reaction frames not shown).

CONCLUSIONS

Nonlinear time history dynamic analysis has become common practice to study the inelastic seismic response of structural systems and to assess their seismic performance. This analytical procedure has been demonstrated to adequately predict the behaviour of seismic force resisting systems that have well defined inelastic mechanisms with stable hysteretic response, such as beam flexural hinging or axial buckling and yielding, when subjected to limited inelastic demand. The analysis of structural systems that involve severe strength and stiffness degradation, strain rate dependency, complex interaction between various structural components or multiple load paths with different response characteristics still represents a challenge that requires careful experimental validation. Physical testing is also required to verify the capacity of structural system to resist against partial or total collapse.

This paper presented various experimental techniques that have been recently implemented and used at the new testing facility at Ecole Polytechnique of Montreal. Test programs devoted to the study the seismic response of structural systems subjected to dynamically applied or multi-directional seismic loading were presented and discussed. In particular, a versatile test setup has been developed to study the response of seismic force resisting systems used in multi-storey buildings. The system can be easily reconfigured to accommodate different structural systems with different heights, number of floors and seismic weights. The system also allows for P-Δ effects to be taken into account and is therefore suitable for global seismic stability response evaluation. Dynamic seismic tests of large scale roof deck diaphragms and real time sub-structure simulations of bridge structures equipped with highly nonlinear and strain rate dependant seismic isolator and damping systems were carried using high performance dynamic actuators. Testing of large scale columns under combined gravity load and bi-directional loading has been completed. Future expansion of the testing facility includes the addition of a multi-axis testing system for hybrid simulations and an upgrade of the actuator capacity of the shake table.

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