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EDUCATIONAL SHAKE TABLE MODELS OF CFS SHEAR WALLS

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ABSTRACT

Small-scale, instructional shake tables, such as the UCIST shake table, are used at many colleges and universities to provide educational and research experiences in seismic behavior of structural systems. This paper describes the development of a physical model and associated educational materials that demonstrate the seismic behavior of shear walls used in cold-formed steel (CFS) building systems. Existing research has demonstrated that much of the non-linear behavior of the shear walls occurs due to the relative motion between the CFS frame and sheathing, which results in the fasteners progressively damaging the sheathing material. The shake table model consists of a hinged steel frame, a rigid sheathing panel, and fasteners surrounded by rubber bushings to provide sufficient relative motion between the frame and sheathing. The dynamic properties of the system can be varied by changing the number of fasteners, the stiffness of the rubber, and the mass of the model. The model can be excited with whitenoise, to characterize the frequency and damping, or with earthquake ground motions to study the effect of shear wall properties on the seismic response. A second type of sheathing panel, which is damaged by the fasteners, demonstrates the effect of accumulated damage on the dynamic response of the system. The physical models, along with companion computational tools in OpenSees and MATLAB, demonstrate that key aspects of the seismic behavior of CFS shear walls can be effectively reproduced in small-scale models for educational use.

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ABSTRACT

Small-scale, instructional shake tables, such as the UCIST shake table, are used at many colleges and universities to provide educational and research experiences in seismic behavior of structural systems. This paper describes the development of a physical model and associated educational materials that demonstrate the seismic behavior of shear walls used in cold-formed steel (CFS) building systems. Existing research has demonstrated that much of the non-linear behavior of the shear walls occurs due to the relative motion between the CFS frame and sheathing, which results in the fasteners progressively damaging the sheathing material. The shake table model consists of a hinged steel frame, a rigid sheathing panel, and fasteners surrounded by rubber bushings to provide sufficient relative motion between the frame and sheathing. The dynamic properties of the system can be varied by changing the number of fasteners, the stiffness of the rubber, and the mass of the model. The model can be excited with whitenoise, to characterize the frequency and damping, or with earthquake ground motions to study the effect of shear wall properties on the seismic response. A second type of sheathing panel, which is damaged by the fasteners, demonstrates the effect of accumulated damage on the dynamic response of the system. The physical models, along with companion computational tools in OpenSees and MATLAB, demonstrate that key aspects of the seismic behavior of CFS shear walls can be effectively reproduced in small-scale models for educational use.

Introduction

Cold-formed steel (CFS) structures commonly use wood-sheathed shear walls to provide lateral resistance to seismic loads. The lateral behavior of a CFS or wood-framed shear wall depends in large part on the interaction between the fasteners and sheathing [1,2]. The CFS framing alone has connections with little or no rotational stiffness and therefore deforms in the shape of a parallelogram under lateral loads (Figure 1). The sheathing, which has substantial in-plane stiffness, moves laterally and rotates about its center while its shape remains nearly rectangular. Thus the relative displaced positions of the framing and sheathing impose a displacement

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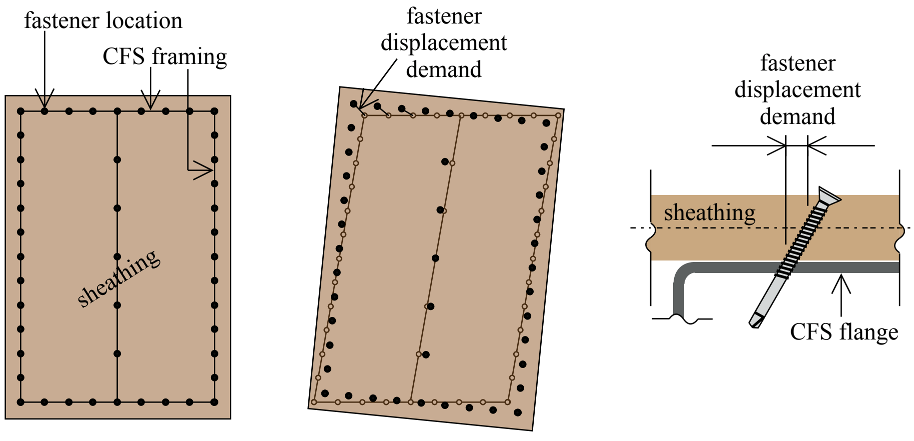


Initial Configuration

Deformed Configuration

Deformed Cross-Section Detail

Figure 1. Deformed shape of frame and panel, showing fastener displacement demand.

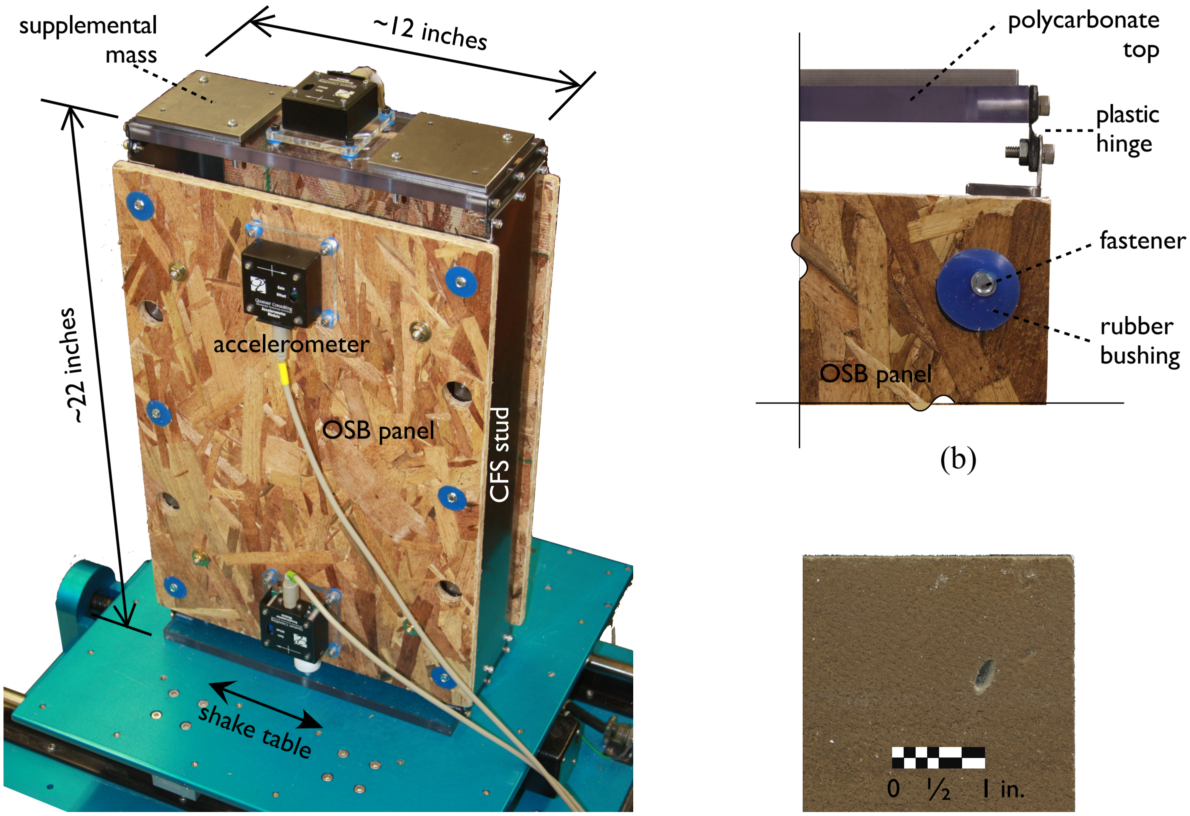
demand on the fasteners, which must be accommodated by a combination of deformation of the fasteners and damage to the sheathing. The fasteners damage the wood sheathing creating local non-linear behavior at every fastener. The lateral force-displacement response of full-scale CFS shear walls typically exhibit pinching and hysteresis as a result of the local non-linearity which occurs at each fastener [3,4].

Many colleges and universities have a small-scale shake table, such as the UCIST shake table [5], for use in advanced undergraduate or graduate courses. The UCIST project has developed educational materials that cover many common structural systems; however, no materials exist that are based on the behavior of CFS or wood-framed sheathed shear walls. This paper describes a series of physical models, experiments and companion computer structural analysis models which help students to learn about the seismic behavior and design of CFS or wood-framed sheathed shear walls. In addition, the experiments expose students to basic principles of structural dynamics, experimental methods in shake table testing, and computer modeling which are applicable to both small and large-scale shake table testing.

Design of the Model

Objectives

In creating effective small-scale shake table models it is not possible to simply scale down a full size structure. Rather, the model must reproduce key aspects of the dynamic behavior of the full scale structure. A notable early example of this approach is John Blume's 1:40 scale model of the fifteen story Alexander Building from the early 1930s [6]. The primary objective of the CFS shear wall model was to reproduce the relative motion between the hinged frame and sheathing, such that the motion was both visible to the naked eye and measurable with accelerometers. The strength and stiffness of a full-scale CFS shear wall depends on the fastener spacing [7]. A



(a) (b) (c)

Figure 2. (a) Shake table model with OSB panels. (b) Detail of fastener and rubber bushing in displaced position. (c) Detail of damage to fiberboard sheathing created by fastener motion.

secondary objective was to create physical damage in the panel due to the motion of the fasteners. Finally the dynamic properties of the structure needed to be easily modified to create various responses.

Description

The basic model, approximately 22 inches high by 12 inches wide, is constructed from a hinged frame with an oriented-strand board (OSB) sheathing panel on each face (Figure 2). In order to provide sufficient relative motion between the frame and sheathing panel, each fastener is surrounded by a 1 inch diameter rubber bushing. The model accommodates a total of 20 fasteners, 10 on each face of the model. The rubber bushing in the model represents the local area of sheathing that interacts with the fastener in a full-scale shear wall. The dynamic properties of the model can be varied by changing the number of fasteners or the stiffness of the individual rubber bushings. A second type of panel, fabricated from a compressed fiber acoustical ceiling tile, can be attached directly to the frame with screws, creating accumulated damage to the panel due to the motion of the fasteners. The total weight of the basic shake table model with OSB panels is approximately 13.5 lb. The dynamic mass of the model can be varied by adding weights in increments of 1 lb to the top of the frame or the face of the OSB panels.

The model is instrumented with three single-axis accelerometers—one on the top of the frame and two on the panel near the upper and lower edges. The panel accelerometers allow calculation of lateral and rotational accelerations of the panel. The shake table also records both its acceleration and displacement.

Rubber Bushings

The rubber bushings that surround each fastener need to be extremely soft in order to allow significant motion to occur with the relatively small mass of the structure. Various types of rubber and foam were tried for the bushings. The most successful material was found to be cast silicone rubber available in a range of durometer hardnesses. The results in this paper are based on bushings of Ecoflex rubber with hardnesses of 30 and 50 on the shore durometer OO scale. The lateral stiffness of the frame is a function of the stiffness, number and location of the bushings. The stiffness of each bushing is a function of its dimensions and the elastic constants of the rubber. The elastic properties of the rubber can be estimated from durometer hardness using data provided by the manufacturer or using mechanics-based relations [8]. Once the elastic properties (modulus and poisson ratio) of the rubber have been estimated, the radial stiffness of a cylindrical rubber bushing loaded from a central shaft and bonded to a rigid cylindrical boundary can be estimated [9]. This method only captures the initial linear stiffness of the rubber bushing whereas the response of a soft rubber may be substantially non-linear at large deformations. Using this methodology the 30-OO rubber bushing was estimated to have a radial stiffness of 13 lb/in; and the 50-OO, 30 lb/in. However, these estimated values were found to be substantially lower than those estimated from the measured natural frequencies of the shake table model.

Educational Modules

We have developed three educational modules, each centered around a physical experiment with accompanying computer structural analysis models in OpenSees [10].

Whitenoise Excitation and System Identification

Whitenoise excitation is used with system identification techniques to estimate the natural frequency and damping ratio of the structure. The natural frequency of the computational model in OpenSees is then tuned to match the measured natural frequency by adjusting the individual fastener stiffness. The UCIST shake table is supplied with a constant displacement amplitude, frequency sweep input that can be used with a fast Fourier transform to identify modal frequencies. However, the frequency sweep is only effective for flexible structures with relatively long periods, and it and can create large amplitude motions at resonance. Therefore, we implemented a whitenoise excitation test for the CFS shear wall model. The whitenoise testing occurs at very small displacement levels thereby capturing the initial linear stiffness of models which may exhibit non-linear response at higher levels of excitation. Further this approach has the advantage of introducing students to whitenoise and system identification techniques which are used with full-scale shake table testing. The whitenoise signal used has a uniform frequency spectrum between 1 and 40 Hz, peak amplitudes of ±0.12 in displacement and ±0.13g acceleration, and a duration of 120 seconds.

Table 1. Summary of twelve model configurations with key results from shake table testing and OpenSees analyses.

Model Name	Model Configuration			Shake Table Test					OpenSees Analysis			
				Whitenoise		Northridge Peak Accelerations				Northridge Peak Accelerations		
	Fastener Hardness (OO)	Fasteners per Face (no.)	Added Weight (lbs)	Natural Frequency (Hz)	Damping Ratio (%)	Frame Lateral (g)	Panel Lateral (g)	Panel Rotational (rad/s/s)	Fastener Stiffness (lb/in)	Frame Lateral (g)	Panel Lateral (g)	Panel Rotational (rad/s/s)
30-4-0	30	4	0	4.78	14.2	1.287	0.764	0.063	32.5	1.217	0.667	0.059
30-4-2	30	4	2	3.63	19.1	1.170	0.892	0.049	25.0	0.813	0.791	0.065
30-6-0	30	6	0	5.62	17.6	1.445	0.718	0.044	35.0	1.224	0.742	0.048
30-6-2	30	6	2	4.47	15.1	1.002	0.836	0.043	27.5	1.023	0.658	0.057
30-10-0	30	10	0	6.64	20.6	1.619	0.798	0.039	32.5	1.256	0.733	0.041
30-10-2	30	10	2	5.51	18.5	1.369	0.650	0.035	30.0	1.081	0.714	0.047
50-4-0	50	4	0	7.39	34.2	1.639	0.774	0.053	77.5	1.101	0.874	0.043
50-4-2	50	4	2	5.93	61.2	1.212	0.599	0.044	67.5	0.776	0.679	0.031
50-6-0	50	6	0	10.23	17.7	1.442	0.752	0.072	112.5	1.704	1.206	0.045
50-6-2	50	6	2	8.58	16.8	1.330	0.619	0.048	107.5	1.672	1.139	0.045
50-10-0	50	10	0	12.44	12.6	1.994	1.090	0.049	112.5	1.623	1.163	0.039
50-10-2	50	10	2	10.25	9.8	1.311	0.711	0.062	105.0	2.025	1.376	0.047

Table 1 summarizes the results from 12 different configurations of the model. The model name specifies the fastener hardness, the number of fasteners per face, and the supplemental mass. Figure 3(a) shows the frequency response plot and measured frequency of 3.63 Hz from Model 30-4-0; Figure 3(b), 10.25 Hz from Model 50-10-2. The measured natural frequencies in Table 1 follow the expected trends for changes in mass and stiffness. The addition of more fasteners or the use of stiffer fasteners increases the lateral frame stiffness and thus the natural frequency. The addition of mass to the top of the frame decreases the natural frequency.

The physical shake table model was also simulated in OpenSees with each bushing included as a discrete spring element connecting the hinged frame to a rigid diaphragm. Figure 4 shows the three mode shapes and frequencies calculated from OpenSees for Model 30-6-0. The first mode is primarily lateral translation on the frame. The second mode is rotation of the sheathing panel. The third mode is mixed frame translation and panel rotation in opposite directions.

The measured first modal frequency was used to estimate the fastener stiffness by varying the fastener stiffness in OpenSees until the measured and computed first modal frequencies were the same. Since the OpenSees model accounts for the location and number of

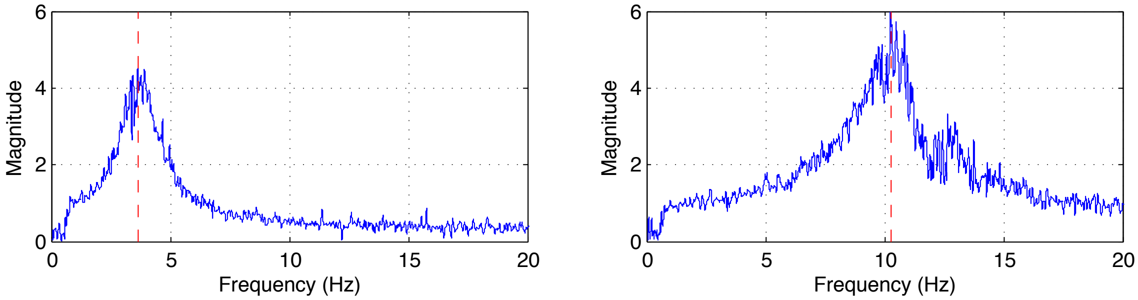


Figure 3. Frequency response functions from whitenoise testing: (a) Model 30-4-2 at 3.63 Hz, and (b) Model 50-10-2 at 10.25 Hz.

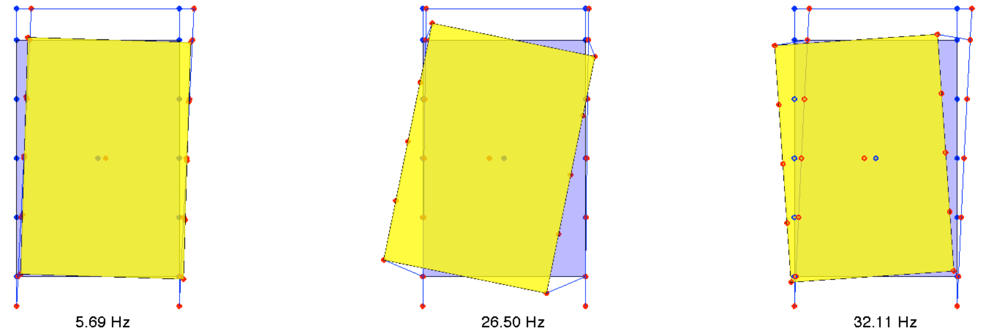


Figure 4. Modes of vibration and modal frequencies for Model 30-6-0 calculated with OpenSees.

fasteners and the dynamic mass, the estimated fastener stiffness should be the same for six configurations tested with a common fastener material. The results in Table 1 show that the fastener stiffness were generally within a limited range, although not identical. The individual fastener stiffness estimated in this manner is also substantially greater than the stiffness estimated from the material properties and bushing dimensions. Given the uncertainty associated with estimation of the bushing stiffness from the material hardness, the fastener stiffnesses from Table 1 were used for the OpenSees analyses with earthquake excitation.

Whitenoise excitation can be used to estimate the damping with two different methods—from the shape of the phase angle plot or from the half-power bandwidth of the frequency response. The damping ratios were estimated with both methods and found to be in close agreement. The damping ratios given in Table 1 were estimated based on the half-power bandwidth and are in the range of 15% to 20%. Models 50-4-0 and 50-4-2 exhibited very broad frequency response curves making estimation of natural frequency and damping highly approximate. The use of soft rubber bushings creates much greater damping than would be expected in real CFS shear walls. Further the damping response from soft rubber may not conform to the assumption of viscous damping as modeled in OpenSees.

Earthquake Excitation

The shear wall model can also be subjected to earthquake ground motions. Physical limitations of the shake table require scaling real earthquake ground motions in time using software provided with the UCIST shake table. The results presented in this paper are based on the north-south record recorded at the Sylmar Olive View Medical Center from the 1994 Northridge earthquake (PEER record number 1086, filename SYL360.AT2). The peak ground acceleration (pga) is 0.843g, discretized every 0.02 seconds. The first 30 seconds of the record were used. The scaled record is limited to a peak table displacement of ±1.2 in (3 cm) by compressing the time scale by a factor of approximately 3.2 which maintains the pga of the original ground motion but shortens the duration to 9.3 seconds with a discretization of 0.0062 seconds.

Figure 5 compares the measured lateral frame acceleration for Model 30-6-2 with that computed from the OpenSees model with the fastener stiffness and damping estimated from the

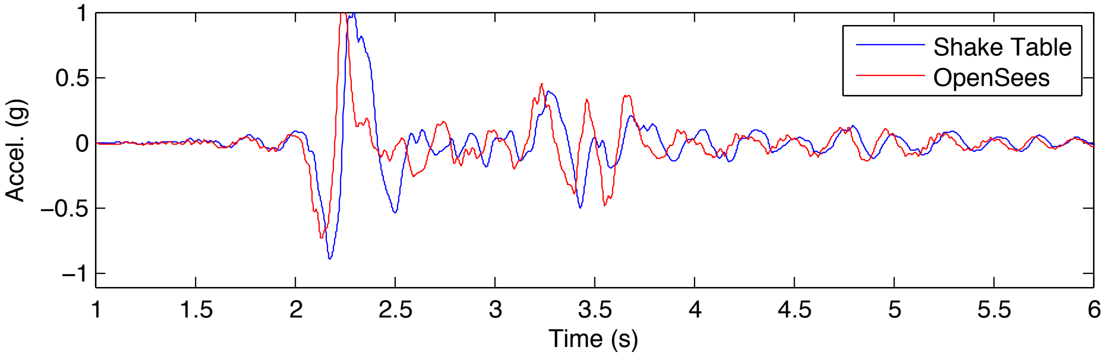


Figure 5. Comparison of lateral frame acceleration (g) of Model 30-6-2 from shake table test and OpenSees analysis.

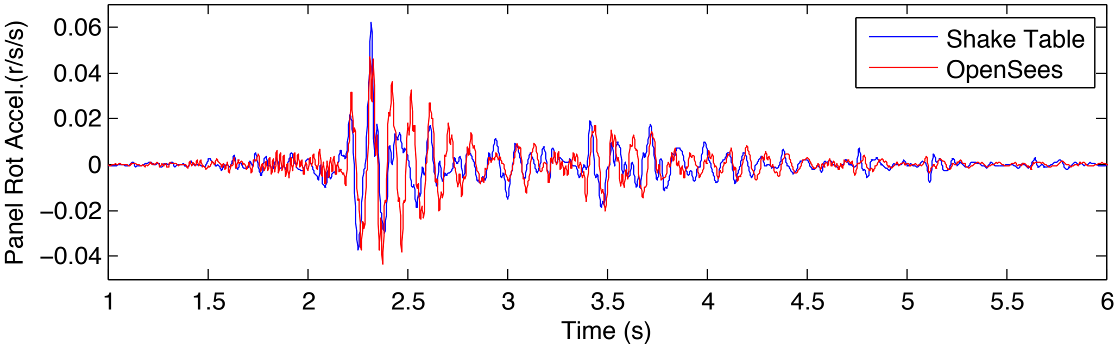


Figure 6. Comparison of panel rotational acceleration (rad/sec/sec) of Model 50-10-2 from shake table test and OpenSees analysis.

whitenoise response. Peak accelerations from the shake table and OpenSees for all 12 model configurations are summarized in Table 1. In general the OpenSees models reasonably approximate the measured responses. For some model configurations and response quantities, the response from OpenSees contained more prominent higher frequency response as compared to the shake table results; for example, the panel rotational acceleration of Model 50-10-2 shown in Figure 6. One possible strategy to reduce the response in the higher frequencies in OpenSees is to define the damping ratio independently in two modes or to use discrete damping elements at each fastener location.

Once the OpenSees model has been tuned to reasonably reproduce the first mode frequency and accelerations, it can be used to estimate other response quantities that are difficult to measure directly, such as base shear, frame displacements, relative displacements at the fasteners, forces at the fasteners, and forces in the frame members.

Sheathing Panel with Damage

The seismic performance of CFS shear walls is affected by damage to the sheathing material immediately surrounding the fasteners [1,2,3,4]. In order to simulate this behavior on the small-scale model, a second type of sheathing panel was fabricated from compressed fiber, acoustical

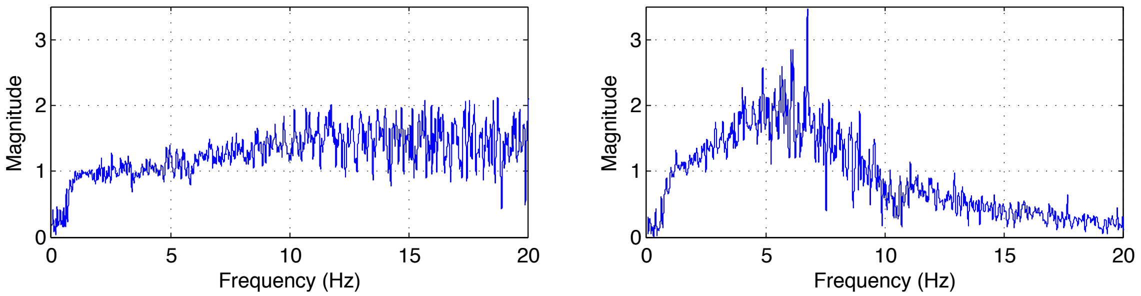


Figure 7. Frequency response functions: (a) with undamaged panel, (b) with damaged panel.

ceiling tiles and attached directly to the CFS frame with sheet metal screws. The relative motions of the frame and sheathing were sufficient for the screws to pivot in metal frame and damage the sheathing material.

In the initial undamaged state, the model responded to low-level whitenoise excitation as a rigid structure (Figure 7(a)). In order to create accumulated damage, the model was subjected to a series of 36 excitations with the Northridge ground motion. The first five excitations applied a reduced displacement amplitude Northridge ground motion with two pounds supplemental mass on the top of the frame. The remaining excitations applied the full amplitude ground motion with four pounds of supplemental mass on the top of the frame. The compressed fiber panels weigh only about 1.0 lbs each, whereas the OSB panels weigh 2.7 lbs each. Greater damage to the panels may have been achievable by adding supplemental mass to the sheathing panels.

During the 36 excitations, relative motion of the sheathing and frame increased in magnitude, becoming clearly visible. The bearing of the fasteners against the sheathing material elongated the holes in a diagonal direction (Figure 2(c)). Once the holes become enlarged beyond the initial diameter, the structure has little to no stiffness at low levels of excitation as the fasteners move across the hole opening. For larger levels of excitation the fasteners bear against the sheathing material and the structure becomes very rigid until the further damage is created. The response of the model in its damaged state is highly non-linear. In a full scale CFS shear wall, the pinching behavior of the lateral force displacement response is caused in part by the development of enlarged holes and damaged material surrounding the fasteners.

Figure 7(b) shows the frequency response to whitenoise after the 36 excitations, which has clearly changed from the rigid response. The change in frequency response reflects the physical damage that the specimen has sustained. Because the response of the damaged specimen is non-linear, the frequency response does not exhibit a well-defined peak, but a broad response over a range of frequencies.

Figure 8 shows three different time histories of the lateral frame acceleration and panel rotational acceleration for increasing levels of damage. Run 1 was excited with a scaled ground displacement of 25% nominal and two pounds of supplemental weight. Run 3 was excited with the full amplitude ground motion and two pounds of supplemental weight. Run 36 was excited

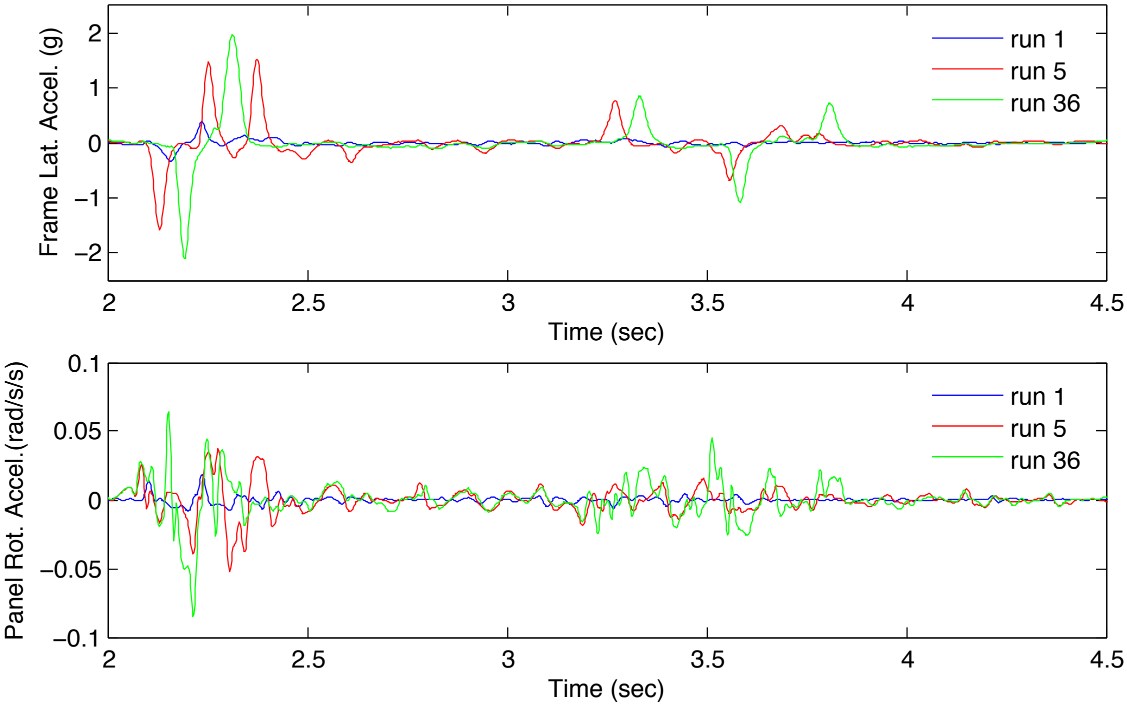


Figure 8. Lateral frame acceleration (g) and panel rotational acceleration (rad/sec/sec) for the model with sheathing damage.

with the full amplitude ground motion and four pounds of supplemental weight. The response of the frame clearly changes as the panels sustain more damage. In particular, the enlarged diagonal holes created by the damage allow substantially increased rotational motion of the panel.

Conclusions

The behavior and design of CFS shear walls under seismic loads depends in large part on the relative motion of the framing members and sheathing at the location of each individual fastener. The relative motion also creates accumulated damage to the sheathing material which causes non-linear response of the shear wall and ultimately limits its lateral strength. A small-scale, instrumented model of a CFS shear wall has been developed for use with the UCIST shake table in advanced undergraduate or graduate courses. The model demonstrates the relative motion of the framing and sheathing, and accumulated damage to the sheathing material. The stiffness and mass of the model can be easily modified. The model can be excited with whitenoise to study frequency and damping response, or with earthquake ground motions to study seismic response. Each shake table test is accompanied by computational tools in MATLAB and OpenSees.

The educational materials can be used to enrich student learning of the behavior of CFS or wood-frames shear walls, as well as fundamental experimental computer modeling techniques for shake table testing and structural dynamics. Ongoing development of the educational resources will include detailed instructions for fabricating the models and conducting the experiments, as well as software for post-processing the data and simulating the response in

OpenSees. The educational resources will include a series of laboratory modules with well-defined learning objectives, typical results, exercises for students and ideas for in-depth student projects. A detailed lab manual will be made available through the CFS-NEES website at http://www.ce.jhu.edu/cfsnees/.

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References

1. Della Corte G, Fiorino L, Landolfo R. Seismic behavior of sheathed cold-formed structures: numerical study. *Journal of Structural Engineering* 2006; 132(4):558-569.
2. Folz B, Filiatrault A. Cyclic analysis of wood shear walls. *Journal of Structural Engineering* 2001; 127(4): 433-441.
3. Fiorino L, Della Corte L, Landolfo R. Experimental tests on typical screw connections for cold-formed steel housing. *Engineering Structures* 2007; 29:1761-1773.
4. Peterman KD, Schafer BW. Hysteretic shear response of fasteners connecting sheathing to cold-formed steel studs. *Research report, CFS-NEES, RR04*; January 2013.
5. Dyke S. University Consortium on Instructional Shake Tables (UCIST). http://engineering.purdue.edu/UCIST/. Last accessed 1 November 2013.
6. Addis, B. *Building: 3,000 Years of Design, Engineering and Construction*. Phaidon 2007; 501-502.
7. American Iron and Steel Institute (AISI). *North American Standard for Cold-Formed Steel Framing–Lateral Design S213*; 2007.
8. Mix AW, Giacomin AJ. Standardized polymer durometry. *Journal of Testing and Evaluation* 2011; 39(4): 1-10.
9. Horton, JM, Tupholme, GE. Approximate radial stiffness of rubber bush mountings. Materials & Design 2006; 27:226-229.
10. McKenna F. OpenSees: The Open System for Earthquake Engineering Simulation. http://opensees.berkeley.edu. Last accessed 1 November 2013.