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EXPERIMENTAL EVALUATION OF SEISMIC RESPONSE OF WOODFRAME RESIDENTIAL CONSTRUCTION

M. H. K. Kharrazi[A], C. E. Ventura[A], H. G. L. Prion[A], G. W. Taylor[B], J. F. Lord[A] and M. Turek[A]
A Department of Civil Engineering, University of British Columbia, Canada
B TBG Seismic Consultants Ltd, Sydney, Canada

ABSTRACT: This paper presents an overview and selected results of a series of full-scale shaking-table tests of various types of low-rise woodframe residential construction typically found in Western North America. The Earthquake 99 Woodframe House Project, a collaborative university-industry research initiative, was initiated in late 1999 and completed in 2001 with the objective to investigate the seismic performance of existing housing stock in British Columbia (BC) and California. The aim was to develop procedures for improved design and retrofit. The first part of the project was mainly concentrated on current construction in California and on new proprietary framing systems, while the second part was focused on existing residential construction in British Columbia. A total of 31 uni-axial shake table tests were conducted on full-scale one and two storey houses with a footprint of 6.1 m by 7.6 m.

1. INTRODUCTION

1.1 Earthquake 99 Woodframe House Project

The Earthquake 99 Woodframe House Project was initiated in 1999 to investigate the performance of existing housing stock in British Columbia and California and develop improved design procedures and guidelines for retrofit. The testing program consisted of three phases.

Phase 1: Quasi-static and dynamic tests conducted on a number of 2.45 x 2.45m walls with different sheathing configurations (Completed in 1999).

Phase 2: Shake table testing of a single storey subsystem with different sheathing configurations (Completed in 2000).

Phase 3: Shake table testing of a two-storey house with different sheathing configurations (Completed in 2001).

Table 1 shows a list of the dynamic tests of phase 2 and 3, which were conducted during the summers of 2000 and 2001. The last phase of the project also included a pushover test on the two-storey house with engineered Oriented Strand Board (OSB) shearwalls and stucco cladding.

1.2 Motivation for the Research

The need for this research project arose from various considerations. Firstly, the Northridge earthquake in 1994 inflicted very heavy damage (in excess of $15 billion) on woodframe residential buildings in southern California, prompting engineers to consider drift control and damage prevention as a design issue in addition to the preservation of life. Secondly, the current construction practice in most of BC currently does not require the approval of a structural engineer for the majority of residential buildings, which is based on the implicit assumption of a “sound and regular” building layout and plan. This, however, does not preclude modern designs, favoring large windows and irregular plan layouts, leading to many forms of contemporary residential housing that are potentially vulnerable to heavy earthquake damage. Many of these issues are being addressed in the forthcoming update of the National Building Code of Canada, which prompted the need for pertinent information on the dynamic behavior of full-scale woodframe buildings.

The undue earthquake vulnerability of residential woodframe construction in British Columbia is exemplified by a number of serious seismic deficiencies, such as:

1. many non-engineered buildings have no effective shear walls,
2. non-engineered buildings typically have no anchorage or hold-downs of the walls;
3. horizontal board sheathing is used as a low-cost form of exterior sheathing in one and two storey buildings;
4. there is a very real risk of loss of vertical load carrying capacity in walls with finger-jointed studs, since finger-joints were never intended for the high flexural stresses that can develop in walls with large lateral deformations;
5. joists over interior load bearing walls are commonly not blocked. This lack of blocking minimizes any effective load transfer from the floor diaphragm to the wall. It also exacerbates damage by effectively eliminating the participation of interior walls in mitigating earthquake damage.

These construction deficiencies were investigated and studied in the Earthquake 99 Woodframe House project by incorporating these in selected tests. Table 1 provides a description of the tests conducted during this project. The table includes the date of the test, the ground motion being simulated and a short description of the structural system being tested. The tests were divided into two main categories, engineered and non-engineered construction. The houses with above-mentioned seismic deficiencies were tested in the second group. The purpose of these tests was to evaluate the performance of these houses and the damage associated with these deficiencies. In the category for engineered woodframe construction, structures such as the California construction style with and without innovative prefabricated nailed wood structural panel shear walls (Simpson Strong-Wall™) were tested.

In parallel with the Earthquake 99 Woodframe House project in Canada, the CUREE-Caltech Woodframe Project was conducted in the United States. This extensive project consisted of coordinated engineering and social investigations, followed by implementation strategies with the objective to reduce future earthquake losses to woodframe construction. Both projects are complementary and provide a wealth of useful information to better understand the seismic behavior of woodframe construction.

2. RESEARCH PROGRAM

2.1 Research Components

The three principal components of the Earthquake 99 research program were:

a.) analytical prediction of earthquake damage, b.) laboratory testing of full scale, multi-storey wood frame buildings and

c.) development of design aids for both technical and non-technical users.

The first component of the research program included the development of a nonlinear time history analytical software package, which was used to predict the seismic response of a building for any type of earthquake. The determination of expected drift, linked with defined damage states would then permit the estimate of building damage under a certain magnitude of earthquake. This part of the study is not being discussed any further in this paper. The second component of the research program, the laboratory testing of full scale, multi-storey wood frame buildings is described in the following section.

Table 1. The Earthquake 99 House project tests schedule

Test #	Run #	Date	Earthquake motion record	Description of the tested house specimen
1	1	31/3/2000	Sherman Oaks	Subsystem woodframe building with OSB wall system and stucco (Engineered).
	2		Canoga Park	
2	1	4/4/2000	Sherman Oaks	Subsystem woodframe building with OSB wall system without stucco (Engineered).
	2		Canoga Park	
3	1	26/4/2000	Sherman Oaks	Subsystem woodframe building with Simpson Strong-Wall™ system with stucco (Engineered)
	2		Canoga Park	
4	1	2/5/2000	Sherman Oaks	Subsystem woodframe building with Simpson Strong-Wall™ system without stucco (Engineered).
	2		Canoga Park	
5	1	5/5/2000	Nahanni	Subsystem woodframe building with horizontal board sheathing (BC) system without stucco and hold-downs (Non-Engineered).
	2		Nahanni	
6	1	10/5/2000	Nahanni	Subsystem woodframe building with horizontal board sheathing (BC) system without stucco and hold-downs, roof blocking and gypsum board on the center wall. (Non-Engineered)
	2		Nahanni	
7	1	26/6/2000	UCSD Canoga Park	Two Storey woodframe building with Simpson Strong-Wall™ system with stucco (Engineered).
8	1	13/7/2000	UCSD Canoga Park	Two Storey woodframe building with Simpson Strong-Wall™ system without stucco (Engineered).
	2		UCSD Canoga Park	
9	1	28/7/2000	Sherman Oaks	Two Storey woodframe building with OSB panel wall system without stucco (Engineered).
	2		Sherman Oaks	Two Storey woodframe building with OSB panel wall system without stucco; gypsum wallboards detached from the interior walls (Engineered).
10	1	13/6/2001	Nahanni	Two Storey woodframe building with OSB panel wall system, hold-downs and stucco. (Engineered)
	2		Landers	
	3		Kobe	
11	1	29/6/2001	Nahanni	Two Storey woodframe building with OSB panel wall system, hold-downs and rain screen stucco. (Engineered)
	2		Landers	
	3		Landers	
	4		Kobe	
12	1	17/7/2001	Landers	Two Storey woodframe building with OSB panel wall system, no stucco, hold-downs or roof blocking (Non-Engineered).
	2		Kobe	
13	1	27/7/2001	Kobe	Two Storey woodframe building with horizontal board sheathing wall system without stucco, hold-downs or roof blocking (Non-Engineered).
14	1	3/8/2001	Landers	Two Storey woodframe building with OSB panel wall system, without stucco. (Engineered)
	2		Kobe	
15	1	29/8/2001	Llayllay (175%)	Two Storey woodframe building with OSB panel wall system, without stucco. (Engineered)
16	1	12/9/2001	Llayllay (175%)	Two Storey woodframe building with OSB panel wall system, without stucco, hold-downs or roof blocking (Non-Engineered).

2.2 Methodology and Results of Shake Table Tests

Full scale laboratory dynamic testing was conducted on two types of specimens, namely single storey sub-system specimens and full two storey buildings (Figure 1). Both types of specimens were intended to model the seismic behavior of a full scale, two-storey single-family house. The house footprint was 7.6 m x 6.1 m. The sub-system test was a less expensive version of the two-storey building test. The second storey of the sub-system test structure was represented by concrete masses to represent the inertia of the second storey. The sub-system tests were conducted to examine the dynamic performance of the first storey and the results were used to refine the design of the more expensive two storey building tests.

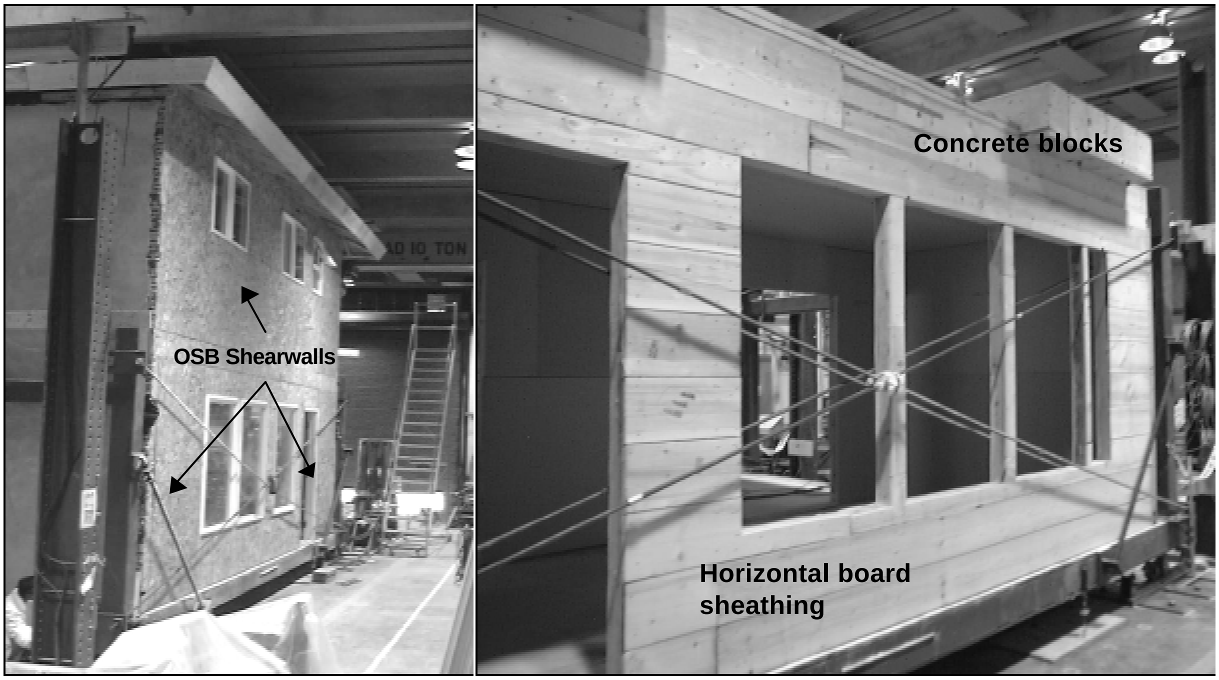


Figure 1. Two-storey house with OSB shearwalls (left) and one-storey subsystem with horizontal board sheathing (right).

All the specimens were subjected to a sequence of test procedures, namely ambient vibration testing, sinusoidal sweep testing, real earthquake motion simulation, followed by another sinusoidal sweep and ambient vibration test. The ambient vibration and sinusoidal sweep test were carried out for identification of the natural frequencies of the house. These were performed before and after each earthquake motion to identify the frequency change of the structure. This information was used to evaluate the degradation of the structural stiffness throughout and after the earthquake motion. The data was also used to obtain the natural frequencies and corresponding mode shapes. The sinusoidal sweep tests were conducted by shaking the specimen for 6 minutes with a sinusoidal wave peak displacement corresponding to 1% of the maximum stroke of the actuator, which is 4.6 mm peak displacement. The shaking frequency was gradually increased from 0.01 to 22 Hz. In recording the shake table data no anti-alias analog filter was used and all the data was recorded at a rate of 200 samples per second. Figure 2 shows the results of sinusoidal sweep tests, which were performed before and after each shake table simulation using the Kobe record in tests # 10, 14 and 13. These plots show that the decrease of the fundamental natural frequency of the non-engineered woodframe specimens is significantly larger than the decrease of fundamental natural frequency of engineered woodframe specimens (Kharrazi 2001).

2.3 Test Setup

The full scale, one and two storey buildings were constructed on top of a horizontal steel frame that acted as the building foundation. The steel frame was supported on low friction rollers that permitted movement in one direction, which was achieved with a high velocity, high stroke actuator. The actuator used has a load capacity of 310 kN and a stroke range of ±450 mm.

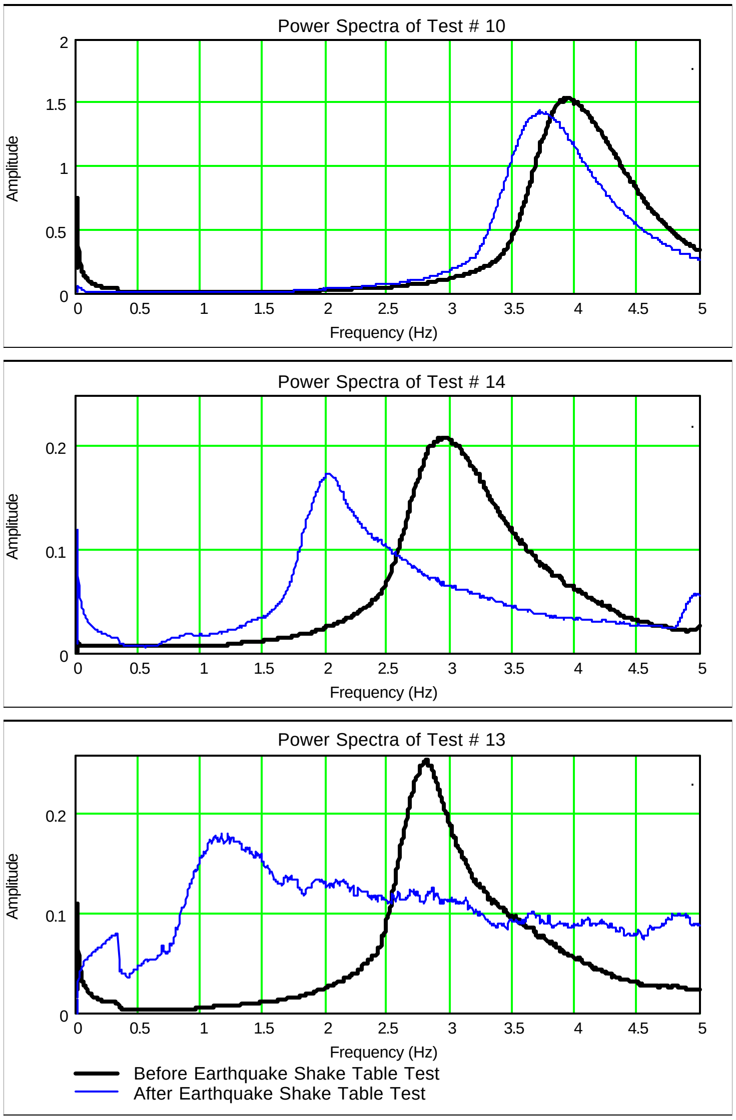


Figure 2. Power spectra of test # 10 (top), test # 14 (mid) and test #13 (bottom).

2.4 Simulated Earthquakes

Important details of the earthquake ground motion records listed in Table 1 are given in Table 2. In order to represent the expected motion of the deep alluvium deposits in the Fraser River delta in the Vancouver, BC region, the Nahanni 1985 earthquake was modified to account for the site effects. An example of the ground motions and associated response spectra used in this project is shown in Figure 3.

2.5 Selected Results

Some of the results of the Earthquake 99 Woodframe House project are presented in this paper. Figure 4 shows three load-deformation diagrams resulting from different earthquake simulation tests on the shake table, using the Kobe earthquake input motion (Tests # 10, 13 and 14). The specimens were built with three different lateral resisting configurations, namely Oriented Strand Board (OSB) sheathing with and without stucco (engineered configuration) and board sheathing (non-engineered configuration). The load used for the diagrams in Figure 4 was calculated as the base shear resulting from adding the storey shears from each floor. Each storey shear was computed as the product of the measured absolute acceleration and the floor mass. The relative displacements shown in Figure 4 correspond to the relative displacement of the first floor with respect to the moving base (drift).

Table 2. Earthquake records used for the Earthquake 99 House project

Name of the Earthquake record	Station	Peak Values			Type
		Displacement (cm)	**Velocity (cm/sec)**	**Acceleration (cm^2/sec)**	
Nahanni 85	UBC modified Nahanni	11.70	33.44	315.9	Crustal
Northridge 94	Sherman Oaks	13.13	54.90	437.14	Crustal
Northridge 94	Canoga Park	12.40	59.84	380.98	Crustal
Northridge 94	UCSD modified Canoga Park	14.13	43.90	372.30	Crustal
Kobe 95	KJMA	19.95	74.32	587.14	Crustal
Landers 92	Joshua Tree	15.73	42.71	278.38	Crustal
Chile 85	Llayllay	8.40	41.79	345.47	Subduction

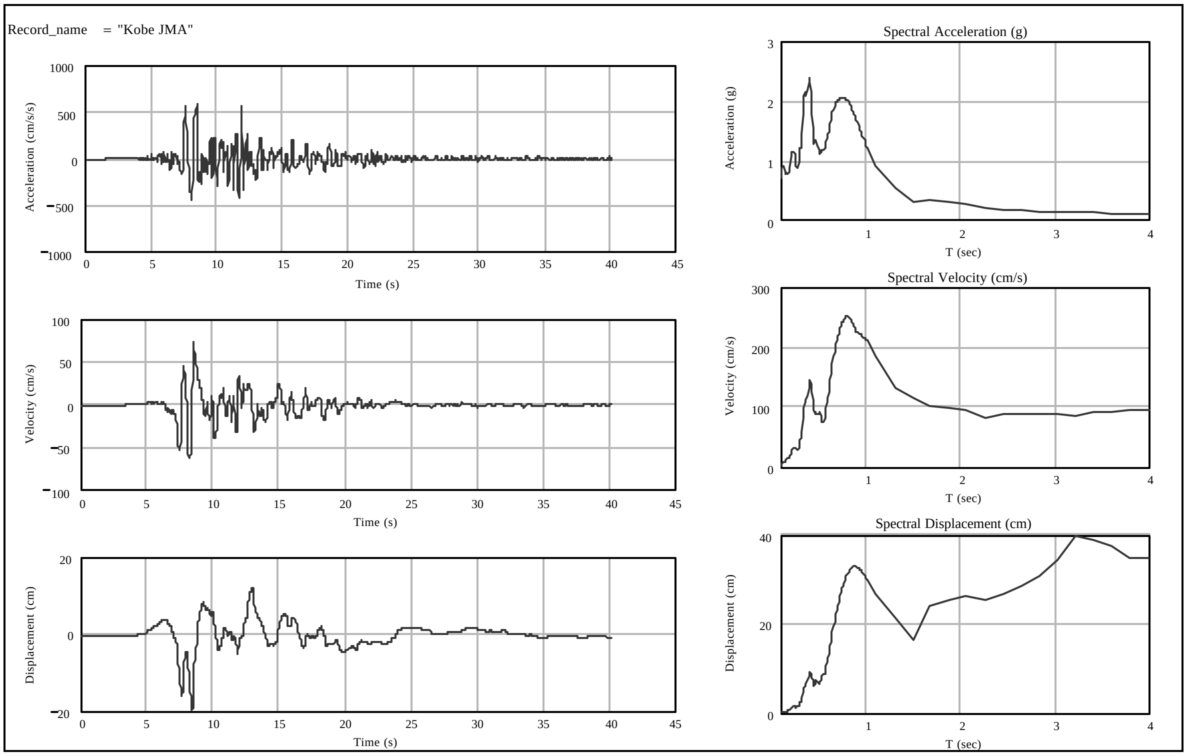


Figure 3. Kobe earthquake motion recorded at KJMA: acceleration, velocity and displacement time histories and response spectra (5% damping)

The engineered woodframe houses with OSB sheathing and stucco exhibited a very stiff and generally linear elastic behavior, compared to the non-engineered building, which underwent significant plastic deformations. Figure 5 includes photos of examples of damage observed after Test #10, 13 and 14. Significant damage, such as failure in joints, cracks in door and window frames and large cracks in gypsum walls was noted after Test #13. In contrast, the damage in specimens of Test #10 and #14 was limited to minor cracks in the gypsum wall and stucco at the corners of the wall openings.

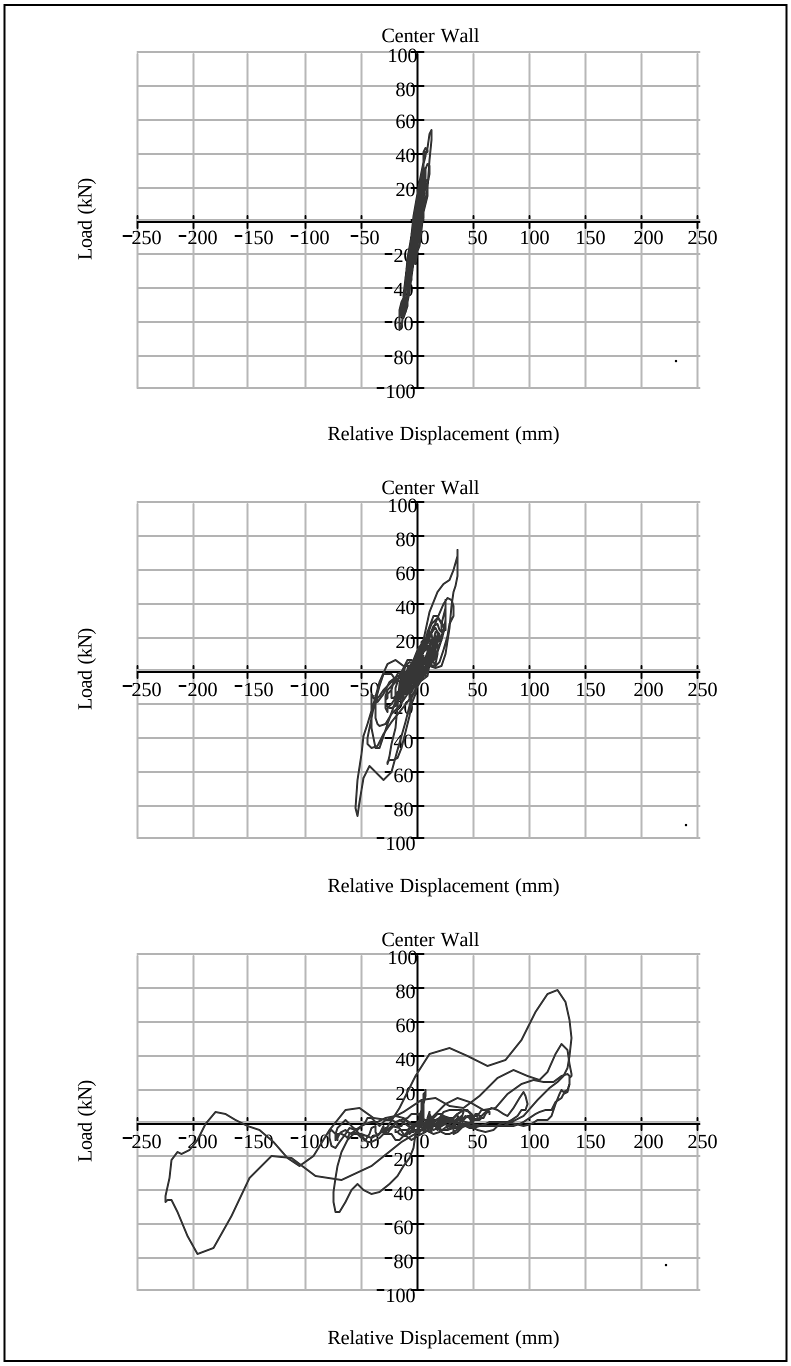


Figure 4. Load – Deformation Diagrams of Test #10 (Top), Test #14 (Mid), Test #13 (Bottom).

2.6 Interim Research Conclusions

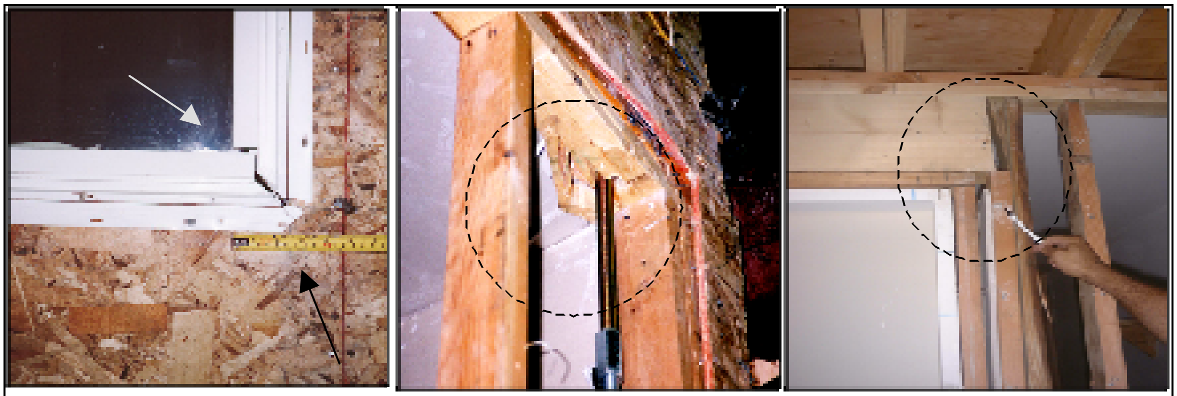
Four of the most important interim research conclusions of this project are:

Drift-Control Design: The use of an inelastic drift-control approach to seismic design is strongly advocated in contrast to the current empirical quasi-elastic force method. Drift control of actual building deflections under real earthquakes is the best method to predict and limit earthquake damage. This approach has the greatest potential for reliable earthquake performance.

Damage Prediction: Sophisticated inelastic time history analytical software has been developed to predict building drift levels for any type of earthquake. The results of the laboratory test program have been used to refine the modeling methods. The ability to reliably predict building drift is a cornerstone of earthquake damage prediction.

Non-Structural Contribution: Non-structural materials such as stucco and gypsum wallboard have a major role to play in reducing earthquake damage. Their contributions need to be recognized in the design process.

High Risk Construction Practice: There are several forms of high-risk residential construction practice in BC that need to be addressed immediately. The concerns that motivated this research about the use of horizontal board sheathing, absence of wall anchorages and hold downs and the lack of effective shear walls in certain types of residences in BC were investigated during the experimental part of this project. The results of this investigation clearly indicate that measures to address these high-risk construction practices will substantially reduce earthquake damage.



Test #13, Example of window and frame damage

Test # 13, Example of frame damage

Test #13, Example of frame damage

Test # 14, Example of gypsum wall cracks

Test #14, Example of glass and window frame damage

Test #10, Example of stucco cracks

Figure 5. Examples of damage after Tests #10, 13 and 14.

3. CONCLUSION

This paper presents some highlights and the most important preliminary research findings of an extensive project aimed at assessing the performance of existing residential buildings in Western North America. Building on the experiences of recent earthquake damage, the experimental studies have confirmed some speculations regarding the contributions from non-structural building components. The superior performance of certain building systems was shown, while weaknesses of some commonly applied building practices have been pointed out. Design recommendations are being developed and will be presented to code committees for inclusion in future revisions of design rules. Vast amounts of data, from dynamic as well as static cyclic tests, have been collected and currently await evaluation. This includes hysteretic and damping characteristics that are essential for the successful analytical modeling of buildings, while dynamic response data is needed for the verification of software programs.

4. ACKNOWLEDGMENTS

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