Report to
Canada Mortgage and Housing Corporation
Homeowner Protection Office
British Columbia Housing Management Commission

STATIC and DYNAMIC EARTHQUAKE TESTING of RAINSCREEN STUCCO SYSTEMS for BRITISH COLUMBIA RESIDENTIAL WOOD FRAME CONSTRUCTION

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Prepared by:
G.W. Taylor, H.G.L. Prion, C.E. Ventura and M. Kharrazi

TBG Seismic Consultants Ltd.
1945 Llewellyn Place
Sidney, BC V8L 1G4
Phone: (250) 656-4009
Fax: (250) 656-4007
Email: gwt@tbgsc.bc.ca

Department of Civil Engineering
University of British Columbia
2324 Main Mall
Vancouver, BC V6T 1Z4
Phone: (604) 822-3864/6946
Fax: (604) 822-6901
Email: ventura@civil.ubc.ca
prion@civil.ubc.ca

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EXECUTIVE SUMMARY

This report documents the earthquake testing of rainscreen stucco systems undertaken at the University of British Columbia (UBC) in the year 2001 for the Canada Mortgage and Housing Corporation (CMHC), the Homeowner Protection Office (HPO) and the British Columbia Housing Management Commission (BCHMC).

The primary objective of this research was a comparative earthquake performance evaluation of rainscreen and non-rainscreen stucco systems. The secondary research objective was the development of refinements to the design of rainscreen stucco systems to improve earthquake performance.

The laboratory testing program comprised eighteen (18) static tests and two (2) dynamic tests. The static tests consisted of reverse cyclic static testing of 1219 mm wide (4'0") by 2438 mm high (8'0") stucco test panels of varying forms of construction. The dynamic tests were conducted on a full scale, two storey single family house with stucco cladding subjected to ground motions of actual earthquakes.

The static test specimens comprised three non-rainscreen panels and fifteen rainscreen panels. The principal parameters investigated in the static test program were type of strapping, type and length of strapping fastener and type and length of lath fastener.

The principal conclusions of our assessment of the static test results are as follows:

(1) Pressure treated plywood strapping has better ductility than pressure treated SPF strapping.

(2) Roofing nails exhibit superior performance to common nails as strapping fasteners.

(3) Short strapping nails (38 mm or 1 1/2") precipitate brittle failure of the cladding. Long strapping nails (64 mm or 2 1/2") give better performance.

(4) Earthquake performance of panels with staple lath fasteners is superior to that for panels with nail lath fasteners. Panels with longer staples (50 mm or 2") exhibit substantially better strength than panels with shorter staples (38 mm or 1 1/2").

Three earthquakes were used in the dynamic tests of the two storey house with stucco cladding. The three earthquakes were the modified Nahanni earthquake (1985), the Landers earthquake (1992) and the Kobe JMA earthquake (1994). These earthquakes had Richter Magnitudes of 6.9, 7.5 and 6.9 respectively.

The two stucco dynamic tests comprised of subjecting the two storey house with stucco cladding to each of the above three earthquakes. The first house was clad with non-rainscreen stucco, the second house with rainscreen stucco. Both test houses sustained no significant earthquake damage.

Significant conclusions arising from our assessment of the overall static and dynamic test program are as follows:

(1) Rainscreen stucco has a comparable earthquake performance to that of non-rainscreen stucco.

(2) Stucco has the potential for substantial mitigation of earthquake damage. Refinements to current rainscreen stucco construction practice will make a major contribution to capitalizing on this impressive mitigation potential.

To optimize the earthquake performance of rainscreen stucco, we have made several specific recommendations on the type of strapping, strapping nailing and lath fastening. These specific recommendations advocate the use of preserved plywood strapping, 64 mm (2 1/2") long strapping roofing nails and 50 mm (2") stainless steel lath staples. This recommended revised form of stucco cladding is referred to as "refined stucco" when used in conjunction with code-compliant engineered shear walls.

Our overall conclusion is that both rainscreen and non-rainscreen refined stucco have the potential to effectively eliminate major structural earthquake damage in residential wood frame buildings (single family and multi-unit construction).

1.0 INTRODUCTION

This report documents the earthquake testing of rainscreen stucco systems undertaken at the University of British Columbia (UBC) in the year 2001 for the Canada Mortgage and Housing Corporation (CMHC), the Homeowner Protection Office (HPO) and the British Columbia Housing Management Commission (BCHMC). This research focused on the seismic performance of stucco exterior cladding systems for residential wood frame construction in British Columbia.

CMHC, HPO and BCHMC contracted with UBC to undertake this research in April 2001. The laboratory testing commenced in June 2001 and was completed in December 2001. This stucco research was undertaken as an integral phase of the larger overall research project "Earthquake 99 Project".

The Earthquake 99 Project is a multi-year research project that is a collaboration of TBG Seismic Consultants Ltd. of Sidney, British Columbia and the Department of Civil Engineering, University of British Columbia. The principal objective of the Earthquake 99 Project is the development of practical, cost-effective methods to substantially reduce heavy earthquake damage to residential wood frame construction.

The objective of this rainscreen stucco research was to evaluate the comparative and absolute earthquake performance of rainscreen stucco systems for residential wood frame construction in British Columbia. To achieve this objective, a static and dynamic test program was implemented to evaluate component and full scale structure behaviour when subjected to recorded earthquakes.

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This report presents details of the work program, the methods of testing used, the design of the static and dynamic test specimens and an in-depth assessment of the test results. This report concludes with recommendations for seismic refinements to current construction practice and a proposal for an extension of this research for this coming year.

2.0 NEED FOR RESEARCH

The need for this research into the earthquake performance of rainscreen stucco systems in British Columbia arose from the following considerations:

(1) Seismicity

British Columbia is located in a region of high seismicity. Compared to California, British Columbia does not have a high frequency of large, damage-inflicting earthquakes. However, the south end of Vancouver Island and the Lower Mainland will be simultaneously subjected to the largest subduction earthquake predicted for North America. The subduction earthquake has a high probability of occurrence this century.

(2) Residential Earthquake Damage

Two recent earthquakes, the 1994 Northridge Earthquake and the 1995 Kobe Earthquake, have inflicted heavy damage on residential construction in two seismically active regions of the world that are better prepared than most for large earthquakes. Without substantial improvements to the earthquake preparedness of British Columbia's housing infrastructure, the consequences of a large earthquake in this province could be devastating.

(3) Stucco Evolution

In response to large scale moisture penetration problems in contemporary residential construction in British Columbia, a new stucco exterior cladding system was developed and introduced into the British Columbia residential construction industry. This new "rainscreen" stucco system was designed to provide a capillary break and to allow drainage of bulk water, thereby substantially reducing moisture penetration. The earthquake performance of this new stucco system was unknown. The objective of this research program was to resolve this uncertainty.

(4) California Stucco

The catalyst for this research was the test results for the California phase of the Earthquake 99 Project. The California phase investigated a stucco cladding system on a framed two storey building with discrete shear walls. Exterior sheathing was used at engineered shear walls only (open studs between engineered shear walls). The lath fasteners, lath and three coat stucco for the California phase were very similar to those for the stucco research described in this report. Testing for the California phase was completed in the summer of the year 2000.

The highlight of this California phase was the unanticipated, excellent earthquake performance of the three coat California stucco system. Given the significance of the California test results and the similarities between California and British Columbia stucco, CMHC in conjunction with HPO and BCHMC determined that the comparable earthquake performance for rainscreen stucco needed to be investigated.

3.0 SCOPE OF RESEARCH

3.1 Research Objectives

The primary objective of this research was to undertake a comparative evaluation of rainscreen and non-rainscreen stucco systems to determine if there is any significant change in earthquake performance through the introduction of the rainscreen cavity.

The secondary objectives of this research were, first, to develop refinements to the design of rainscreen stucco systems for improved earthquake performance and, secondly, to assess the ability of rainscreen stucco to withstand large earthquakes.

3.2 Scope of Research

To pursue the above objectives, the scope of this research was formulated as follows:

(1) Component Static Testing

A series of eighteen (18) stucco panels were fabricated and tested to determine the influence of the rainscreen cavity, strapping materials, strapping fasteners, types of lath and lath fasteners.

These stucco panels were evaluated by reverse cyclic quasi-static testing. Each panel had the same geometry with the parametric variations as noted above.

The primary test output is the hysteretic static force versus deformation curves for each test cycle for each panel. This parametric test data is crucial for the determination of strength, ductility and earthquake damage estimates.

(2) Full Scale Dynamic Testing

Two full scale tests were conducted to compare the earthquake performance of rainscreen and non-rainscreen stucco for actual wood frame buildings subjected to actual large earthquakes.

The test buildings were two storey, 93 m^2 single family houses (plan dimensions 7.6 m in direction of shaking by 61 m) built by a residential construction contractor. The houses featured all materials and components that would have an influence on the seismic performance, including exterior cladding (stucco), drywall, doors and windows. Floor and roof loads were simulated with concrete blocks attached to the relevant surfaces.

The primary test output was the drift time history of the first and second storeys. These drift time histories permit a comparative and absolute assessment of the earthquake performance.

(3) Test Results Assessment

Upon completion of the above laboratory test program, a detailed assessment of the test results was undertaken. The parametric data from the static tests was used to predict earthquake damage (drift) for the two dynamic tests.

(4) Final Report

This report represents the final report for this wood frame stucco-clad wall assembly research. As noted in the introduction, this report concludes with recommendations on refinements to current construction practice and proposed follow-up research in the coming year.

4.0 RESEARCH PROJECT TEAM

The principal project team members for this research project are as follows:

(1) Department of Civil Engineering - University of British Columbia

Dr. Carlos Ventura, P.Eng.
Professor

Dr. Ventura is the Director of the Earthquake Engineering Research Laboratory at UBC and has assumed the role of UBC project manager for the Earthquake 99 Project.

Dr. Helmut Prion, P.Eng.
Associate Professor

Dr. Prion has assisted Dr. Ventura in all phases of the Earthquake 99 Project and has assumed full responsibility for all static testing and the day-to-day management of the stucco research phase.

Mehdi Kharrazi
Research Assistant

Mr. Kharrazi has assisted with the testing and preparation of the report and is responsible for a substantial part of the data analysis.

(2) TBG Seismic Consultants Ltd.

Dr. Graham Taylor, P.Eng.
Principal

Dr. Taylor has assumed the responsibilities of project manager for the overall Earthquake 99 Project and has worked closely with Dr. Prion on this stucco research phase.

(3) British Columbia Wall and Ceiling Association

Gregg Lowes
Executive Director

Mr. Lowes has acted a technical advisor for all stucco construction detailing incorporated in this stucco research.

(4) RDH Building Engineering Ltd.

David Young, P.Eng.
Project Engineer

Mr. Young provided technical advice on building envelope issues related to the construction of the test panels.

(5) Canada Mortgage and Housing Corporation

Silvio Plescia, P.Eng. has acted as CMHC's technical reviewer throughout this stucco research. CMHC's project management and day-to-day coordination have been provided by **Mark Salerno** and **Anand Mishra** of the BC & Yukon Regional Business Centre.

(6) Homeowner Protection Office

John Bell
Senior Research Officer

John Bell has been HPO's representative on the steering committee for the review of this research project.

(7) BC Housing

Justin Dinsdale
Building Envelope Coordinator

Justin Dinsdale has been BC Housing's representative on the steering committee for the review of this research project.

5.0 EARTHQUAKE 99 PROJECT

As noted in the Introduction, this stucco research has been undertaken as an integral phase of the larger "Earthquake 99 Project". Full details of the Earthquake 99 Project are given in the TBG report "Work Plan for Earthquake 99 Project Ninth Edition" dated June 2001.

To permit this stucco research to be placed in context within the larger Earthquake 99 Project (EQ99), we will highlight several EQ99 research findings for residential wood frame construction as follows:

(1) Several forms of contemporary British Columbia residential construction are unduly vulnerable to heavy earthquake damage.

(2) Earthquake damage can be reliably predicted for residential construction.

(3) Non-structural building components (stucco cladding, drywall) have a major influence on earthquake performance.

(4) Non-structural building components have a major role to play in the development of practical, cost-effective retrofit methods for substantial damage mitigation.

6.0 TEST SETUP

6.1 Introduction

All testing, both static and dynamic, was performed in the Structures Laboratory at the University of British Columbia.

6.2 Static Test Setup

The purpose of these static tests was to determine the variation of shear strength with lateral deformation for a range of stucco components of different forms of construction. The rate of loading for these static tests was slow compared with that for the dynamic tests as discussed in Section 6.3. The results of these static tests were used to model stucco behaviour in the analytical software developed to predict earthquake damage.

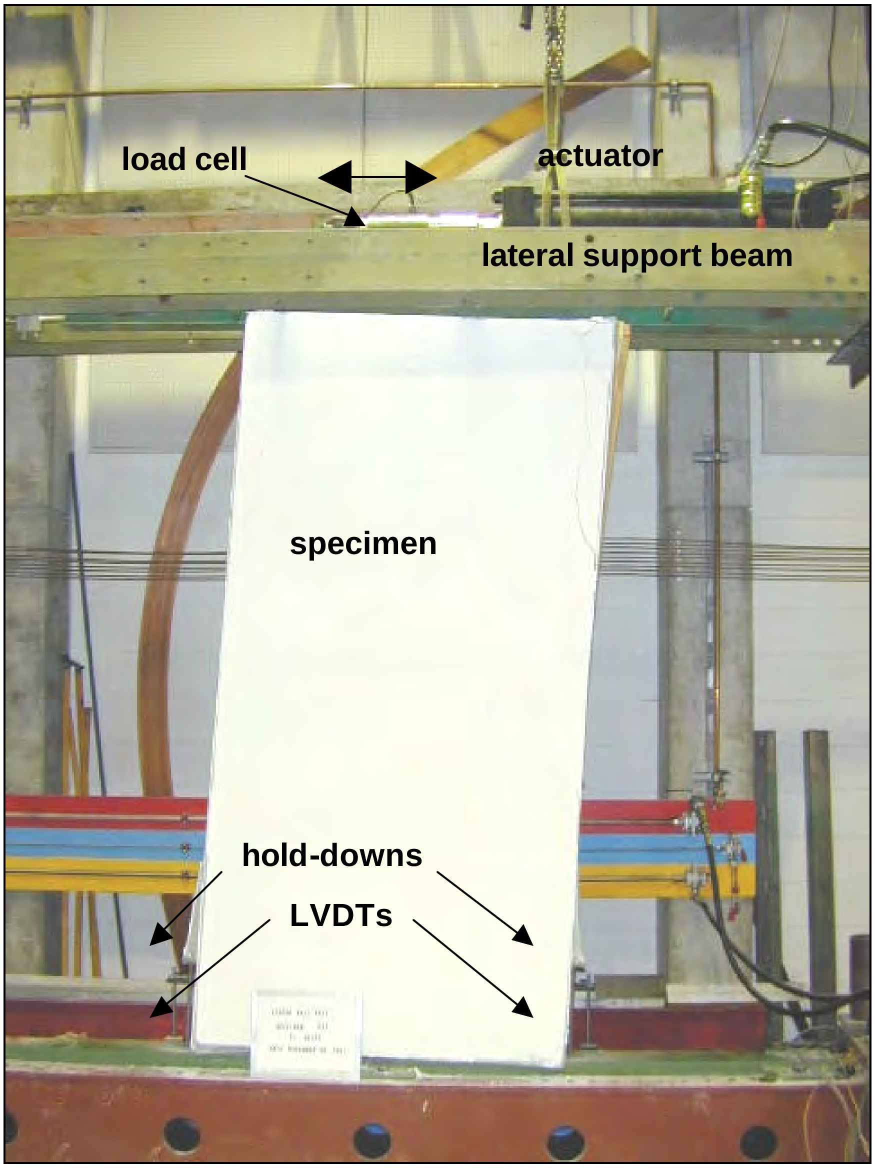


Fig. 1. Static test on stucco shear wall panel

The equipment used to perform the reverse cyclic static testing of the stucco test panels is illustrated in Appendix B. Features of the static test setup are as follows:

(1) All test panels were 2438 mm (8'0") in height.

(2) Each test panel was secured against sliding and overturning by anchor bolts and holdowns respectively.

(3) Actuator and load cell have a 550 kN capacity and a 600 mm stroke.

(4) All test data was electronically recorded.

(5) Recorded test data included resistance at top of panel, lateral deformation or drift at top of panel and uplift at each holdown.

6.3 Dynamic Test Setup

The purpose of the dynamic tests was to investigate the behaviour of full scale buildings subjected to past recorded earthquakes. The dynamic test results were especially valuable in refining and verifying the reliability of the earthquake damage estimation software that has been developed as a valuable end product of the Earthquake 99 Project.

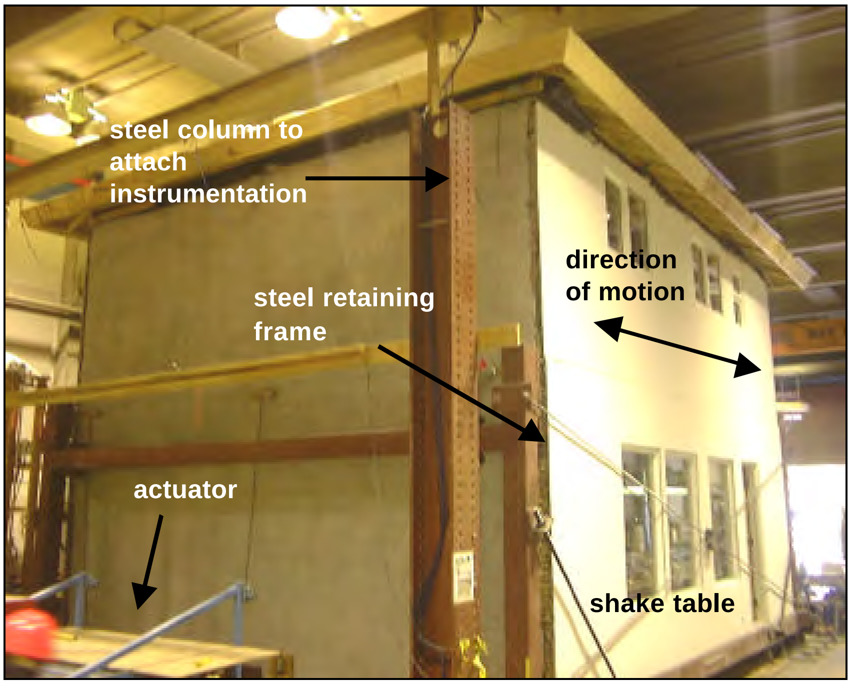


Fig. 2. Dynamic shake table test of two-storey single-family woodframe house with stucco

The test setup for the dynamic tests comprises a horizontal steel frame supported on low friction rollers that permit uni-directional motion. The steel frame acts as the foundation for the two storey test house. The steel frame is driven by a high capacity actuator mounted on the plan centreline of the frame. The actuator has a peak capacity of 300 kN and a maximum stroke of 1000 mm.

A maximum of thirty-two channels of test data were recorded electronically for each test. The primary data recorded for each test included actuator force, steel frame displacement and acceleration, first storey drift and acceleration (location of upper floor) and roof drift and acceleration.

The dynamic test setup is illustrated in the photographs given in Appendix C.

7.0 TEST SPECIMENS

7.1 Static Test Specimens

A total of eighteen stucco panels were statically tested. The test specimen identification numbers were #S-12 to #S-16, #S-18 to #S-20 and #S-27 to #S-36.

Each test panel comprised the following:

(1) Wood frame comprised of 38 mm x 89 mm members (studs, single top plate and single sole plate)

(2) Vertical strips of 89 mm wide, 11 mm thick OSB sheathing nailed to each vertical stud with 50 mm nails at 300 o.c.

(3) Vertical strapping aligned with each vertical stud and nailed to OSB sheathing for a rainscreen stucco application (strapping omitted for non-rainscreen stucco)

(4) Stucco system (three coat cementitious stucco with welded wire mesh lath)

Construction details for each stucco test panel are given in Appendix D.

7.2 Dynamic Test Specimens

Drawings for the two dynamic test specimens (two storey single family house) are given in Appendix E.

With reference to the drawings in Appendix E, the drawings for the non-rainscreen dynamic test are D1-490-60 Rev A to D1-490-68 Rev A. The stucco system for the exterior walls of this test was the same as that for static test panel #S-14 (38 mm welded wire mesh, 38 mm staples). Refer to Appendix D for details of test panel #S-14.

The only drawing for the rainscreen dynamic test is D1-490-69 Rev A. The stucco system for the exterior walls of this test was the same as that for static test panel #S-20 (heavy duty K-lath, 38 mm staples). Refer to Appendix D for details of test panel #S-20.

7.3 Staples

Staples were the dominant lath fastener for the static tests. Staples were the exclusive lath fastener for the dynamic tests. Note that nails are the dominant lath fastener in current British Columbia practice. Refer to Appendix D for test specimen lath fastener details.

The staples for static tests #S-14, #S-18 to #S-20 and both dynamic tests were electroplated 16 gauge staples, either 38 mm or 50 mm long. The staples for static tests #S-31 to #S-36 were 16 gauge stainless steel staples, either 38 mm or 50 mm long.

8.0 TEST PROCEDURES

8.1 Static Test Procedure

All static tests were reverse cyclic static tests that met the following test protocol requirements:

(1) Each test panel was subjected to a maximum of 14 cycles.

(2) Test cycles were conducted in pairs.

(3) Maximum lateral displacement at the top of the panel for each test cycle pair was 6 mm, 12 mm, 24 mm, 48 mm, 96 mm, 144 mm and 192 mm. These lateral displacements represent approximate drifts of 0.25%, 0.5%, 1%, 2%, 4%, 6% and 8% respectively.

(4) Testing was stopped when the test specimen had effectively failed or the last cycle (maximum drift) was applied.

8.2 Dynamic Test Procedure

The following three earthquakes were chosen for the dynamic testing:

(1) Modified Nahanni Earthquake (1985)

- Crustal earthquake on soft soils;
- Richter Magnitude 6.9;
- 10 km from epicentre;
- Peak Ground Acceleration (PGA) = 32.2 %g, Peak Ground Velocity (PGV) = 33.4 cm/sec, Peak Ground Displacement (PGD) = 11.7 cm.

(2) Landers Earthquake - Joshua Tree Fire Station (1992)

- Crustal earthquake on softer soils;
- Richter Magnitude 7.5;
- 15 km from epicentre;
- PGA = 28.4 %g, PGV = 42.7 cm/sec, PGD = 15.7 cm.

(3) Kobe JMA Earthquake (1994)

- Crustal earthquake on softer soils;
- Richter Magnitude 6.9;
- 2 km from epicentre;
- PGA = 59.9 %g, PGV = 74.3 cm/sec, PGD = 19.9 cm.

The three crustal earthquakes were chosen to represent a gradual progression in severity of ground motion shaking for different durations of shaking. The Modified Nahanni earthquake has the lowest severity of ground motion shaking with a duration of strong ground motion of only two (2) seconds. The Landers earthquake is of intermediate severity and its strong ground motion lasts twenty (20) seconds. It also has two significant bursts. The Kobe JMA earthquake has the highest severity of ground motion of the three earthquakes. The strong pulses for this third choice of earthquake last approximately three (3) seconds.

The test procedure for each dynamic test was as follows:

(1) A low amplitude sinusoidal ground motion with increasing frequency (sine sweep) was applied to determine the natural frequencies (first natural frequency in particular).

(2) The test structure was then subjected to the Modified Nahanni earthquake followed by the Landers earthquake.

(3) A second sine sweep was then performed to determine changes in the natural frequencies due to earthquake damage.

(4) The test structure was then subjected to the Kobe JMA earthquake followed by a third and final sine sweep.

9.0 STATIC TEST RESULTS

9.1 Introduction

As noted previously, a total of eighteen (18) stucco test panels were tested. The principal parametric variations for each test panel were as below:

(1) Non-rainscreen Test Panels

Panel No.	Lath	Lath Fasteners
#S-12	50 mm WWM*	38 mm nails
#S-13	50 mm WWM	38 mm nails
#S-14	38 mm WWM	38 mm staples

* WWM = Welded Wire Mesh

(2) Rainscreen Test Panels

Panel No.	Strapping	Lath
#S-15	SPF, 38 mm nails	38 mm WWM, 38 mm nails
#S-16	SPF, 64 mm nails	38 mm WWM, 38 mm nails
#S-18	SPF, 64 mm nails	38 mm WWM, 38 mm staples
#S-19	SPF, 64 mm nails	Exp. metal, 38 mm staples
#S-20	SPF, 64 mm nails	K-lath, 38 mm staples
#S-27	SPF, 50 mm nails	38 mm WWM, 50 mm nails
#S-28	Plywood, 50 mm nails	38 mm WWM, 50 mm nails
#S-29	SPF, 64 mm nails	38 mm WWM, 50 mm nails
#S-30	Plywood, 64 mm nails	38 mm WWM, 50 mm nails
#S-31	SPF, 64 mm nails	38 mm WWM, 38 mm staples
#S-32	Plywood, 64 mm nails	38 mm WWM, 38 mm staples
#S-33	SPF, 64 mm nails	38 mm WWM, 50 mm staples
#S-34	Plywood, 64 mm nails	38 mm WWM, 50 mm staples
#S-35	SPF, 64 mm common	K-lath, 50 mm staples
#S-36	Plywood, 64 mm common	K-lath, 50 mm staples

Note that the strapping fasteners for test panels #S-35 and #S-36 were 64 mm common nails. All other nails were roofing nails. All nails were hot-dipped galvanized.

The staples for test panel #S-31 to #S-36 were stainless steel. The staples for test panel #S-14, #S-18 to #S-20 were electroplated steel.

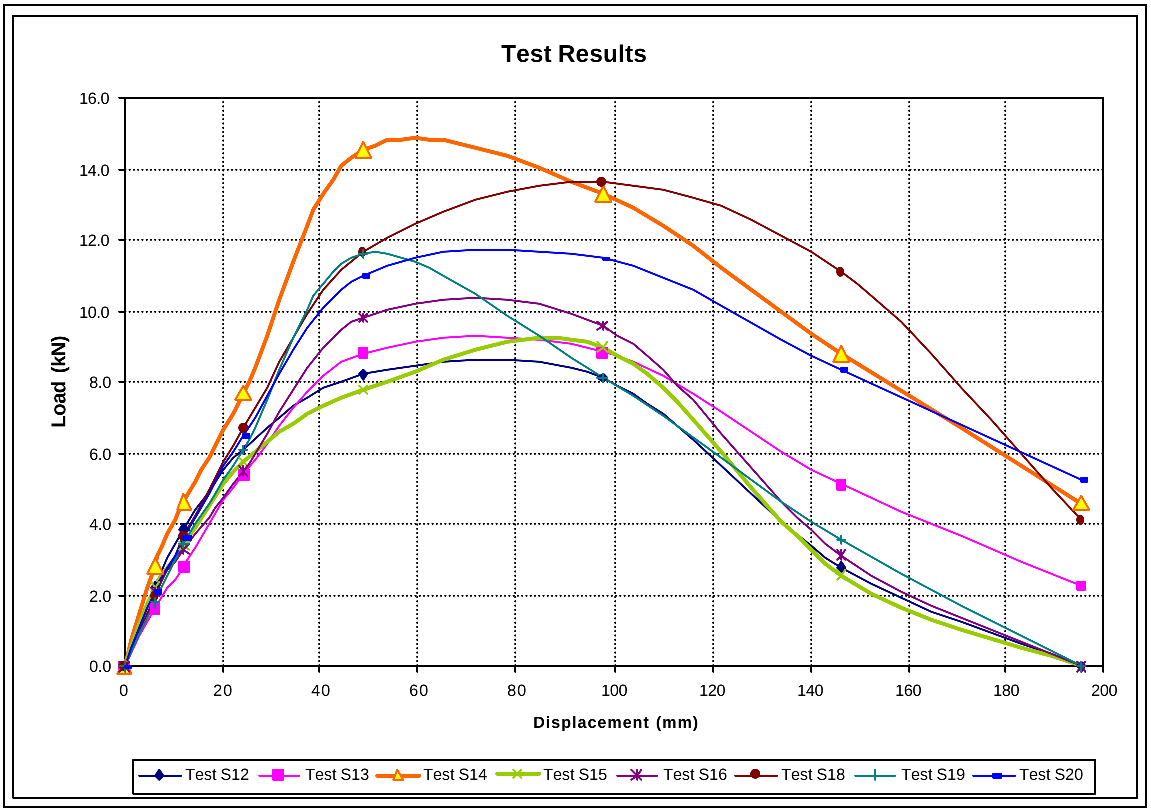
Refer to Appendix D for test panel construction details.

9.2 Static Test Results

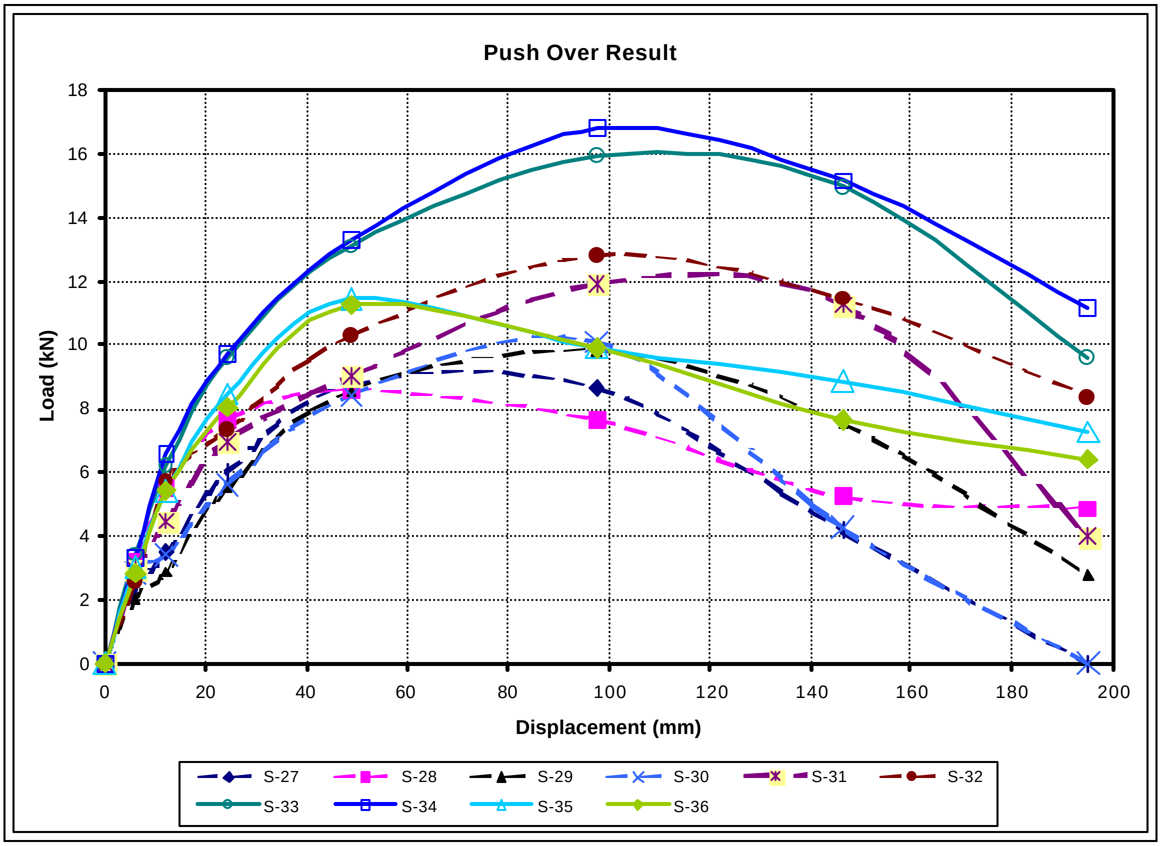
Details of the static test results are given in Appendix G. Photographs of the static testing are given in Appendix J.

A summary of the primary static test results is as below:

Panel No.	Peak Resistance & Drift	Test Termination Resistance & Drift
#S-12	16.2 kN @ 4%	6.3 kN @ 6%
#S-15	18.2 kN @ 4%	0.0 kN @ 6%
#S-34	32.8 kN @ 4%	21.8 kN @ 8%



Series 1 Static Envelope Curves



Series 2 Static Envelope Curves

9.3 Strapping Splitting Tests

As noted in Appendix D, a strapping splitting test was conducted to examine the effect of different combinations of strapping and lath fasteners on possible splitting of the two types of strapping used. An additional wood frame was constructed for this test. This additional frame was constructed free of building paper, lath and stucco for ease of examination of possible strapping splitting.

9.4 Assessment of Static Test Results

Our overall assessment of the static test results for the eighteen stucco test panels is as follows:

(1) Strapping

(a) Strapping Parameters

The three principal strapping parameters investigated in the static test program were:

- Type of strapping material;
- Type of strapping nails;
- Length of strapping nails.

(b) Strapping Material

For illustration of the influence of the type of strapping material, refer to the plotted results for the test panel pairs #S-27 and #S-28, #S-29 and #S-30, #S-31 and #S-32 and #S-33 and #S-34. The first test panel of each pair used 19x89 treated SPF strapping. The second test panel of each pair used 19x89 treated plywood strapping. The plotted results show significantly less strength degradation at high drift levels for the test panels with plywood strapping.

(c) Strapping Nail Type

Two types of strapping nails were tested. Both types of strapping nails were hot-dipped galvanized and 64 mm long. In test panel pair #S-33 and #S-34, roofing nails were used. In test panel pair #S-35 and #S-36, common nails were used. All other aspects of the construction of the four test panels were identical. The strength performance of the test panels with roofing nails was substantially better than that with common nails (almost 40% higher strength).

(d) Strapping Nail Length

Three lengths of strapping roofing nails were tested (38 mm, 50 mm and 64 mm). Test panel #S-15 used 38 mm strapping roofing nails. The entire rainscreen assemblage (strapping, sheathing, stucco) fell off the wood frame at 4% drift (100 mm displacement). This unacceptable brittle behaviour is addressed in more detail in the interim report noted in Section 9.6. A similar test panel #S-16 with 64 mm long strapping roofing nails did not exhibit this brittle behaviour. Test panel #S-27 with 50 mm strapping roofing nails also exhibited no brittle behaviour similar to that for test panel #S-16.

(e) Strapping - Overall Assessment

Our overall assessment for the strapping tests is that plywood is distinctly preferable to SPF, roofing nails are superior to common nails and roofing nails must be at least 50 mm long (64 mm length preferable).

(2) Lath

(a) Lath Type

This test program did not include type of lath as one of the principal test parameters. The limited number of lath types did not constitute a comprehensive assessment.

The four lath types used in this test program were as follows:

- 38 mm, 17 gauge welded wire mesh;
- 50 mm, 16 gauge welded wire mesh;
- Heavy duty K-lath;
- Expanded metal mesh.

(b) Lath Assessment

The three welded wire meshes used in the test program exhibited good strength and ductility characteristics. There were not sufficient tests to adequately compare each weld wire mesh.

Only one test panel used expanded metal lath (test panel #S-19). Staples were used to fasten the expanded metal lath to the sheathing and studs. This test panel exhibited inferior strength and ductility performance to comparable panels with welded wire mesh lath (test panels #S-18 and #S-20). This inferior performance was due to the difficulty of adequately fastening the main ribs.

(3) Lath Fasteners

(a) Lath Fastener Types

The four types of lath fasteners used in the test program were as follows:

- 38 mm hot-dipped galvanized roofing nails;
- 50 mm hot-dipped galvanized roofing nails;
- 38 mm stainless steel staples;
- 50 mm stainless steel staples;
- 50 mm electroplated staples.

(b) Lath Nails

Refer to test panel #S-16 for the 38 mm lath nails and test panel #S-27 for the 50 mm lath nails. The two test panels have comparable peak strengths but the 50 mm lath nails provide superior ductility. Test panel #S-16 exhibited pronounced strength degradation.

(c) Lath Staples

Refer to test panel #S-31 for the 38 mm stainless steel staples, test panel #S-33 for the 50 mm stainless steel staples and test panel #S-18 for the 38 mm electroplated staples.

Test panel #S-33 exhibited 33% more capacity than that for the shorter stainless staples. The strength results for test panel #S-18 are intermediate between the results for test panel #S-31 and test panel #S-33.

(d) Lath Fasteners - Overall Assessment

Substantial improvements in lath fastener performance are achieved by using longer fasteners and by using staples rather than nails. Our overall assessment is that 50 mm staples are the preferred lath fastener.

9.5 Code Compliance

The stucco test panels were fully compliant with the 1995 National Building Code of Canada (NBCC95) and the 1997 Uniform Building Code (US).

Given that both of the above codes apply to non-rainscreen stucco, the most significant code issue is the depth of penetration of the lath fastener. NBCC95 requires 25 mm of penetration into the framing member or full depth penetration of the sheathing. UBC97 does not have a specific penetration requirement for lath nails and staples. However, UBC97 requires lath screws to penetrate wood framing by a minimum of 16 mm.

Our test program results highlighted the significance and importance of the lath fastener penetration depth for seismic performance. For lath nailing, Test panel #S-27 (50 mm lath nails - 16 mm stud penetration) exhibited substantially better ductility than Test panel #S-16 (38 mm lath nails - 4 mm stud penetration). For lath staples, Test panel #S-33 (50 mm lath staples - 16 mm stud penetration) developed 30% higher resistance than Test panel #S-31 (38 mm lath staples - 4 mm stud penetration).

For seismic loading, our assessment is that lath fasteners (nails and staples) should meet one of the following two alternative penetration requirements:

- Minimum penetration of 25 mm into framing member.
- Total penetration of sheathing and minimum penetration of 16 mm into framing member.

9.6 Interim Test Report

Our assessment of the brittle failure initiated by short strapping nails prompted the issuing of a brief interim test report to CMHC on June 25, 2001. Refer to Appendix F for a copy of this interim report.

10.0 DYNAMIC TEST RESULTS

10.1 Dynamic Test Results

The test result details for the two dynamic tests are given in Appendix H. The non-rainscreen stucco test was conducted on June 13, 2001. The rainscreen stucco test was conducted on June 29, 2001. Photographs of the dynamic tests are given in Appendix J.

The most significant test results are the maximum drifts of the first and second storeys for the Kobe JMA earthquake. A summary of these results is as below:

Dynamic Test	**Maximum Storey Drifts (mm)***	
	First Storey	**Second Storey**
Non-rainscreen	17.2 mm	5.1 mm
Rainscreen	21.5 mm	6.9 mm

* The total drift of the second storey is the sum of the first and second storey drift

Note that the maximum inelastic storey drift permitted by the Uniform Building Code 1997 is 61 mm (2.5% of the storey height). The National Building Code of Canada 1995 (NBCC95) does not have a comparable maximum inelastic drift requirement. However, NBCC95 does specify a pseudo-inelastic maximum inter-storey drift requirement of 51 mm (2.0% of storey height).

10.2 Assessment of Dynamic Test Results

Our overall assessment of the dynamic test results is as follows:

(1) Absolute Performance

Both test structures (non-rainscreen and rainscreen) performed very well for the strong ground motions of the Kobe JMA earthquake. The maximum storey drifts were no more than 35% of the maximum drifts permitted by the UBC77 code. Neither test structure sustained any significant earthquake damage. The only evidence of earthquake damage was small cracks emanating from the re-entrant window and door corners.

(2) Comparative Performance

The earthquake performance of both tests was comparable. The non-rainscreen test house was stiffer than the rainscreen house (influence of rainscreen strapping). Within the context of maximum drifts permitted by the code, the difference between the two test results is not significant.

11.0 CONCLUSIONS

Our overall conclusions arising from this stucco research program are as follows:

(1) Current Rainscreen Stucco

From a seismic engineering perspective, current rainscreen construction practice can be substantially improved by the following refinements:

- Use of long roofing nails to secure strapping;
- Use of staples rather than nails for lath fastening;
- Replacement of SPF strapping with plywood strapping.

(2) Comparative Earthquake Performance

Rainscreen stucco has a comparable earthquake performance to that of non-rainscreen stucco.

(3) Absolute Earthquake Performance

Both rainscreen and non-rainscreen stucco performed very well when subjected to strong earthquake ground motions.

(4) Damage Mitigation

Both rainscreen and non-rainscreen refined stucco have the potential to effectively eliminate major structural earthquake damage in residential wood frame construction.

The ability of rainscreen and non-rainscreen stucco to substantially reduce earthquake damage is highly cost-effective in both the design of new construction and the retrofit of existing construction.

(5) Multi-unit Construction

The results of this research apply equally to both single family and multi-unit wood frame buildings.

12.0 RECOMMENDATIONS FOR CURRENT CONSTRUCTION PRACTICE

This stucco research has demonstrated the impressive potential of rainscreen and non-rainscreen stucco systems to substantially mitigate earthquake damage. To capitalize on this damage mitigation potential, we recommend the following refinements in current construction practice to optimize seismic performance:

(1) Strapping

The preferred type of strapping is pressure treated 19x75 plywood secured to the sheathing and studs with 64 mm hot-dripped galvanized roofing nails at 300 mm spacing.

(2) Lath

Welded wire mesh appears to perform well. The following lath was tested in this research:

- 38 mm 17 gauge WWM;
- 50 mm 16 gauge WWM;
- Heavy duty K-lath.

Comprehensive evaluation of different lath types was not part of the scope of work of this research. We did evaluate expanded metal mesh and concluded that its performance was inferior to welded wire mesh.

(3) Lath Fasteners

Staples rather than nails are recommended for fastening the lath to the sheathing and studs.

The minimum length of staples is 38 mm for non-rainscreen stucco and 50 mm for rainscreen stucco.

Maximum recommended staple spacing for studs at 400 mm spacing (600 mm stud spacing was not included in research) is 150 mm vertically and 400 mm horizontally.

We recommend the preferred practice of installing staples with the staple legs at diagonally opposite sides of the intersection of the horizontal and vertical wires of the welded wire mesh. If the vertical wire is not suitably centered on the stud to ensure staple penetration into the stud, the staple is to be installed vertically with the staple legs on either side of the horizontal wire.

(4) Staple Corrosion Protection

The recommendation for the preferred method of corrosion protection for the staples (electroplating or stainless steel) should be provided by RDH Building Engineering Ltd.

(5) Stud Penetration

All nails and staples provided in accordance with recommendation (3) are to be centered on the studs to ensure a minimum penetration of 25 mm into the stud or total penetration of the sheathing in combination with a minimum penetration of 16 mm into the stud.

All nails and staples provided in addition to those specified in recommendation (3) are exempt from the above minimum stud penetration requirement.

(6) Transition Period

Some of our above proposed refinements to current construction practice will require a transition period to facilitate adoption by the industry.

We recommend that the strapping nailing requirements given in (1) above be implemented immediately. The type of strapping and choice of lath fastener can be introduced over a short transition period.

We do not propose to make any specific recommendations on short term changes to lath nailing practice over the transition period. Staples have demonstrated a clear seismic performance superiority to nailing. We recommend the transition to lath staples be made as soon as possible, especially for buildings in high soil amplification locations.

13.0 RECOMMENDATIONS FOR FURTHER RESEARCH

We are of the opinion that the importance of stucco as a major earthquake damage mitigator warrants further complementary research to capitalize on the success of the test program presented in this report.

The primary objective of further stucco research is an in-depth assessment of the seismic performance of perforated stucco shear walls.

The presence of large wall openings has a profound influence on shear walls under lateral seismic loading. In the full scale testing of the two storey house with stucco cladding, the stucco exhibited inherent characteristics of accommodating wall openings without substantial loss of strength. This characteristic is highly significant. Further research is recommended to better assess the influence of wall openings on stucco performance.

The recommended test program should include both "engineered" and "non-engineered" perforated stucco shear walls.

Secondary objectives of further stucco research should include evaluation of different types of lath and corrosion of lath fasteners (nails, electroplated staples and stainless steel staples).