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EXPERIMENTAL INVESTIGATIONS OF LARGE SCALE TLD-STRUCTURE INTERACTION VIA REAL-TIME HYBRID SIMULATION

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ABSTRACT

In real-time hybrid simulation (RTHS), as a cost-effective experimental testing technique, computer simulations are coupled with physical testing. RTHS divides the test structure into analytical and experimental substructures, and synchronizes them as the equations of motion are being solved in real-time. When conducted properly, the load-rate dependent characteristics of the test structure could be accurately captured by the RTHS. This paper presents real-time hybrid simulation of a three story structure equipped with a large scale tuned liquid damper (TLD) using a recently developed computational/control platform at University of Toronto. TLDs are cost effective and low maintenance vibration absorbers that can be utilized to suppress structural vibrations under dynamic excitation. They dampen energy through liquid boundary layer friction, the free surface contamination, and wave breaking. However, highly nonlinear and velocity dependent behaviour of these devices makes it difficult to establish representative analytical models for TLDs that are accurate for a wide range of operation. In this study, by employing RTHS the TLD will be tested physically as the experimental substructure and the remaining structure will be modeled analytically as the analytical substructure. This will facilitate the investigation of TLD-structure interaction for a wide range of influential parameters while using a user-programmable computational/control platform to carry out the real-time hybrid simulations.

Keywords: Real-time hybrid simulation, vibration mitigation, tuned liquid damper (TLD), TLD-structure interaction

1. INTRODUCTION

Experimental testing plays a key role in performance assessment of structures when subjected to extreme events such as earthquakes, explosions, etc. If performed accurately, the results obtained from experiments can facilitate the development of reliable analytical models for structural components which provides a valuable basis for predicting the global behavior of structural systems in similar situations. This will in turn lead to the safer yet cost-effective design and construction of next generation structures. Experimental methods that have been widely used to assess the dynamic behavior of structures include shake-table, quasi-static, traditional pseudodynamic testing and hybrid simulation. In the last two methods physical testing is combined with computer simulation.

Hybrid simulation has started as an extension to the pseudodynamic (PSD) testing method where physical testing of only critical components is combined with a computational model of the remaining structure. Thus it offers an economical and practical way to address the need to obtain the system level behavior. In this method, the test structure is divided into two parts: the components of the test structure for which a reliable analytical model is not available are isolated and tested physically in the laboratory, while the rest of the system is modeled analytically in a computer (Dermitzakis and Mahin 1985). These are known as experimental substructure and analytical substructure, respectively. When the experimental substructure has load-rate dependent vibration characteristics, the hybrid simulation needs to be conducted in real-time (Nakashima et al. 1992, Horiuchi et al. 1999, Mercan and Ricles 2009). This requires efficient and robust computational resources as well as a well-synchronized data communication platform (Mercan and Ricles 2009). RTHS became an important tool to experimentally capture the rate-dependent vibration characteristics of complex structural systems and example applications of which can be seen in the recent literature (Christenson et al. 2008, Carrion et al. 2009, Karavasilis et al. 2011, Wu et al. 2013, Chae et al. 2013, Malekghasemi et al. 2013). In RTHS, since only the critical components of the test structure need to be constructed and tested physically and remaining parts are modeled analytically, a wide range of substantial parameters and loading cases could be investigated in a timely and cost-effective manner (Ashasi-Sorkhabi et al. 2013).

A user programmable computational/control platform was designed, implemented and validated by the authors at the University of Toronto that offers RTHS capabilities (Ashasi-Sorkhabi and Mercan 2014). This paper presents a practical application where the developed RTHS platform is utilized to investigate the interaction of a three story structure equipped with a large scale rectangular tuned liquid damper (TLD). During the tests the large scale TLD is built and tested physically in the lab while the three story structure is modelled analytically in a computer. For this purpose, a large size shake table is designed and built that represents the roof of the test structure and is driven by the developed RTHS platform. Due to the unique flexibility that RTHS method offers several structural systems with different configurations and floor numbers could be studied experimentally.

1.1 Tuned liquid dampers (TLD)

Owing to their low maintenance requirements, cost effectiveness and ease of installation, tuned liquid dampers (TLDs) attracted considerable attention (Chen et al. 1995, Kim et al. 2006). TLD is a liquid (usually water) filled tank that absorbs energy through several mechanisms including liquid boundary layer friction, free surface contamination, and wave breaking. The 51-story One King West building in Toronto is an example where TLDs have been installed to control the structural vibrations (Hamelin, 2007). Nagasaki Airport Tower, Tokyo International Airport Tower, Shin-Yokohama Prince Hotel and Yokohama Marine Tower in Japan (Hamelin, 2007; Tamura et al. 1995) and One Rincon Hill Tower in San Francisco, U.S.A. (Kareem et al. 1999) are examples of worldwide application of TLDs.

Rectangular TLDs in one-directional motion have been investigated extensively (Fujino et al. 1988, Tamura et al. 1988, Tamura et al. 1995, Fujino et al. 1998,Reed et al. 1998). When a TLD is subjected to motion with large amplitudes, due to the horizontal component of the liquid velocity related to the wave motion, wave crests descend as the amplitude increases and the waves are no longer continuous. This is known as wave breaking. At this point simple linear models can no longer describe the liquid behavior and wave breaking changes the sloshing frequency of the liquid (Reed et al. 1998). Additionally, this complicated, nonlinear phenomenon influences the shear force developed at the interface of the TLD with the structure which counteracts the motion of the structure and is difficult to be modeled accurately. In the literature, the TLD action is classified as either deep or shallow water damping behavior (Sun et al. 1992). Waves in the range of $0.5>h/L>0.05$ to 0.04 are considered as shallow water waves, where h and L are water depth and wave length, respectively. Banerji et al. (2000) and Seto (1996) showed that higher energy dissipation could be obtained if the h/L ratio is maintained less than or equal to 0.15. When subjected to large amplitude excitations, shallow water TLDs demonstrate highly nonlinear behavior as a result of wave breaking occurrence which leads to significant amount of energy dissipation by the damper (Sun et al. 1992). Studies by Morsy (2010) also showed that when wave breaking occurs in TLDs, the resulting damping ratio can be an order of magnitude higher than the damping ratios experienced in TLDs with no wave breaking..

Mass ratio (the ratio of the mass of water to that of the structure) is an important parameter influencing the performance of TLD-structure system. Mass ratios in the range of 1% (Sun et al. 1992, Yu et al. 1999) up to 4% (Banerji et al. 2000) have been suggested in the literature. However, experimental validation is lacking for higher mass ratios where previous studies on this topic consisted of pure numerical simulations. With a relatively small mass ratio, without significantly contributing to the overall inertia of the system, TLDs can provide appreciable reductions in structural displacement and acceleration. The liquid sloshing frequency is another parameter that plays an influential role in the TLD behavior. Previous experimental studies (Kosaka et al. 1992, Sun et al. 1992) have shown that the effectiveness of the TLD is maximized when the liquid frequency is a value near to the excitation frequency where the liquid is in resonance with the tank motion.

2. REAL-TIME HYBRID SIMULATION EXPERIMENTAL SETUP

2.1 Mechanical setup

A 2.0m x 1.5m uniaxial shaking table with a payload of 1.5 ton that is designed and constructed in University of Toronto's structural lab. Two fatigue rated hydraulic actuators each with stroke of ±127 mm (±5 inch) and maximum force capacity of 33 kN (±7,500 lbf) are utilized to drive the shaking table. Each of the hydraulic actuators is driven by an electro servo-valve with flow capacity of 63 L/min (16.5 gpm) rated at 7 mPa (1000 psi). A built-in ±127 mm (±5 inch) AC LVDT and a dynamic load cell with a capacity of ±50 kN (±12,500 lbf) provide the displacement and force feedbacks from each actuator. The two actuators are coupled physically through a rigid coupler to increase the force capacity of the shaking table to 66 kN.

The table can produce any type of uniaxial motion, including sinusoidal, random, and earthquake motions. The computational/control platform developed by the authors for RTHS experiments was used to conduct displacement control of the shake table.

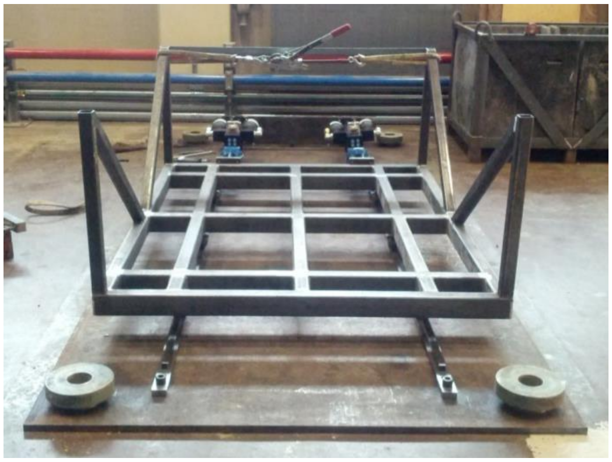

Figure 1: Uniaxial shake table

2.2 Real-time hybrid simulator

A quad-core real-time processor and a field programmable gate array (FPGA) are the key components that constitute the computational/control platform developed to conduct RTHS tests. The architecture of the designed controller and all associated signal routings are summarized in Figure 2. As indicated in the figure the simulation contains two nested loops: an inner loop and an outer loop. During RTHS experiments, the command displacements to be imposed to the test structure are computed within the outer loop. A numerical integration algorithm is employed to solve the second order ordinary differential equation of motion expressed by:

$$[1] \qquad \mathrm{M}\ddot{\mathrm{x}}(\mathrm{t}) + \mathrm{C}\dot{\mathrm{x}}(\mathrm{t}) + \mathrm{R}(\mathrm{x}, \dot{\mathrm{x}}, \ddot{\mathrm{x}}, \mathrm{t}) = \mathrm{F}(\mathrm{t})$$

where, M is the mass matrix, C is the damping matrix (representing the inherent structural damping), R is the restoring force vector, F is the effective or applied external force vector. Also, the outer loop handles all the tasks related to the state determination of analytical substructure and input/output file manipulations. Finally, the inner loop is the servo-control loop of the system, where the command displacements are imposed to the experimental substructure using the hydraulic actuators. All data communication between the controller and the hardware including the servo valves, LVDTs and load cells is carried out in the inner loop (Ashasi-Sorkhabi and Mercan 2014).

2.3 Software

Unlike the turn-key controllers, the controller used in the current setup has been designed as a flexible control/computational platform that must be configured by the user to perform specific tasks. Thus, along with the servo-control laws, several other tasks must be considered and implemented to ensure safe start-up, satisfactory performance and safe shut-down of the system. LabVIEW, MATLAB and Simulink are the programming tools that were used to develop the user interface of the RTHS platform that performs all the associated computational, control and data acquisition tasks. The main part of the developed program resides on a multi-state Host VI (VI is the generic term used for codes developed in LabVIEW) which is labeled real-time VI, and an FPGA VI together with several sub VIs (equivalent to sub functions in MATLAB) all coordinated by a LabVIEW project.

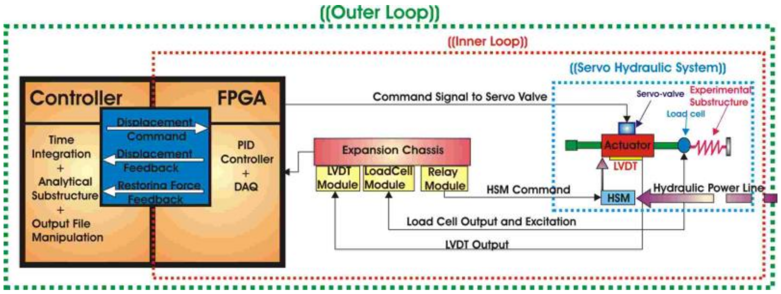

Figure 2: RTHS facility integrated control system architecture

2.4 Ground motions

This RTHS study uses a ground motion suite with seven earthquake records. The important characteristics of the considered ground motions are summarized in Table 1.

Table 1: Structural and modal properties of the 3-story structure

No.	Earthquake	M_w	Station	Dist.(km)	PGA (g)	Duration (s)
EQ1	Imperial Valley 1940	6.95	El Centro,Array 09	12.99	0.3129	40.00
EQ2	Nahanni Canada 1985	6.76	6095 site 1	6.8	2.0508	20.56
EQ3	Northridge,1994	6.69	Simi Valley-Katherine	12.18	0.8774	24.99
EQ4	Chi-Chi Taiwan 1999	7.62	CHY028	32.67	0.822	90
EQ5	Duzce Turkey 1999	7.14	Bolu	41.27	0.728	55.9
EQ6	Erzincan Turkey 1992	6.69	95 Erzincan	8.97	0.496	20.78
EQ7	Kocaeli Turkey 1999	7.51	Duzce	98.22	0.312	27.185

2.5 Experimental and analytical substructures

A three-story linear moment resisting frame (MRF) structure equipped with a tuned liquid damper on the roof level is considered as the test structure. Structural and modal properties of the building are listed in Table 2. The damping matrix of the structure is obtained assuming Rayleigh proportional damping with 2.0% damping ratio in the 1st and 3rd modes.

Table 2: Structural and modal properties of the 3-story structure

Floor	Story Stiffness, (N/m)	Floor Mass, (kg)	Mode	Frequency (Hz)	Effective Mass, (kg)
1	676,800	30,240	1	0.418	38,017
2	306,675	18,900	2	0. 6703	8,676
3	54,285	3,960	3	1.0153	6,401

A large scale water tank, constructed from ¼ inch thick transparent plexi-glass sheets, is used as the TLD during the RTHS experiments. The physical properties of the TLD are configured to mitigate the vibrations due to the first mode of the structure by tuning its sloshing frequency to the fundamental frequency of the test structure. Table 3 summarized the geometrical and sloshing properties of the TLD.

Table 3: Properties of the tested TLD

Net length (mm)	Net width (mm)	TLD height (mm)	TLD Mass (kg)	Water height (mm)	Water mass (kg)	Sloshing hrequency (Hz)
1978	779	1200	125	300	462	0.418

During the RTHS experiments the TLD is isolated and tested physically on the shake table (i.e. experimental substructure) that simulates a segment of the building roof while the rest of structure is modelled analytically on the real-time controller (i.e. analytical substructure). In each iteration of the outer control loop, the displacement commands are computed and imposed to both analytical and experimental substructures. Then, the restoring forces computed for the analytical substructure and measured from the TLD are fed back to the integration algorithm for next step command generation. To account for the effects of the ground motion records on the test structure, the corresponding effective floor forces are computed and applied laterally to the structure while running the experiments. Figure 3 presents a schematic overview of the RTHS experiments that are carried out in this study. Two experiments are carried out for each ground motion input: the structure without TLD and the structure with one TLD tuned to the first modal frequency. Throughout the experiments conducted in this study, the ground accelerations are scaled such that peak roof displacement of the uncontrolled structure is around 110 mm .

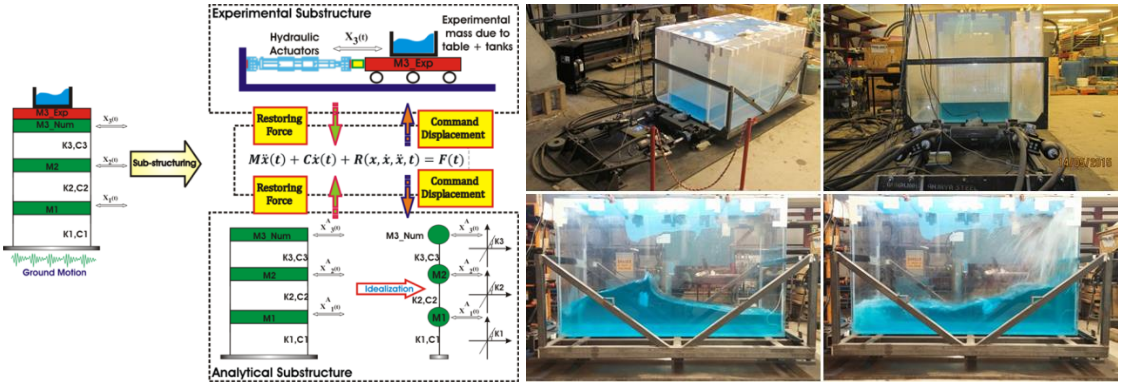

Figure 3: Schematic view of the RTHS experiments(left); experimental substructure (right)

3. PRELIMINARY SIMULATION OF TLD-STRUCTURE INTERACTION USING YU'S MODEL

3.1 TLD model by Yu et al. (1999)

In the model developed by Yu, the dissipated energy by an equivalent Nonlinear-Stiffness-Damping (NSD) model is matched by that of the TLD. A set of experimental responses are adopted to obtain the equivalent stiffness and damping ratio for the NSD model (Yu et al., 1999). The equivalent stiffness and damping ratio were investigated as a function of the wave height, water depth, amplitude of excitation and the tank size. Non-dimensional value of the amplitude (Λ) was found to be the most appropriate parameter describing the stiffness and damping ratio:

[2] $$\Lambda = \frac{A}{2a}$$

where, A is the amplitude of excitation and a is the half length of the tank in the direction of motion. Then, the equivalent damping ratio and the stiffness hardening ratio are computed as a function of Λ. The equivalent damping ratio is obtained from Equation 3:

[3] $$\xi_d = 0.5\,\Lambda^{0.35}$$

The stiffness hardening ratio, κ, which is the ratio of the equivalent stiffness of the NSD model (kd) to the TLD stiffness, is also presented for two ranges of Λ depending on the wave breaking occurrence:

[4] $\kappa = 1.075\ \Lambda^{0.007}\quad \Lambda \leq .007$ for weak wave breaking

[5] $\kappa = 2.52\ \Lambda^{0.25}\quad \Lambda \leq 0.03$ for strong wave breaking

Figure 4(a) shows a single degree of freedom oscillator with a tuned liquid damper mounted on the oscillator. Figure 4(b) shows the equivalent two-degree-of-freedom model where the TLD is replaced with the NSD model of the TLD. The equivalent model is used to investigate the interaction of TLD-structure system. The equations of motion are presented in matrix form as shown in Equation 6:

[6] $$\begin{bmatrix} m_s & 0 \\ 0 & m_d \end{bmatrix}\begin{Bmatrix} \ddot{x}_s \\ \ddot{x}_d \end{Bmatrix} + \begin{bmatrix} c_s + c_d & -c_d \\ -c_d & c_d \end{bmatrix}\begin{Bmatrix} \dot{x}_s \\ \dot{x}_d \end{Bmatrix} + \begin{bmatrix} k_s + k_d & -k_d \\ -k_d & k_d \end{bmatrix}\begin{Bmatrix} x_s \\ x_d \end{Bmatrix} = \begin{Bmatrix} F_e \\ 0 \end{Bmatrix}$$

where ms, cs, ks, xs, $\dot{x}$s and $\ddot{x}$s are the mass, damping, stiffness, displacement, velocity and acceleration of the structure, respectively. The same parameters with the subscripts "d" refer to the NSD model. In this model, the parameter A in Equation 2 is obtained from the structural displacement where the TLD is mounted on (usually the top floor). Therefore, each time the displacements cross zero, the stiffness and damping ratio of the NSD model are updated based on equations 3, 4, and 5.

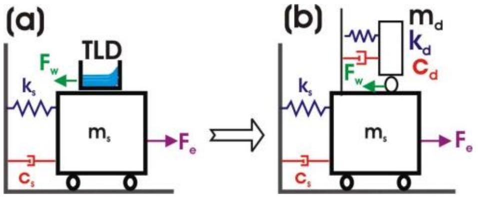

Figure 4: a) SDOF with a TLD b) SDOF with NSD model

3.2 Numerical simulation of TLD-structure system under ground motion

Prior to the RTHS experiments and to obtain a preliminary understanding of TLD-structure interaction, numerical simulation of the test structure with and without the TLD is carried out under the given seismic loadings. The Newmark-beta integration algorithm with constant acceleration and time step size of 0.001 sec is utilized to solve the equation of the motion. As a sample set of results, the roof displacement and acceleration responses of the test structure under Northridge ground acceleration are shown in Figure 5.

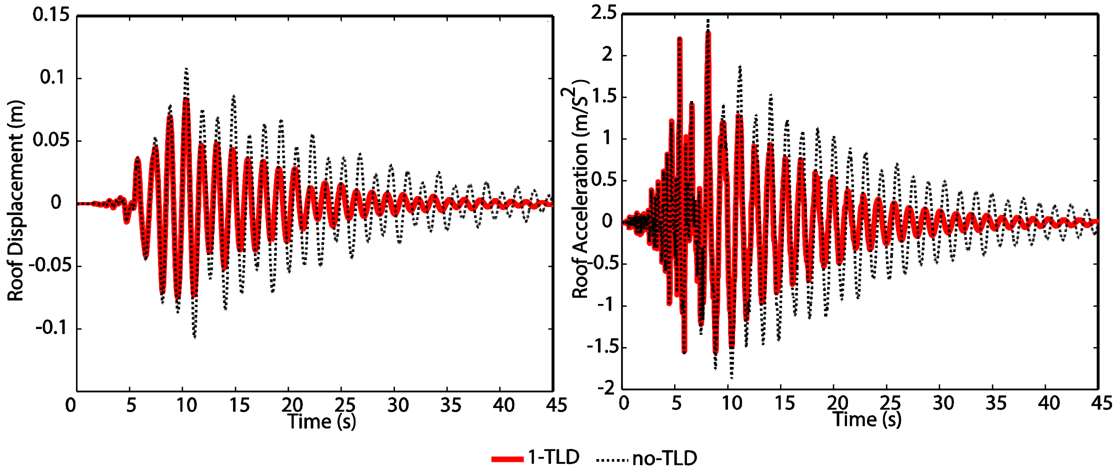

Figure 5: Roof response of the structure under Northridge 1994 (EQ3): displacement (left), acceleration (right)

4. RTHS RESULTS OF THREE STORY STRUCTURES EQUIPPED WITH TLD

As a sample set of the results, the time plots of the TLD-structure response under EQ3 ground motion (i.e. Northridge, 1994) are presented. In Figure 6, the floor displacements of the uncontrolled structure are compared to the ones of the structure with one TLD. In Figure 7, the time history plots of the floor accelerations are presented. The summary of the observations for this test case is tabulated in Table 4.

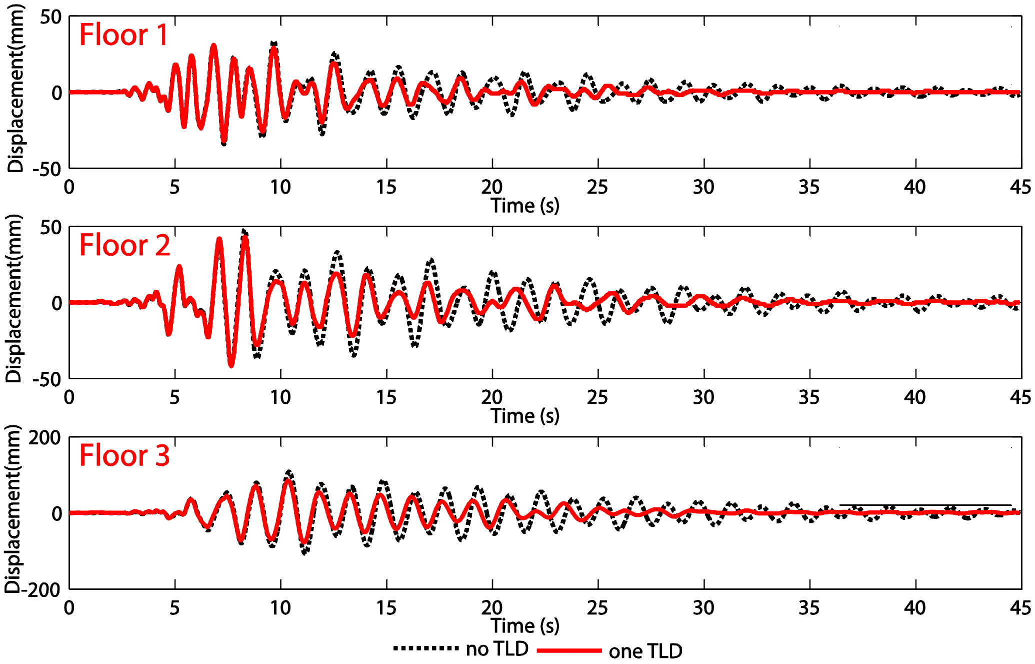

Figure 6: Displacement response of structure under EQ3, Northridge 1994

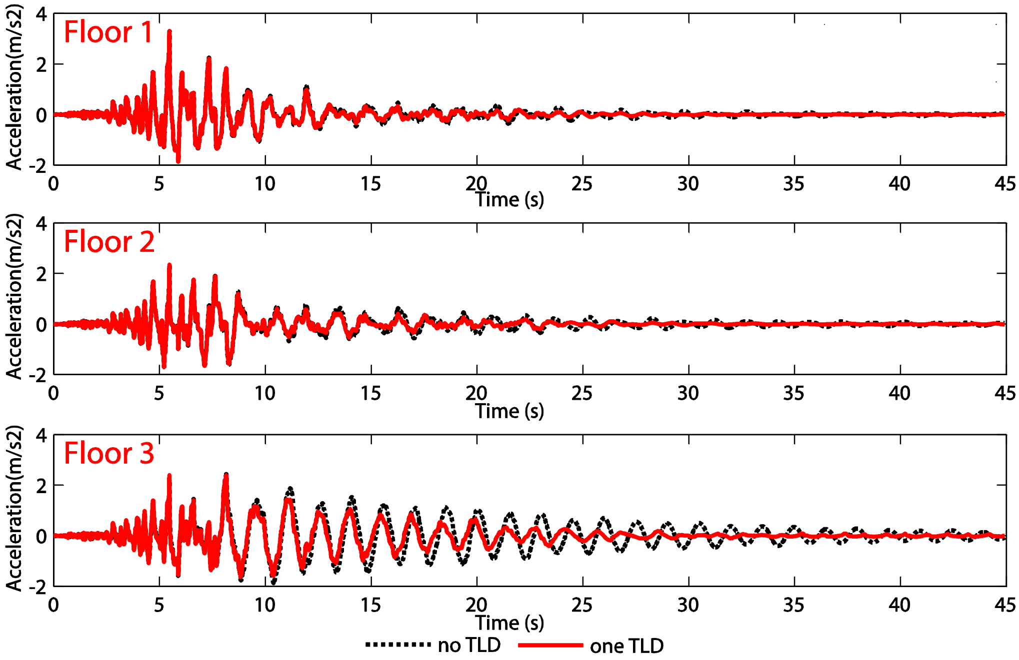

Figure 7: Acceleration response of structure under EQ3, Northridge 1994

It can be seen from these results that having one TLD tuned to the fundamental frequency of the structure is efficient in enhancing the structural response. In particular, for the test set under EQ3 (Table 4), with only one TLD, 21%reduction in the roof peak displacement, 1.7% reduction in the roof peak acceleration, 35% reduction in RMS of the roof displacements and 28% reduction on the RMS of the roof accelerations obtained. By studying the RTHS results obtained from the other earthquake records it was found that the efficiency of the TLD as a supplemental damping system is also dependant on the characteristics of the input ground motion, particularly its frequency content. Therefore, to get a general conclusion, the results obtained from other ground motions should also be studied which could be found in Ashasi-Sorkhabi (2015).

Table 4: Summary

Response type		Absolute value of response		Response reduction (%)
		no-TLD	1-TLD	no-TLD
Displacement (mm)	Floor 3 (max)	108.22	85.19	21.28
	Floor 3 (rms)	33.33	21.61	35.16
	Floor 2 (rms)	11.97	8.77	26.73
	Floor 1 (rms)	8.80	6.93	21.25
Acceleration (m/s2)	Floor 3 (max)	2.44	2.40	1.64
	Floor 3 (rms)	0.61	0.44	27.87
	Floor 3 (rms)	0.32	0.29	9.375
	Floor 1 (rms)	0.36	0.35	2.78

5. COMPARISON OF RTHS RESULTS AND NUMERICAL SIMULATION USING YU'S MODEL

In this section the results obtained from RTHS experiments are compared to the preliminary numerical simulation predictions. As a sample, the comparison results for test cases under EQ2 and EQ3 are shown Figures 8 and 9, respectively. As displayed in these figures, for the first few cycles of the test, the numerical simulation with Yu's model is generally able to track the experimental results however, gradually deviates from the RTHS results. The numerical simulation found to be under-estimating the peak displacements. As such the results obtained show more effectiveness for TLD during experiments compared to the pure simulation. This could be due to the weakness of the numerical model in modelling the TLD behavior during wave breaking that happened during the tests. Wave breaking is a nonlinear phenomenon, and previous studies showed that it is challenging for the numerical models to capture the wave breaking effects (Malekghasemi et al. 2013). Additionally, it could be clearly seen in the figures that the discrepancy between the numerical predictions and the experimental results varies with the ground motion record applied to structure.

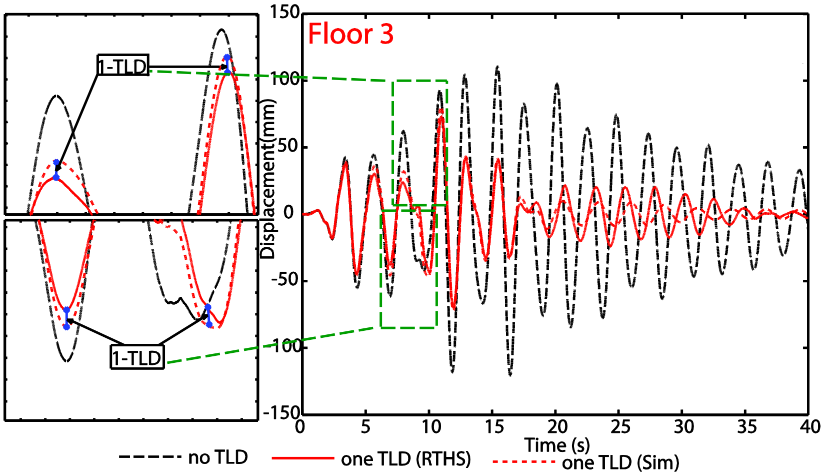

Figure 8: RTHS vs. numerical simulation with Yu's model for EQ2

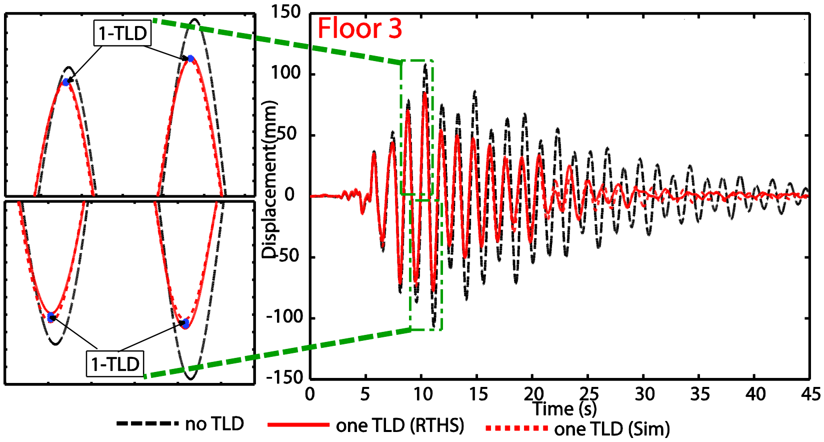

Figure 9: RTHS vs. numerical simulation with Yu’s model for EQ3

6. CONCLUSION

This paper presents a practical application of the RTHS platform that was developed earlier by the authors at the University of Toronto. The RTHS technique is employed to study the effectiveness of rectangular tuned liquid dampers (TLDs) in vibration mitigation of building structures due to seismic loads. RTHS experiments of a three story shear building equipped with a TLD on the roof level are conducted in this study considering several earthquake records. For this purpose, a large scale TLD is built and tested physically as the experimental substructure while the rest of structure is modelled numerically in the computer. The TLD that was tested in this study, to the best of authors’ knowledge, is the largest liquid damper that has ever been tested and this was possible due to the unique flexibility that the RTHS method offers where only the critical part(s) of the test structure is (are) tested physically and the rest is modeled by a numerical model. This property of the RTHS method also enables the user to easily test several configurations of the test structure as well as loading patterns since all the required changes are done on the numerical portion of the system without the need for the experimental part to be altered or re-constructed.

A preliminary analytical model of the TLD-structure interaction was formulated based on a simplified TLD model developed by Yu et al. (1999). This was followed by a numerical simulation of 3-story building equipped with a TLD subjected to seismic inputs. Due to highly nonlinear and velocity dependent characteristics of liquid dampers, available analytical models are unable to accurately capture the behavior of the TLD –structure system particularly when wave breaking occurs inside the TLD. Therefore, a comprehensive experimental study was carried out to get a sound understanding of the TLD-MDOF structure interaction utilizing the RTHS platform. It was observed from the experimental results that installing one TLD on the roof of an MDOF structure and tuning it to the first modal frequency generally improves the seismic response of the building, though, the efficiency is not constant and varies by the earthquake type.

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