The May, 1999 issue No. 3 of the CUREe-Caltech Woodframe Project Newsletter featured an overview of the March, 1999 Invitational Workshop on Seismic Testing, Analysis and Design of Woodframe Construction. The two-day workshop brought together experts in testing and analysis and allowed them, through structured feedback, to influence the Project’s testing program. The intended outcome was the development of a technically sound research program that will now be followed over the course of the remaining 2-1/2 years of the Project. As subcontracts are awarded and specific testing or analysis projects begin, future issues of this Newsletter will keep readers informed. Investigators plan to re-evaluate each component as the Project progresses in collaboration with the Building Codes and Standards Element and with the Project and Advisory Committees.

The managers of Element 1 (Testing and Analysis) Frieder Seible, André Filiatrault and Chia-Ming Uang (Professors and Associate Professor, UC San Diego, respectively) have written a proposed research plan summarized here. The plan incorporates input from the Workshop, the Project and Advisory Committees, and external reviewers. Their strategy (Figure 1) incorporates five main research tasks with some of the shake table tests of large-scale woodframe systems to be conducted in the early stages of the Project. The results of these shake table tests will then shape the testing and analysis to be performed in the following tasks.

**Research Strategy**

The Workshop participants recognized a lack of understanding of the seismic behavior of woodframe structural systems. They discussed the fact that very few numerical models capable of analyzing the seismic behavior of three-dimensional woodframe structures currently exist, and only limited experimental data have been generated at the system level. In light of these deficiencies, Element 1 will emphasize the testing and analysis at both the component level and system level.

**Shake Table Tests**

Woodframe Project researchers believe that the level of confidence associated with the seismic analysis and design of woodframe construction is much lower than for concrete or steel construction. There is a corresponding need for more test data on the seismic response of complete full-scale woodframe structures to improve the understanding of the state-of-the-art and the state-of-practice of analysis and design. The low weight-to-strength ratio of wood structures and the availability of high performance shake tables has indicated that shake table tests appear to be the most attractive procedure for system testing.

The Testing and Analysis plan is to conduct three different shake table projects: tests of a simplified full-scale two-story single family house, tests of a full-scale multi-story...
CUREe - CALTECH WOODFRAME PROJECT
ELEMENT 1: TESTING AND ANALYSIS
RESEARCH STRATEGY

1.1.1 Single-Family House
1.1.2 Multi-Story Apartment Building
1.1.3 Simplified Model

1.2 International Benchmark
1.3.1 Rate of Loading + Loading Protocol Effects
1.3.2 Testing Protocols
1.3.3 Dynamic Characteristics

1.4.1 Anchorage
1.4.2 Diaphragms
1.4.3 Cripple Walls
1.4.4 Shear Walls
1.4.5 Soft/Weak Stories

1.4.6 Non-Structural Elements
1.4.7 Innovative Systems
1.4.8 Connections

1.5.1 Analysis Software
1.5.2 Demand Aspects
1.5.3 Reliability Analysis

Figure 1. Proposed Research Strategy for Task 1
apartment building with tuck-under parking garages, and
tests of a simplified box-type woodframe building model.
The last test will be conducted on the shake table at the
University of British Columbia (UBC) in Vancouver,
Canada, and will be part of an already funded research
project at UBC.

International Benchmark

Workshop participants also recognized the significant
amount of research on the seismic behavior of woodframe
construction conducted outside California. Project re-
searchers think the Woodframe Project could benefit by
tying into these research activities. To foster collabora-
tion, they propose to organize an International Benchmark
for which US researchers inside and outside California,
as well as the international community, will be invited to
blind-predict the inelastic seismic response of one of the
woodframe buildings tested. This will provide a unique
opportunity to assess numerical models developed within
the Woodframe Project and other research projects, or in
the realm of practice, and to improve coordination among
the Woodframe Project and international researchers.

Rate of Loading and Loading Protocol Effects

The seismic behavior of woodframe structures can be in-
fluenced by the rate of loading and by the loading proto-
col used. In order to develop common testing protocols
for the Woodframe Project, the influence of these two
parameters needs to be evaluated experimentally in the
early stages of the Project. The plan is to use a reduced
number of specimens (shearwalls) for this portion of the
program.

Three objectives of this task include 1) perform static and
dynamic cyclic tests on shearwall specimens with and
without nonstructural finish materials; 2) relate the cyclic
response obtained from other loading protocols (e.g., Se-
quential Phased Displacement Protocol) with the response
obtained with the Woodframe Project Test Protocol; and
3) evaluate the near-fault effect on the behavior of
shearwalls.

Testing Protocols

Several testing protocols have been proposed for the cy-
clic testing of woodframe structural components. It will
be necessary to establish common testing protocols for
all component tests and shake table tests. For shake table
testing, multiple seismic hazards need to be established
and multi-axis excitations need to be considered.

The main objectives are to 1) develop a long-duration
ground motion protocol for component tests; 2) develop
a near-fault protocol for component tests; 3) establish
long-duration ground motions for shake table tests; 4)
establish near-fault ground motions for shake table tests;
and 5) develop a protocol for force-controlled elements
(e.g., hold-downs).

Dynamic Characteristics of Woodframe Buildings

The representative dynamic characteristics (natural fre-
frequencies and damping) of woodframe construction are
needed to develop the testing protocol. A code-type pe-
riod formula is also necessary for design purposes. Ob-
jectives considered for this task include 1) collect exist-
ing strong-motion data from instrumented woodframe
buildings to perform system identification; 2) perform
field vibration tests on woodframe buildings to enhance
the existing database; and 3) develop a period formula
for different types of woodframe buildings.

Component Testing

This research task is composed of seven different sub-
tasks related to the testing of woodframe sub-assemblies.

Anchorage

Woodframe buildings can move off their foundations
during an earthquake, causing fires from broken gas lines
and other utility connections, and damaging foundations,
floors, walls, windows, as well as building contents. It is
very expensive to lift a woodframe building up, put it
back on its foundation, and repair the damage. This sub-
task will enable researchers to 1) evaluate the cyclic be-
behavior of various anchorage systems; 2) evaluate the ef-
effect of dead load on anchorage performance; 3) evaluate
various fastening hardware details on anchorage perform-
ance; 4) develop effective anchorage systems for retro-
f; 5) evaluate the effect of foundation concrete strength
on the anchorage performance; and 6) evaluate the effect
of the sill plate thickness on the anchorage performance.
Diaphragms

The seismic lateral loads are transmitted to shearwalls via floor and roof diaphragms. In most design applications, it is assumed that diaphragms are rigid; wood diaphragms have traditionally been considered flexible. In reality, the flexibility of diaphragms can change the dynamic characteristics of the structure and also the way the lateral loads are transmitted to shearwalls. Furthermore, the behavior of diaphragm-shearwall connections is not well understood. Tests will evaluate the in-plane stiffness, strength and internal force distribution of blocked, unblocked and glued floor diaphragms; the behavior of typical floor-wall connections; the effect of panel orientation; the effect of panel thickness; the effect of blocking substitutes; the effect of nail schedules and types; and the effect of openings and re-entrant corners.

Cripple Walls

In California, woodframe buildings frequently are built without a basement. A short wooden stud wall, called a cripple wall, on a concrete foundation often supports the first floor in such buildings. (See Figure 2.) If the cripple walls are not braced laterally during an earthquake, they can collapse and the building will fall, causing damage to the foundation, floor, walls, windows, and utility connections as well as the contents of the buildings. It may also cause fires from broken gas lines. Again, it becomes very expensive to repair the damage. Researchers will evaluate the cyclic behavior of cripple walls in order to improve their analysis and design for retrofit and new construction. The behavior of stepped cripple walls (eg., a hillside house) will be of particular interest.

Shearwalls

Woodframe construction using shearwall and diaphragm systems is a very cost-effective lateral load resisting system. Although a substantial amount of experimental work has been done over the past few decades on the structural behavior of wood-based shearwall systems, several issues required for seismic analysis and design are still missing. Woodframe Project testing will be coordinated with the FEMA-funded, City of Los Angeles - UC Irvine shearwall project (under the direction of Nick Delli...
Quadri of the Los Angeles Building and Safety Department and Professor Gerry Pardoen) for the City of Los Angeles.

Testing shearwalls will enable Project researchers to evaluate the hysteretic behavior of bearing and non-bearing shearwalls designed according to current code requirements, including the effects of openings, nonstructural finish materials, nail schedules, panel thicknesses, nail types, and lower grade framing lumber on the performance of shearwalls. Other topics include the behavior of stapled shearwalls, the effect of blocked vs. unblocked shearwalls, and the effect of the omission of hold-down connections and lumber deterioration (e.g., moisture), multiple-component timber shearwalls, aspect ratios, boundary conditions, panel type (e.g., plywood, OSB, etc.), construction flaws, and the behavior of multi-story shearwalls.

Soft/Weak Stories

Woodframe apartment buildings with a row of garages on one side of the ground floor are vulnerable to soft or weak story collapse. (See Figure 3.) The partial collapse of the Northridge Meadows Apartment Building and numerous other apartment buildings during the Northridge Earthquake has shown the vulnerability of this type of building.

Researchers will evaluate various seismic design and retrofit strategies (steel frames, shearwalls, bracing, etc.) for woodframe buildings with first-floor parking garages.

Nonstructural Elements

A large portion of the cost associated with the repair of a
woodframe building after an earthquake is related to damage to nonstructural components. The relation between damage to nonstructural components and structural response needs to be established for performance-based design. This task will require an extensive literature review. If necessary, limited testing may be considered. Researchers will study how nonstructural components affect the seismic response of woodframe structures, measure the damage threshold of various nonstructural components, and establish structural response criteria to limit damage to components as well as a repair cost–damage relationship.

Innovative Systems

Innovative seismic design strategies such as energy dissipation and isolation systems have been developed for steel and concrete buildings and for some masonry ones as well. So far, only very limited research has been conducted to develop similar systems for woodframe buildings. Project researchers plan to evaluate the applicability of innovative systems to woodframe construction.

Connections

Although a substantial amount of experimental work has been done on the monotonic and cyclic behavior of sheathing-to-framing connections, information is still needed for a complete understanding of sub-assemblage behavior. Additional testing is needed to develop an appropriate database of connector hysteretic models to be implemented in the software package. Project researchers plan to review the literature on monotonic and cyclic testing of various types of sheathing-to-framing connections, and evaluate the effect of sheathing, framing and connector types, nail penetration, and loading orientation with respect to the sheathing and the framing.

Analysis

Three different projects are related to the seismic analysis of woodframe construction: Analysis Software, Demand Aspects, and Reliability Analysis.

Analysis Software

Current structural analysis packages are not very efficient in modeling woodframe buildings. Several inherent properties of woodframe construction (e.g., material properties, lateral load-resisting systems, etc.) make analyses of woodframe construction less precise than analyses of concrete or steel structures. For example, hysteretic rules for woodframe members are usually not available in commercial nonlinear dynamic analysis packages. Project researchers plan to develop a specialized computer platform for the nonlinear seismic analysis of woodframe buildings with user-friendly pre- and post-processors. A particular emphasis of the software will be towards nonlinear pushover analyses of three-dimensional woodframe structures.

Demand Aspects

In order to develop a performance-based seismic design procedure for woodframe construction, deformation and force demands must be established for various earthquake intensities. Furthermore, design engineers have questioned the applicability for woodframe construction of the redundancy factors developed for other materials. Studies by Project investigators will include evaluation of the seismic demands on various components of both conventional and engineered woodframe structures, deformation demands in deformation-controlled elements of woodframe structures (e.g., shearwalls), and force demands in force-controlled elements of woodframe structures (e.g., hold-downs). They will establish redundancy factors for woodframe structures and evaluate the torsional effects on woodframe buildings.

Reliability Analysis

Considering the large uncertainties inherent to wood properties and seismic loading, a performance-based seismic design procedure needs to be established in a reliability-based framework. Project investigators plan to integrate information from other tasks to develop a reliability-based framework for the seismic design of woodframe construction.
Shake Table Tests of a Simplified Two-Story Single-Family House: Proposed Test Structure and Testing Protocol

One of two shake table tests of large-scale woodframe systems will be conducted in the early stages of the Woodframe Project, and results of these shake table tests will shape the testing and analysis to be performed in subsequent tasks. A proposed test structure and testing protocol for a simplified full-scale two-story single-family house, recently submitted for review, are briefly described in this article. Testing at the University of California at San Diego, under the direction of André Filiatrault, is scheduled for fall, 1999.

The Test Structure

The structure to be built and used for testing represents a simplified full-scale two-story single-family house that incorporates several characteristics of recent residential construction. Simple construction promotes clear interpretation, and so does not include complicated geometry features such as floor cantilevers and roof offsets. Woodframe Project Manager of Element 3 (Codes and Standards) John Coil, assisted by Kelly Cobeen and James Russell, collaborated on the architectural and structural plans for the test structure, which have been circulated for review by a number of practicing engineers.

The footprint of the structure is 16 ft x 20 ft. It will be anchored to the shake table in such a way that shaking will occur along the short dimension of the structure (north-south direction). The construction will be full scale, but the plan dimensions of the structure are smaller than would be typical for a residence due to the restrictions of the shake table. Designers attempted to maintain the character of typical shearwalls within the smaller plan dimensions.

The lateral load resisting system of the test structure parallel to the shaking direction (east and west elevations) consists of exterior shearwalls along with two interior shearwalls on the second floor. The openings of these walls have been designed to replicate effects induced by a large garage door opening on one side of a residence. The lateral load-resisting shearwalls support gravity loads with an interior bearing wall and a glued laminated beam on the second floor. In the north and south elevations, exterior shearwalls provide a torsional restraint to the test structure. The openings in these walls, which are perpendicular to the shaking direction, have been kept conservative and symmetrical to aid in simplifying the interpretation of the experimental results.

The design has been prepared based on the engineering design provisions of the 1994 edition of the Uniform Building Code (UBC, 1994) and common design practice in California. The design assumes seismic zone 4 and an $R_w$ factor of 6, used for shearwalls with a combination of wood structural panel and gypboard sheathing, and a bearing wall system. In keeping with the higher
shearwall aspect ratios permitted by the 1994 UBC, the
design aspect ratios go up to 2.7. The 1997 UBC require-
ment for steel plate washers at anchor bolts and 3x foun-
dation sill plates for shearwall loads over 350 plf have
been incorporated. This new requirement attempts to keep
the sill from being the weak link in a test seeking to de-
terminate building behavior. One aspect in which the resi-
dence design is different from typical California construc-
tion is the specification of “dry” (19% maximum mois-
ture content) solid sawn framing. This is intended to help
reduce the variation of moisture content over the dura-
tion of the testing.

All wood structural panels will be sheathed with Oriented
Strand Board (OSB) and will be fastened to the framing
with common nails or gun nails of equivalent diameter.
The second floor structural walls will be tied to the first
floor walls by steel straps. The first floor walls will be
tied down to the foundation by steel connector devices.

Testing Objectives

The goals of the shake table testing of the sim-
plified two-story house are intended to pro-
vide data for use in other Project activities
(e.g., development of analytic tools, integra-
tion of results from other component and full
scale tests, recommendations for code
changes, etc.). To maximize the information
that can be gathered and learned, multiple tests
will be conducted at various stages of comple-
tion of the building’s lateral force resisting
system. The primary objective of this shake
table testing is to measure and quantify the
building’s overall dynamic characteristics and
its component responses for various construction configu-
rations, and to document how the distribution of forces
within the structure may change between the various con-
figurations. However, another fundamental objective is
to establish relationships between ground motion sever-
ity, deflections, damage and repair costs, and to provide
data for defining realistic performance objectives. The
data collected from the tests will be used in the develop-
ment of analytic models for complete buildings and the
prediction of damage states and failure modes. The shake
table test results will also provide a basis for calibration
of the Project’s other individual component and full scale
building test results and their integration into analytic
models.

UCSD Uniaxial Seismic Simulation Facility

The seismic tests will be conducted on the uniaxial earth-
quake simulation system at UC San Diego, featuring a
4.8 ton shake table of all-welded steel construction.

The control system of the shake table includes an ad-
vanced, second-generation digital controller incorporat-
ing a Three Variable Control (TVC), together with Adap-
tive Inverse Control (AIC), On-Line Iteration (OLI) tech-
niques and Resonance Canceling Notch Filters. This ad-
vanced control system allows the reproduction of earth-
quake ground motions with high fidelity.
Experimental Set-Up

The test structure will be anchored to the shake table by a rigid steel base that will be bolted on the top plate of the table. The base will incorporate outrigger arms in the east and west directions to accommodate the footprint of the test structure. Threaded steel studs, welded to the top flange of the steel base, will be used as anchor bolts for the sill plates. A structural reaction wall is available near the shake table to perform quasi-static and cyclic testing by linking the second floor or roof of the test structure to the wall and using the shake table as a horizontal loading device.

Construction and Testing Sequences

To maximize the experimental data that can be extracted from the test structure, multiple quasi-static and shake table tests will be conducted at various stages of construction. The test structure will be repaired between test stages to return the lateral load resisting system to its initial strength and stiffness. Three types of tests will be performed at various stages of construction:

Quasi-Static and Cyclic Tests

The purpose of the quasi-static and cyclic tests is to evaluate the hysteretic behavior of various configurations of the lateral load-resisting system of the test structure. Tests will be performed in the direction of the shaking by linking the second floor diaphragm or the roof of the test structure to the reaction wall adjacent to the shake table, using the shake table as a horizontal loading ram. A moderate drift level (estimated at 0.25%) will prevent significant damage to the structure. Tests will also be conducted in the direction perpendicular to the shaking at the very end of the test program. These tests will require the fabrication of a reaction frame to load the second floor diaphragm and the roof of the test structure with four hydraulic actuators, and will be conducted up to a drift level corresponding to the capacity of the lateral load-resisting system of the test structure (estimated at 4% drift).

Frequency and Damping Estimation Tests

The purpose of the frequency evaluation tests is to identify the natural frequencies and mode shapes of the test structure at various construction phases and damage states.

Figure 3 Proposed Locations of the String Potentiometers and Accelerometers in the North-South and East-West Directions.
The purpose of the damping evaluation tests is to estimate the modal equivalent viscous damping ratios of the test structure at various construction phases and damage states.

**Simulation of Ground Motions**

The purpose of the seismic tests is to examine the response of the test structure under simulated earthquake ground motions. Professor Helmut Krawinkler is currently developing these ground motions at Stanford University under Task 1.3.2 of the CUREe-Caltech Woodframe Project. For each test stage, various intensities will be considered for each ground motion record. These intensities will be established based on nonlinear time-history dynamic analyses of the test structure under the different ground motions provided by Krawinkler. Various performance limit-states will be considered: fully operational limit-state, operational limit-state, life safety limit-state, and near collapse limit-state.

**Instrumentation**

More than 250 channels will be used to collect as much information as possible within the limits of the existing high-speed data acquisition system at UC San Diego. The global response (horizontal displacements and accelerations) of the test structure and the shake table will be monitored by 21 string potentiometers and 33 accelerometers. All displacement measurements will be taken from an absolute reference located outside of the shake table surface.

All steel straps will be instrumented by strain gauges. Special load cells attached to the anchor bolts will monitor the loads in all hold-down devices. The racking deformation of each shearwall will be measured by pairs of diagonally mounted displacement transducers. The west wall of the test structure will include detailed instrumentation to monitor the relative motions between the framing, the nails, and the sheathing. The uplift at the ends of each shearwall will be measured by displacement transducers between the end studs and the foundation. The shear deformations of the second floor diaphragm will be monitored by six pairs of diagonally-mounted displacement transducers, while the flexural deformations will be obtained by displacement transducers installed at various locations on the north and south chords of the diaphragm. Horizontal accelerometers will also be installed along the east-west span of the second floor diaphragm to obtain an estimate of the distribution of inertia forces in the diaphragm. Displacement transducers will also monitor the slippage between the sill and the foundation in the north-south and east-west directions. Finally, special devices incorporating load-cells and strain gauges are currently being developed to directly measure the in-plane shear force induced in each shearwall of the test structure.

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For more information on the two-story house testing, contact:

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For more information on the CUREe-Caltech Woodframe Project, visit the CUREe website and click on “Projects:”  
http://www.curre.org
Order Form

The Proceedings of the Invitational Workshop on Seismic Testing, Analysis and Design of Woodframe Construction is now available.

Fifty-six experts in the field participated in the Workshop, which was held March 5 and 6, 1999 in Los Angeles. The 175-page Proceedings contains a total of 24 papers, summary reports on the three group sessions, and a collection of comments by the workshop participants.

To purchase a copy of the Proceedings, please send a check or money order (no credit cards), payable to CUREe, to:

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