

FINITE ELEMENT ANALYSIS OF A CONVENTIONAL WOOD SHEAR
WALL USING DETAILED NAIL PARAMETERS AND
THERMAL PERFORMANCE OF VARIOUS
GREEN FRAMING ARRANGEMENTS

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By

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ABSTRACT

Finite Element Analysis of a Conventional Wood Shear Wall Using Detailed Nail Parameters and Thermal Performance of Various Green Framing Arrangements

By

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Finite element analysis of nonlinear nailing parameters using OpenSees was used to model the load-displacement response of a conventional wood shear wall. Load-displacement data from previous physical testing and CASHEW modeling were used to compare and assess the abilities and shortcomings of the OpenSees model. The OpenSees model closely predicted the load-displacement response when using calibrated nail parameters under reverse static cyclic loading. Application of external nail parameters from the CUREE-Caltech Woodframe project predicted specimen failure after reaching its ultimate strength.

Thermal transmittance (U-value) and thermal resistance (R-value) of several idealized green framing wall arrangements were calculated through a finite element program called THERM. Green framing wall assemblies tested in this study included a staggered stud wall, pressboard I-beam wall, and a rigid external insulated wall to determine their respective thermal transmittance and resistance values. THERM predicted that the rigid external insulated wall condition has the most promise for elimination of thermal bridging.

Understanding the combination of both mechanical and thermal performance of various green framing arrangements will assist the architect/engineer in designing framing types that meet or exceed building codes and maximize energy efficiency.

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CHAPTER 1

Introduction

In 2014, buildings consumed approximately 41% of energy produced in the United States (U.S. Energy Information Administration 2014). Buildings utilize vast amounts of raw materials that contribute significantly to greenhouse gas emissions that affect climate change. Strong scientific evidence indicates that the Earth's climate has significantly changed causing ocean acidification, decreased snow cover, extreme weather events, warmer oceans, and rising sea levels due to melting Arctic sea ice (NASA 2015). Conservation of Earth's resources by reuse of building materials and increasing energy efficiency of buildings can help mitigate the effects of climate change.

Most residential dwellings such as single family homes, apartment buildings, condominiums, and pre-fabricated homes in the United States are constructed out of timber. The building envelope of a home is defined by its walls, floors, insulation, and fenestrations. Thermal bridging occurs when a conductive element of the building envelope bypasses or passes through the thermal barrier providing a path of lesser resistance through the insulation. It allows more heat to bypass the thermal barrier and either decrease or increase interior temperatures (Totten et al 2008). With the advent of new wood framing techniques and materials that reduce framing material usage, these thermal bridges may be reduced creating a more energy efficient home (APA 2014a; O'Brien and Smith 2008).

However, the usage of these advanced framing techniques and materials may not be accepted by the local jurisdiction in areas that are prone to high seismic activity or

wind load. These new framing techniques need to be proven just as capable of resisting seismic and wind load in order to be adopted into a local jurisdiction's building code.

Using new materials and advanced framing techniques not only reduces material consumption in building construction, and also reduces the thermal bridges created in conventional framing techniques, therefore making residential homes more energy efficient, and overall, reducing the cost of heating and cooling a home. Overall, these efforts if adopted may help mitigate the negative effects of climate change.

There are two components to this thesis: Mechanical Modeling and Thermal Modeling. The Mechanical Modeling portion will explore the use of a finite element analysis program called OpenSees (Open System for Earthquake Engineering Simulation, PEER 2013). OpenSees is used in simulating the response of geotechnical and structural systems when subjected to seismic or other types of loads.

Wood studs are identified by their nominal dimensions. For instance, a wood stud referenced in a lumber mill as a nominal 2x4 stud (units are in inches), has actual dimensions of 1.5 in x 3.5 in (38.1 mm x 88.9 mm). A nominal 2x6 wood stud (units are in inches) has actual dimensions of 1.5 in x 5.5 in (38.1 mm x 139.7 mm).

A conventional 2x6 shear wall will be built in OpenSees to predict response of the wall to applied lateral loads. These results will be compared to physical test results and CASHEW (Cyclic Analysis of SHEar Walls) results for calibration and validity of the OpenSees model (Rodriguez-Nikl et al 2014; Rodriguez-Nikl et al 2013; Folz and Filiatrault 2001). CASHEW is a computer program that is able to predict response behavior for conventionally framed shear walls under arbitrary quasi-static cyclic loading (Folz and Filiatrault 2000).

This work demonstrates that OpenSees can be used to model shear walls with nail-level detail. Therefore, OpenSees can be used to model the more complicated Staggered Stud walls to explore aspects of the behavior that CASHEW misses. With the calibrated OpenSees model, different innovative wood framing techniques and materials may be explored to predict hysteretic behavior in future research.

The Thermal Modeling portion will use a program called THERM to model the thermal conductivity of the various idealized wall configurations also using finite element computations (LBNL 2012).

Wall configurations range from conventional 2x4 and 2x6 walls, to advanced framing configurations such as the staggered stud wall, rigid external insulated wall, and the pressboard I-beam wall. Comparison of the thermal conductivity values will determine whether the selected idealized advanced framing techniques are more energy efficient than the conventional framed walls.

California has stringent standards for energy conservation in new construction and modernizations that require conditioned spaces. Title 24, published by the California Building Standard Commission, prescribes the requirements for structural, mechanical, electrical, and plumbing in regards to residential and commercial buildings (CEC 2012). In order to utilize the standard and/or advanced framing types, compliance to Title 24 is fundamental in obtaining a building permit in California.

Proposed green framing arrangements are presented here in the hopes that these techniques would be viable both mechanically in terms of seismic performance and thermally in terms of insulative properties.

- *Advanced Framing* – Also known as Optimum Value Engineering (OVE), was introduced by the National Association of Home Builders (NAHB) in the 1970s to reduce framing material while maintaining structural integrity. (APA 2014b; BSC 2009). It involves wall stud spacing 24 in (609.6 mm) O.C. instead of the conventional 16 in O.C. (406.4 mm) as well as the possibility of using single headers, elimination of redundant studs at the corners, elimination of redundant support members and perhaps elimination of jack studs for door header support. However, this framing arrangement may not perform well in seismically prone areas due to the eliminating of redundancies in framing. While it shows promise in increasing insulation, further investigation is needed.
- *I-Joists for Stud Framing* – Several resources have mentioned the use of I-Joists in lieu of conventional stud framing as necessitated by increased wall thickness for thermal efficiency and reduction of thermal bridging as shown in Figure 1 (Weyerhaeuser 2015; Krigger and Dorsi 2009) It is assembled by meshing pressboard between two structural composite lumber (SCL) flanges. The thinness of the pressboard allows for additional batt insulation in the wall cavity.

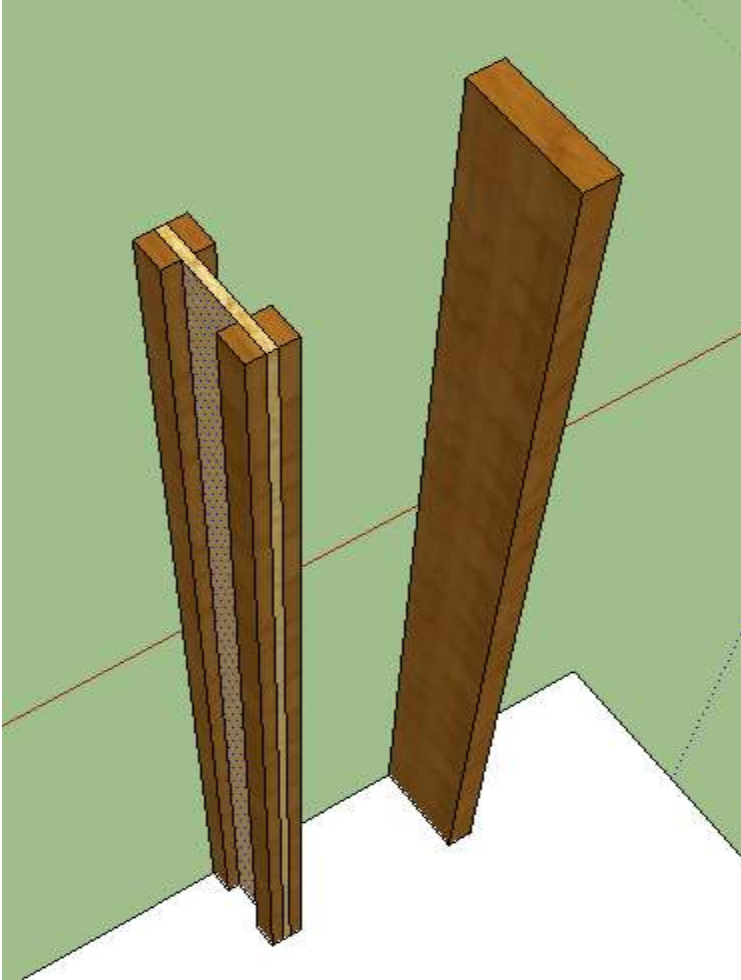


Figure 1. I-Joist Compared to Conventional Wood Stud (HISE 2013)

- *Staggered Stud Wall* – Consists of 2x4 wood studs alternating 12 in (304.8 mm) on a 2x6 double header and sill plate as shown in Figure 2. By introducing of a gap between the 2x4 framing and sheathing/gypsum board, it introduces additional insulation at those stud sections increasing thermal efficiency.

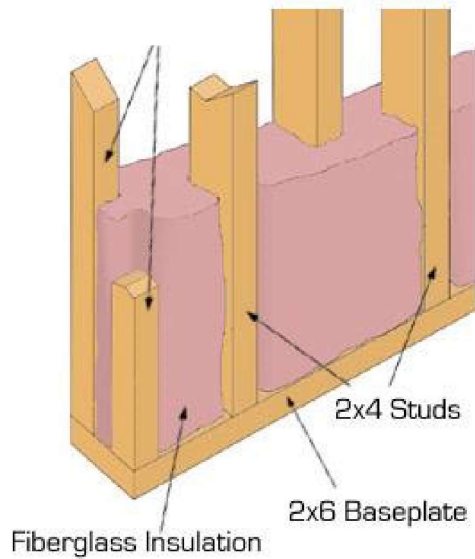


Figure 2. Staggered Stud Wall (APA 2014b)

- Rigid External Insulation: Wood Structural Panel Siding over Foam Insulation* – An alternative to additional interior insulation with framing modifications is to place insulation on the exterior of the building to reduce thermal bridging. Figure 3 is an example of a rigid externally insulated wall with a rain screen. However, when implementing this type of construction, there are challenges to integrity of the external insulation as studied by Deress and Martin (2015) which can affect thermal performance. During construction, temporary fasteners holes are made to hold the sheathing to the wall and then filled in creating instabilities in the insulation. Also, attachment of the exterior wood battens is blind, so mistakes are often made with fastening the batten to the wood stud also creating instabilities in the exterior rigid insulation.

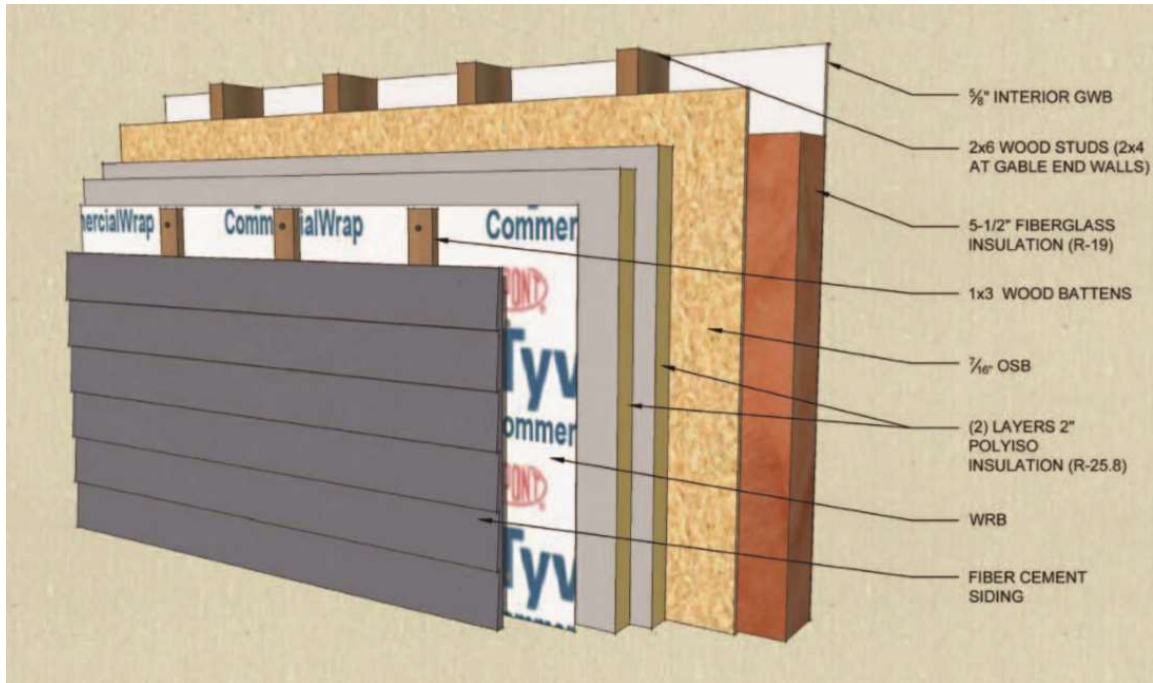


Figure 3. Rain Screen Over Continuous Insulation Exterior Wall Assembly (Deress and Martin 2015)

The building envelope, such as the wall and its components, are defined by thermal properties such as thermal conductivity and thermal resistance. Heat energy is transferred when there is a temperature differential in the wall assembly. Three different modes of heat transfer are conduction, convection, and radiation. For purposes of the idealized wall condition, only conduction is applicable to the wall types presented. Conduction occurs when there is a collision between faster and slower molecules resulting in transfer of kinetic energy. The rate of heat conduction through a wall is dependent upon the material, thickness of the material, and temperature difference. Rate of heat conduction through a wall can be related through Equation 1 (Çengel et al, 1998). Since the temperature of the wall is defined in one direction, heat flow through a plane wall is defined in one-dimension.

$$\dot{Q}_{conduction\ wall} = kA \frac{T_1 - T_2}{L} \quad (1)$$

$\dot{Q}_{conduction\ wall}$ = rate of change of the energy of the wall (BTU/hr)

k = thermal conductivity of the material (BTU/(hr · ft · °F))

A = surface area of heat flow (ft²)

$T_1 - T_2$ = material temperature difference (°F)

L = thickness or length of material (ft)

The thermal conductivity, which is a measure of the material's ability to conduct heat, can be solved by rearranging the rate of heat conduction equation. As a construction industry standard, instead of defining a wall by its thermal conductivity, it is often described by its thermal resistance (R-value) which measures the resistance against heat conduction as defined by Equation 3. The units of the R-value are °F · ft² · hr/BTU.

THERM calculates the thermal transmittance of the wall or commonly known as a U-factor. This U-factor is inversely proportional to the R-value of the wall as shown by Equation 4. The units of the U-value are BTU/°F · ft² · hr as stated in THERM.

$$k = \dot{Q} \frac{L}{A(T_1 - T_2)} \quad (2)$$

$$R_{wall} = \frac{\Delta T}{\dot{Q}} = \frac{L}{k} \quad (3)$$

$$R_{wall} = \frac{1}{U} \quad (4)$$

The best insulating materials have a U-value that is close to zero. The higher the numerical value for R, the better the insulating material. For frame of reference for U-

values, Title 24 specifies the maximum U-value for walls, e.g., 0.102 for a wood framed wall with R-13 insulation. (Energy Performance Services 2015).

For the one-dimensional heat flow presented in THERM, the overall R-value of the wall can be obtained by adding all the R-values together to obtain as shown in Equation 5.

$$R_{Total} = R_1 + R_2 + R_3 \dots \quad (5)$$

If the wall components are stacked so that they are parallel to the one-dimensional heat flow direction, then the overall R value of the wall is calculated by Equation 6 where the overall wall resistance is equal to one divided by the reciprocal of all the material resistances. If the wall assembly consists of combination of series and parallel resistances, the parallel resistances are calculated first as a material layer then added in series for the overall wall resistance value. Air films and air cavities also need to be considered in the overall resistance calculation in the same way as physical wall materials.

$$R_{Total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots} \quad (6)$$

CHAPTER 2

Mechanical Modeling Setup and Results

Wood-framed residential dwellings are engineered to be able to withstand lateral forces such as wind and earthquake loads with shear walls. A wood shear wall typically consists of framing members such as vertical wood studs attached to a header and sill, covered with sheathing material such as plywood, nails that are spaced in intervals that give the shear wall its strength to resist lateral forces, and hold-downs and anchor bolts that resist uplift.

Mechanical Modeling Setup

A conventional 2x6 (609.6 mm x 1828.8 mm) shear wall with an overall dimension of 8 ft x 8 ft (2438.4 mm x 2438 mm) will be created in OpenSees to model cyclic behavior with respect to the sheathing to framing (nailing) parameters. The nonlinear nailing parameters will be described in detail. If the OpenSees model is successfully validated, it then can be used in other advanced framing arrangements to predict cyclic behavior with OpenSees.

Model Configuration

In order to use OpenSees to predict the cyclic behavior using nailing parameters, the model has to be calibrated to physical data taken from a similar setup. Physical lateral displacement and force measurements (Rodriguez-Nikl et al 2013) for a 2x6 conventional stud wall were used to calibrate the OpenSees model. Figure 4 shows the physical setup used for wall testing (Rodriguez-Nikl et al 2013).

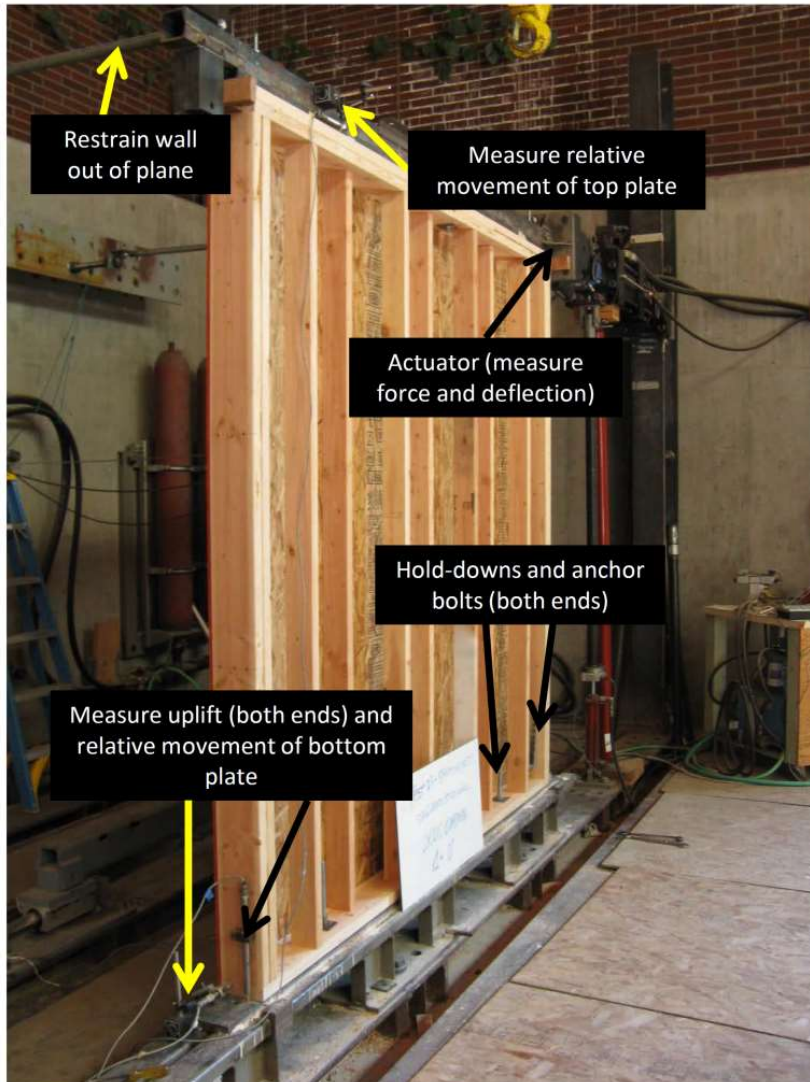


Figure 4. Test setup for staggered stud wall tests (Rodriguez-Nikl et al 2013)

A drawing of the specimen is provided in Figure 5. Reference framing nodes and sheathing shell configurations can be found in Appendix A and B respectively. The OpenSees code used to generate the model can be found in Appendix C. The double 2x6 (609.6 mm x 1828.8 mm) posts are modeled as one large end post with actual dimensions of 3x5.5 (914.4 mm x 1676.4 mm). The header is also modeled as one wood beam instead of two as depicted in the drawing. The wood studs are spaced 24 in (609.6 mm) on center. Also, instead of modeling individual anchor bolts and hold downs, the

OpenSees model was restrained by rollers at all bottom nodes with the exception of node 1001 which was pinned. The OpenSees model was aligned with the centerline of the wood members.

The top of the wall is restrained for out of plane movement at each of the corners. At the left upper corner of the wall, a forced displacement is applied according to the ASTM E2126-10 protocol that will be discussed in the following section. Two sheets of Oriented Strand Board (OSB) Sheathing 4x8 (1219.2 mm x 2438.4 mm) are attached to the 2x6 (609.6 mm x 1828.8 mm) studs by 8d cooler nailing [2-3/8 long (60 mm) x 0.113 in (2.87 mm) in diameter].

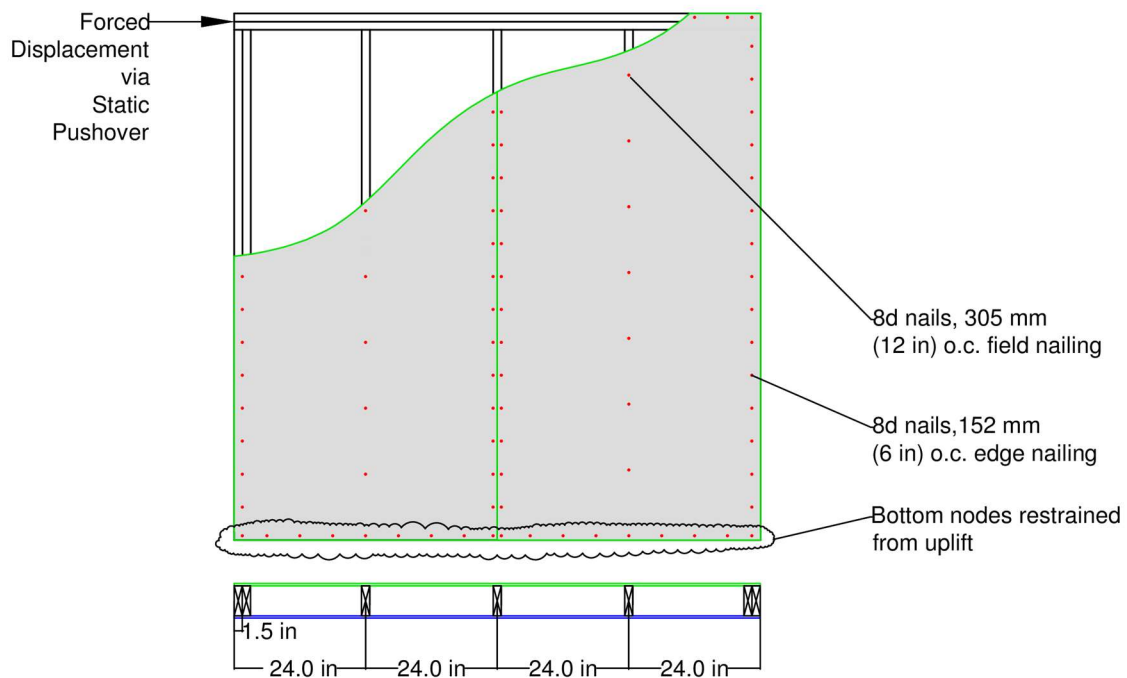


Figure 5. Drawing of Conventional 2x6 Shear Wall Model

Loading Protocol

ASTM E2126-10 Test Method C (CUREE Basic Loading Protocol) was used for all testing (physical, CASHEW, and OpenSees). (ASTM 2010). CUREE stands for Consortium of Universities for Research in Earthquake Engineering whose research is used to further knowledge on how earthquakes affect wood framed structures.

Previous physical testing (Rodriguez-Nikl, et al 2013), used a reference deformation value of 3.0 inches for cyclic testing. The theoretical reference deformation is calculated by taking the post-peak monotonic deformation capacity that corresponds to 80% of the ultimate force displacement then multiplying by a factor of 0.6. (Ekiert and Hong 2006). The actual reference deformation that was used for the physical tests was modified to 3.0 based on engineering judgement. The amplitude of the testing cycles is based off the actual reference deformation (Δ) value as shown in Table 1.

Table 1. Test Method C – Amplitude of Primary Cycles (from ASTM 2010)

Pattern	Step	Minimum Number of Cycles	Amplitude of Primary Cycles ^a (% Δ)
1	1	6	5
2	2	7	7.5
	3	7	10
3	4	4	20
	5	4	30
4	6	3	40
	7	3	70
	8	3	100
	9	3	$100 + 100\alpha_a$
	10	3	Additional increments of $100\alpha_a$ (until specimen failure)

^a $\alpha_a=0.5$ for testing

Figure 6 reflects the cyclic displacement loading pattern with a reference deformation value of 3.0. The loading pattern begins (Step 1) with six displacement

cycles of equal magnitude at 5% of the reference deformation, which in our case is 0.15 in (3.81 mm). The subsequent steps increase in primary amplitude per Table 1-1, followed by trailing cycles that are 75% of the primary cycle per step. The loading protocol increases in amplitude according to the loading schedule until failure of the model.

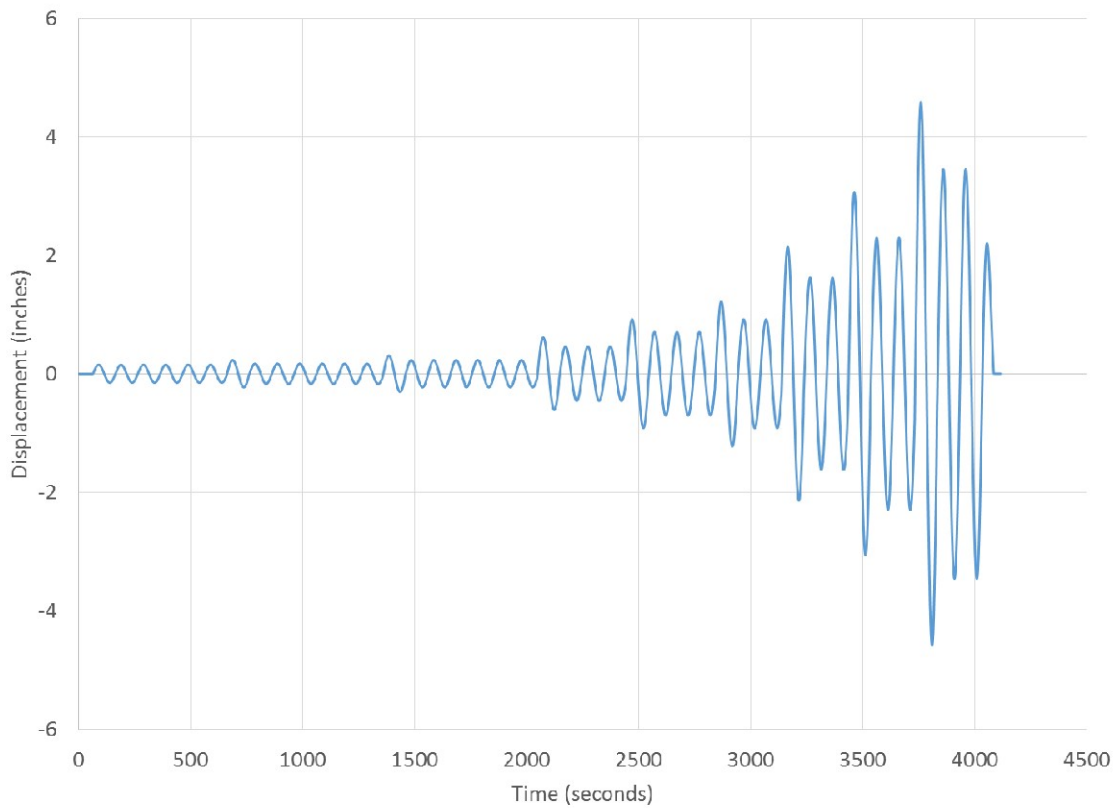


Figure 6. Cyclic Displacement Pattern (Test Method C)

OpenSees Parameters

OpenSees is an open source computer program for material and geometric nonlinear, finite element analysis of structures. It utilizes a Tool Command Language (TCL) script to perform the finite element analysis by modeling, analyzing, and providing output (Tcl Developer Xchange 2014).

Modeling. In order to model the 2x6 conventional wall in OpenSees, nodes, elements, shells, and constraints need to be defined. The OpenSees code that was used to generate the model can be found in Appendix C. The modeling commands are referenced from the OpenSees manual example problems, as well as the OpenSees User Documentation (Mazzoni et al 2007; OpenSees 2010). The model uses consistent units of kips and inches. The commands used in OpenSees will be italicized throughout the thesis. Figure 7 illustrates how the framing and sheathing connection are connected together in OpenSees.

The OpenSees model of the 2x6 conventionally framed wall is defined three dimensionally with six degrees of freedom (DOF). DOF 1,2, and 3 are in the x,y, and z direction respectively. DOF 4,5, and 6 rotate around the x, y, and z axis respectively.

The overall strategy to creating the conventional wall in OpenSees is to construct the wall in layers. The layers consist of framing nodes, framing elements that connect the nodes together, connections where the header and sill join the stud members, sheathing nodes, shells that define the sheathing material, and the nails that connect the sheathing node to the framing node.

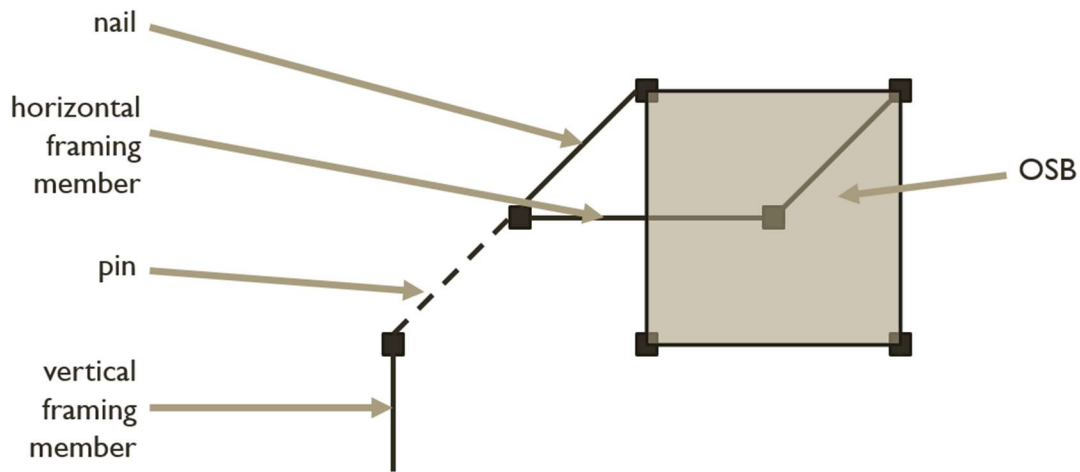


Figure 7. Framing and Sheathing Connection Diagram in OpenSees

Nodes define the end points of the element (the wood framing), and the points where the nail attaches onto the framing. The nodes are modeled with the *node* command. Appendix A shows all the framing nodes for the 2x6 wood studs. Nodes 1001 through 1034 define the horizontal wood studs while nodes 2001 through 2069 define the vertical wood studs. The node locations are defined at nail locations. Since there are two OSB sheathing panels oriented vertically that are being nailed to the framing as shown in Figure 5, edge nails are spaced 6 in (252 mm) apart while interior field nails are spaced 12 in (305 mm) apart.

Frame elements are represented as line segments in Appendix A. The wood studs are modeled with the *elasticBeamColumn* command which models the frame elements as linear and elastic. For instance, Nodes 1001 and 1002 are connected by an element which is labeled element 10011002. Table 2 summarizes the properties that were used in OpenSees to create the wood elements. The *geomTransf* command defines the orientation of the wood stud cross section. As defined in Table 2, a geometric transfer tag of 1

orients the wood stud in the horizontal direction while a geometric transfer tag of 2 orients the wood stud in the vertical direction.

Table 2. Properties of Wood Elements in OpenSees

Stud Location	A (in ²)	E (ksi)	G (ksi)	Iz (in ⁴)	Iy (in ⁴)	Geometric Transfer
Sill Plate	7.875	1600	600	1.48	18.09	1
Header	15.75	1600	600	11.81	36.18	1
Left and Right End Posts	15.75	1600	600	36.18	11.81	2
Interior Vertical Studs	7.875	1600	600	18.09	1.48	2

Sheathing nodes were also generated as shown in Appendix B. Nodes 3001-3153 define the sheathing nodes for the 4x8 (1219.2 mm x 2438 mm) OSB sheathing on the left hand side, while nodes 4001-4153 define the sheathing nodes for the 4x8 OSB sheathing on the right hand side. The OSB sheathing is modeled with the *ShellMITC4* command which is defined as a four node linear elastic shell element. Table 3 defines the *ElasticMembraneSection* parameters that are needed for the *ShellMITC4* command.

Table 3. *ElasticMembraneSection* Parameters

Element	E (ksi)	Poisson's Ratio	Thickness of Shell (in)	Mass Density (kip · s ² /in · 1/in ³)
OSB Sheathing	494	0.3	0.375	1.499 x 10 ⁻⁸

OSB shell tags 5001-5128 define the 4x8 sheathing on the left hand side while shell tags 6001-6128 define the 4x8 sheathing on the right hand side. For instance, shell 5001 is defined by nodes 3001, 3002, 3011, and 3010 moving counter-clockwise around the shell.

Connectors between framing elements at the header and sill are idealized by hinges which need to be modeled explicitly in OpenSees. For instance, the OpenSees model calls for the command *equalDOF* at nodes 1001 and 2001 for DOF 1,2,3,4 and 5

where node 1001 is the master node. Since node 1001 is defined as the master node, node 2001 is slaved (constrained) to move with node 1001 at DOF 1,2,3,4, and 5. Since DOF 6 was omitted from the *equalDOF* command, the frame at that connection point is allowed to rotate about its z-axis (DOF 6).

The header nodes 1019 through 1034 are also constrained to node 1018 only for DOF 1 (x-direction) to ensure that the entire header is moving when a forced displacement is introduced at the upper left hand corner as shown in Figure 5. Nodes 1018 and 1034 are being restrained by the *fix* command at DOF 3 to prevent out of plane movement just like the experimental setup.

At the sill plate, nodes 1002 through 1017 are constrained by a roller and pinned at node 1001. Nodes 1001-1017 are also restrained in the z-direction (DOF 3) to prevent out of plane movement to mimic the idealized fixity provided anchor bolts and hold downs typical for a shear wall.

The nails that connect the sheathing to the framing are modeled by the *uniaxialMaterial* command in OpenSees which is a *zerolength* element. A *zerolength* element is defined by two nodes at the same location. The *uniaxialMaterial* specifies that a *SAWSMaterial* be used which is a SDOF hysteretic model developed by CUREE (OpenSees 2010). Although the *SAWSMaterial* is intended to represent entire walls, “global deformation response of a wood shear wall is qualitatively very similar to that of the individual sheathing-to-framing connectors used in the construction of the wall” (Folz and Filiatraut 2000, Folz and Filiatraut 2004a, Folz and Filiatraut 2004b). The *SAWSMaterial* will be defined for the nail to model hysteretic behavior in both the x and y directions (DOF 1 and 2). The *SAWSMaterial* requires 10 input parameters that make

up the 8d ordinary nail as summarized in Table 4 and graphically illustrated in Figure 8 as follows (Fonseca et al 2002; Folz and Filiatraut 2001):

1. F_0 = y-Intercept of the envelope with slope r_1S_0
2. F_1 = y-Intercept of the hysteretic pinching branch with slope r_4S_0
3. du = connector displacement at maximum load
4. S_0 = initial connector stiffness
5. r_1 = secondary stiffness divided by S_0
6. r_2 = degradation stiffness divided by S_0
7. r_3 = unloading stiffness divided by S_0
8. r_4 = pinching stiffness divided by S_0
9. α = stiffness degradation factor
10. β = strength degradation factor

Table 4. *SAWS Material* Parameters for 8d cooler nails

F_0 (kip)	F_1 (kip)	du (in)	S_0 (kip/in)	r_1	r_2	r_3	r_4	α	β
0.145	0.028	0.42	3.3	0.062	-0.025	1.40	0.018	0.70	1.10

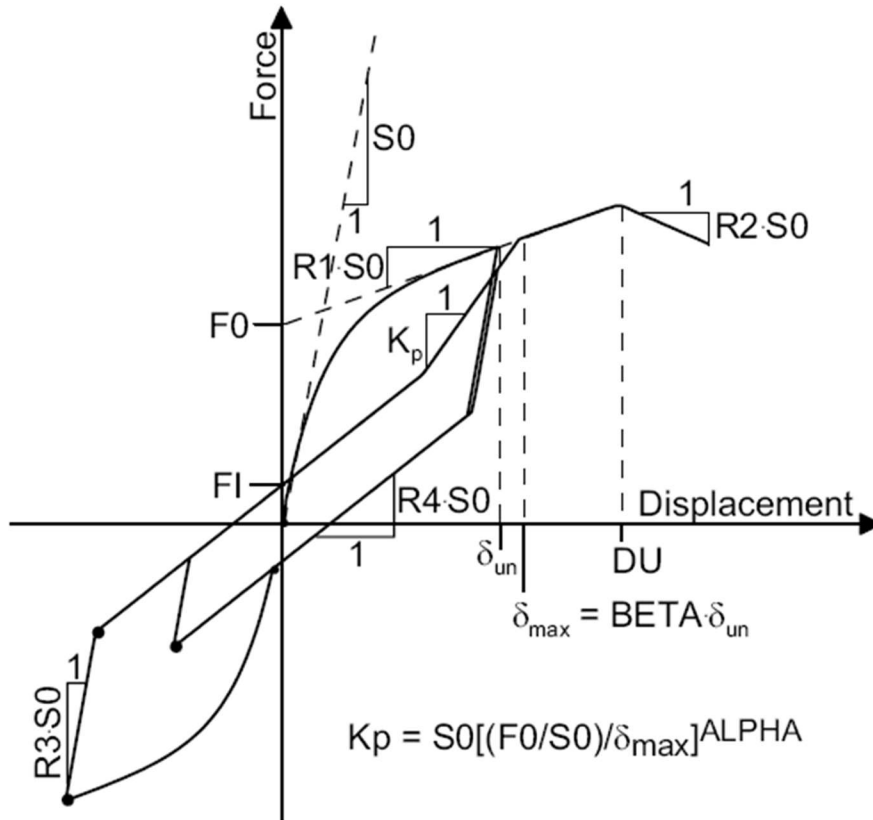


Figure 8. Hysteretic Response of a Sheathing-to-Framing Connector^a
 (from Folz and Filiatrault 2001)

^aMaximum nail force: $F_{max} = F_0 + R_1 S_0 (du)$

The nails are labeled 7001 through 7055 for the left OSB sheathing panel while nails that are labeled 8001 through 8055 are for the right OSB sheathing panel. For instance, nail 7001 connects nodes 3001 and 1001 together where node 3001 belongs to the sheathing and node 1001 belongs to the framing respectively.

Analysis. A Static Reversed Cyclic Analysis was performed where displacement cycles were imposed in the positive and negative direction per ASTM E2126-10 Test Method C. Displacement values from the physical testing (Rodriguez-Nikl et al 2013) were utilized to run the analysis in OpenSees.

The following parameters listed below are required for a static reversed cyclic analysis (OpenSees 2010). To accomplish this in OpenSees, a *timeSeries* is defined where

the load factor is linearly proportional with the time in the domain. A plain *pattern* load is introduced at node 1018 (located at the upper left hand corner) as depicted in Figure 5.

The load pattern extrapolates displacements defined from an input file. The plain *constraints* command allows homogenous single-point constraints with the *fix* command. The plain *numberer* command assigns the DOF based on how the nodes are stored in the domain (holds the state of the model at time t and $(t + dt)$). The *system* command generates a linear systems of equations and solves the system of equations by specifying *BandGeneral* which solves banded unsymmetric matrices.

All the search algorithms used such as Newton-Raphson, Newton with Initial Tangent, Broyden, and Newton with Line Search will need to check whether convergence has been achieved at the end of each iteration step.

EnergyIncr test type has been specified to check whether half the product of the displacement increment and unbalance in the linear systems of equations generated is less than the convergence tolerance of 0.1

All the search algorithms used such as Newton-Raphson, Newton with Initial Tangent, Broyden, and Newton with Line Search will need to check whether convergence has been achieved at the end of each iteration step.

Output. An element *recorder* will record the force at each displacement step. In particular, it records the force at the element labeled 10011002. Although the recorder has the capability to record all 6 DOF's for the element in question, we are interested in the force with respect to the x direction (F_x). The *recorder* results are reflected in Figure 9 through Figure 16 where the force is compared to the imposed displacement.

Mechanical Modeling Results

In order to use the OpenSees model to predict the performance of a shear wall under cyclic loading, the model needs to be calibrated to previous test results for validation purposes. Table 5 outlines the sheathing-to-framing connector parameters (SAWS Material Parameters) that will be used to calibrate the OpenSees model.

Figure 9 through Figure 16 reflect a visual fit of the CUREE-Caltech Woodframe Project data with the original experimental results from Rodriguez-Nikl et al (2013). No formal optimization was carried out, only eyeballed for fit. In terms of computational time, approximately an hour and a half was needed for each run. A Microsoft Surface Pro 3 Tablet with a dual core Intel CPU Core i5-1600 Mhz was utilized to run OpenSees.

The nail parameters for CASHEW were fit to pre-test results (unpublished work by Rodriguez-Nikl). The second set of nailing parameters labeled “OpenSees Modified” in Table 5 were modified by the experimenter. Nailing parameters S_0 , r_1 , r_3 , and r_4 have been modified from the CASHEW reference files to better fit the previous physical data results. The other nails parameters that were assessed were obtained from previous studies carried out as part of the CUREE-Caltech Woodframe Project (Fonseca et al 2002). The intention of the CUREE-Caltech study was to be able to provide a database for sheathing to framing connections that can be used in future studies to predict shear wall behavior.

Table 6 summarizes the CUREE-Caltech test parameters that were used to define the nailing parameters. An 8d cooler nail was used which dimensionally matches the physical nails used in Rodriguez-Nikl et al (2013).

The average sheathing-to-framing parameters for the CUREE-Caltech tests were

used to test the OpenSees model. Only the edge distance is variable for the nailing parameters and based on the edge of the sheathing. Table 7 summarizes the peak strength under cyclic loading for each of the nailing conditions presented.

Using the original parameters used in CASHEW, Figure 9 compares the OpenSees results to the physical data and CASHEW results. The figure illustrates that the pinched hysteresis loop visually fits that of the physical test results and CASHEW model. Based on the OpenSees model with the original/CASHEW *SAWSMaterial* parameters, there is a 9.5% difference in the force required to reach ultimate strength versus what OpenSees predicts and a 13.8% difference for the displacement. The difference is likely due to the fact that there may be some framing flexibility variability when under cyclic loading due to the ability to specify the modulus of elasticity in OpenSees. CASHEW assumes that the frame is rigid with no input for the modulus of elasticity.

Further calibration of the OpenSees model was investigated by modifying nail parameters S_0 , r_1 , r_3 , and r_4 . Figure 10 reflects the OpenSees model with modified nailing parameters which compare the force-displacement data generated from OpenSees with the previous test results. Figure 10 shows that the hysteretic curves from OpenSees form a better fit with the previous physical test results.

For the 8d cooler nail with an edge condition of +2" as shown in Figure 11, OpenSees reports the error "Strain too large" after reaching its maximum strength. The hysteresis curve has a maximum force of 4067.44 lb (18.09 kN) with the associated imposed displacement of 1.5566 in (39.5384 mm). As expanded in Figure 12, the predicted OpenSees curve closely matches the physical test up until the wall reaches its ultimate strength.

An 8d cooler nail with a nailing edge of 3/8” reaches its peak strength at 3067.64 lb (13.6455 kN) with the associated imposed displacement at 1.0281 in (26.1137 mm) as shown in Figure 13. This is a similar response to the 8d cooler nailing with an edge condition of +2” except that its peak strength and displacement at ultimate load.

An 8d cooler nail with a nailing edge of 1/4” reaches its peak strength at 2742.49 lb (12.1992kN) with the associated imposed displacement at 0.5873 in (14.9174 mm) as shown in Figure 14. Next, a 8d cooler nail with a nailing edge of 3/16” reaches its peak strength at 2015.81 lb (8.9667 kN) with an imposed displacement at 0.4847 in (12.31134 mm) as shown in Figure 15. The last CUREE-Caltech nailing condition is an 8d cooler nail with nailing edge 1/8” reaches its peak force strength at 1820.35 lb (8.0973 kN) with an imposed displacement 0.3770 in (9.5758 mm) of as shown in Figure 16.

As reflected in the results in Table 7, there is a noticeable decrease in ultimate strength in the shear wall given the CUREE nailing parameters respectively as the edge nailing becomes reduced.

A comparison was made between the modified nailing parameters and the different edge conditions for an 8d cooler nail as summarized in Table 8 to see how closely the CUREE nail parameters matched the OpenSees modified nail parameters. As shown in Table 8, there are significant differences between the CUREE-Caltech nailing parameters versus the modified nailing parameters, especially with the r_2 degradation stiffness ratio and r_4 pinching stiffness ratio.

Table 5. Test Matrix of Sheathing-to-Framing Connector (SAWS Material) Parameters

Model	Fig.	F ₀ (kip)	F _i (kip)	du (in)	S ₀ (kip/in)	r ₁	r ₂	r ₃	r ₄	α	β
CASHEW /OpenSees	9	0.145	0.028	0.42	3.3	0.062	-0.025	1.40	0.018	0.70	1.10
OpenSees Modified	10	0.145	0.028	0.42	5.5	0.050	-0.025	0.75	0.006	0.70	1.10
CUREE 8d nail +2" edge	11	0.1621	0.0353	0.3030	4.5115	0.0585	-0.0586	0.9485	0.0751	0.60	1.10
CUREE 8d nail 3/8" edge	13	0.1233	0.0476	0.2027	3.9163	0.0761	-0.1496	1.5292	0.0857	0.60	1.10
CUREE 8d nail 1/4" edge	14	0.0852	0.0309	0.1011	3.1583	0.2716	-0.6308	1.6040	0.2524	0.60	1.10
CUREE 8d nail 3/16" edge	15	0.0781	0.0296	0.0816	3.1109	0.1957	-0.2239	1.3370	0.2184	0.60	1.10
CUREE 8d nail 1/8" edge	16	0.0633	0.0256	0.0660	2.9846	0.2789	-0.3747	1.3888	0.2773	0.60	1.10

Table 6. CUREE-Caltech Test Parameters

Parameter	Value
Sheathing Panel	7/16 in OSB
Wood Member	Douglas Fir/Larch
Moisture Condition	Wet (>19%) / Dry (<12%)
Fastener Type	8d Cooler Nail
Edge Distance	+2", 3/8", 1/4", 3/16", 1/8"
Overdrive Depth	0"
Number of Layers	1 Layer
Sample Number	Average of 10 Samples

Table 7. Summary of Test Results and Model Prediction under Cyclic Loading

Parameter	P_u	% difference	Δ_{Pu}	% difference
	(lbs)	P_u	(in)	Δ_{Pu}
Physical Testing ^a	4290.77	-	1.88	-
CASHEW Model	4223.14	1.58	1.97	4.79
OpenSees Model	3883.30	9.49	2.14	13.83
OpenSees Model Modified	4337.58	1.09	2.14	13.83
CUREE-Caltech Edge Nail +2"	4067.44	5.20	1.56	17.02
CUREE-Caltech Edge Nail 3/8"	3067.64	28.51	1.03	45.21
CUREE-Caltech Edge Nail 1/4"	2742.49	36.08	0.59	68.62
CUREE-Caltech Edge Nail 3/16"	2015.81	53.02	0.48	74.47
CUREE-Caltech Edge Nail 1/8"	1820.35	57.58	0.38	79.79

Note: ^a Rodriguez-Nikl et al 2013

P_u = ultimate load, Δ_{Pu} = displacement at ultimate load

Table 8. Nailing Parameter Differences Between CUREE and Modified Nails

Model (Difference)	F_0 %	F_i %	du %	S_0 %	r_1 %	r_2 %	r_3 %	r_4 %	α %	β %
CUREE 8d nail +2" edge	11.79	26.07	27.86	17.97	17.00	134.40	26.47	1151.67	14.39	0
CUREE 8d nail 3/8" edge	14.97	70.00	51.74	28.79	52.20	498.40	103.89	1328.33	14.39	0
CUREE 8d nail 1/4" edge	41.24	10.36	75.93	42.58	42.58	2423.20	113.87	4106.67	14.39	0
CUREE 8d nail 3/16" edge	46.14	5.71	80.57	43.44	291.40	795.60	78.27	3540.00	14.39	0
CUREE 8d nail 1/8" edge	56.34	8.57	84.29	45.73	457.80	1398.80	85.17	452.17	14.39	0

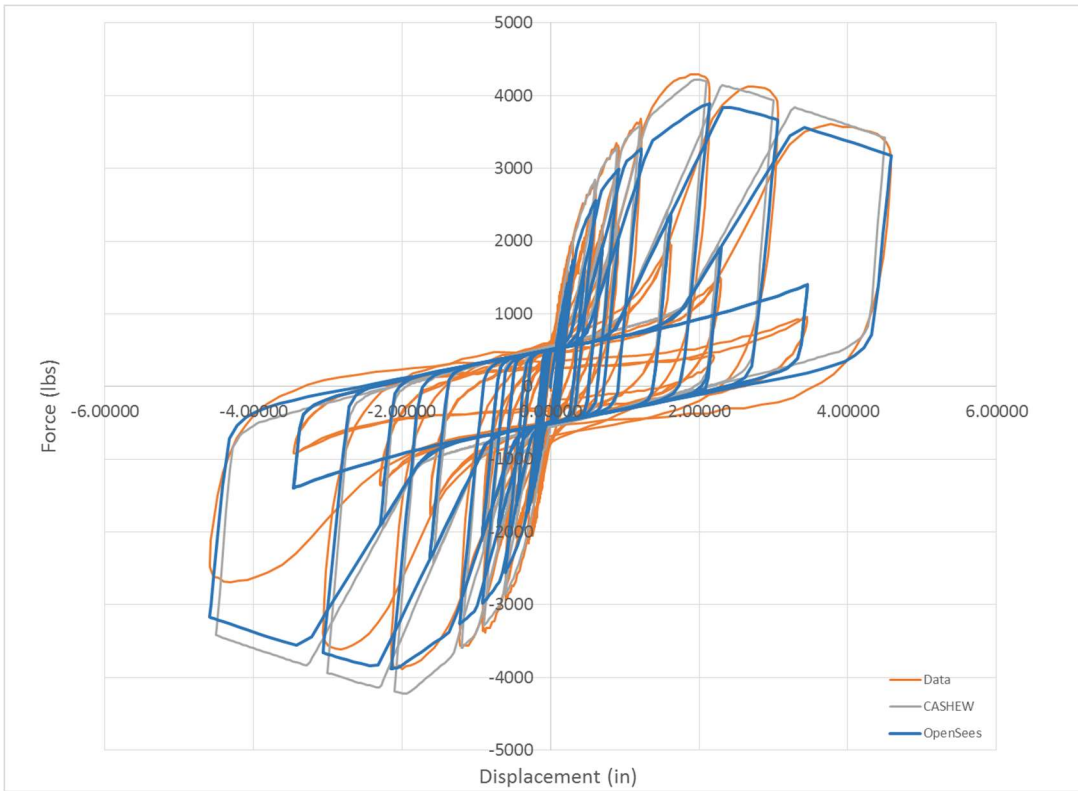


Figure 9. OpenSees Model with Original Nail Parameters

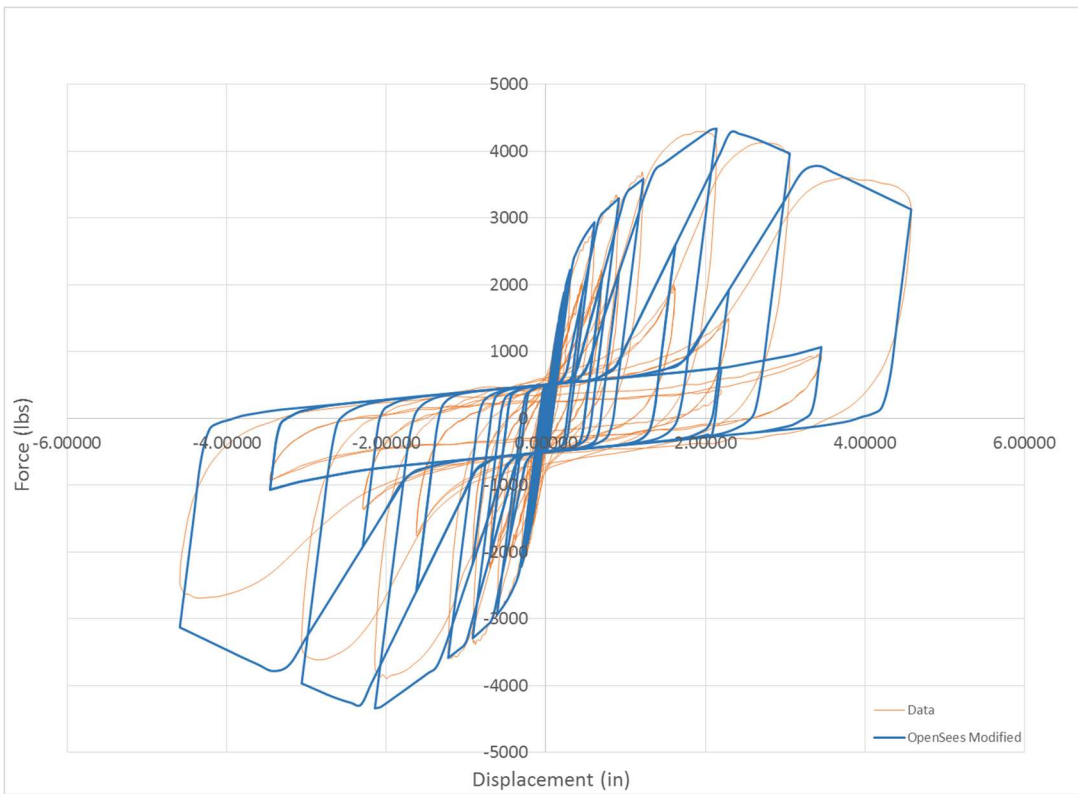


Figure 10. OpenSees Model with Modified Nail Parameters

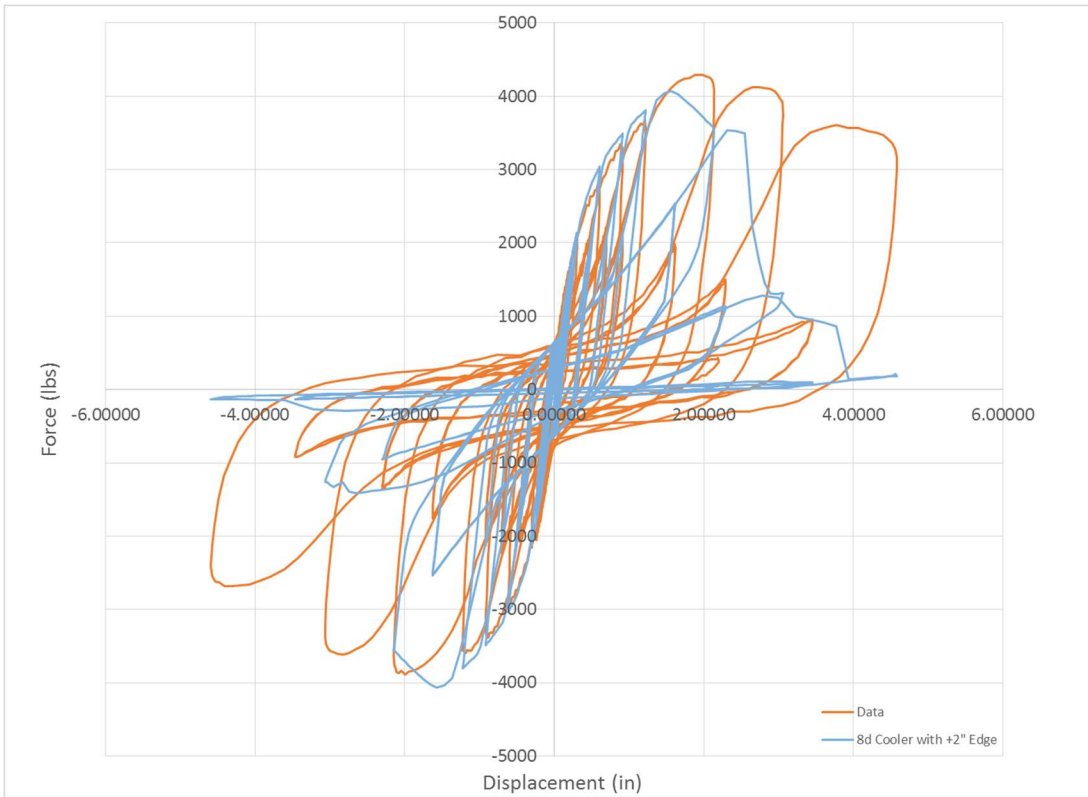


Figure 11. OpenSees Model with 8d Cooler Nail and +2” Edge Nailing

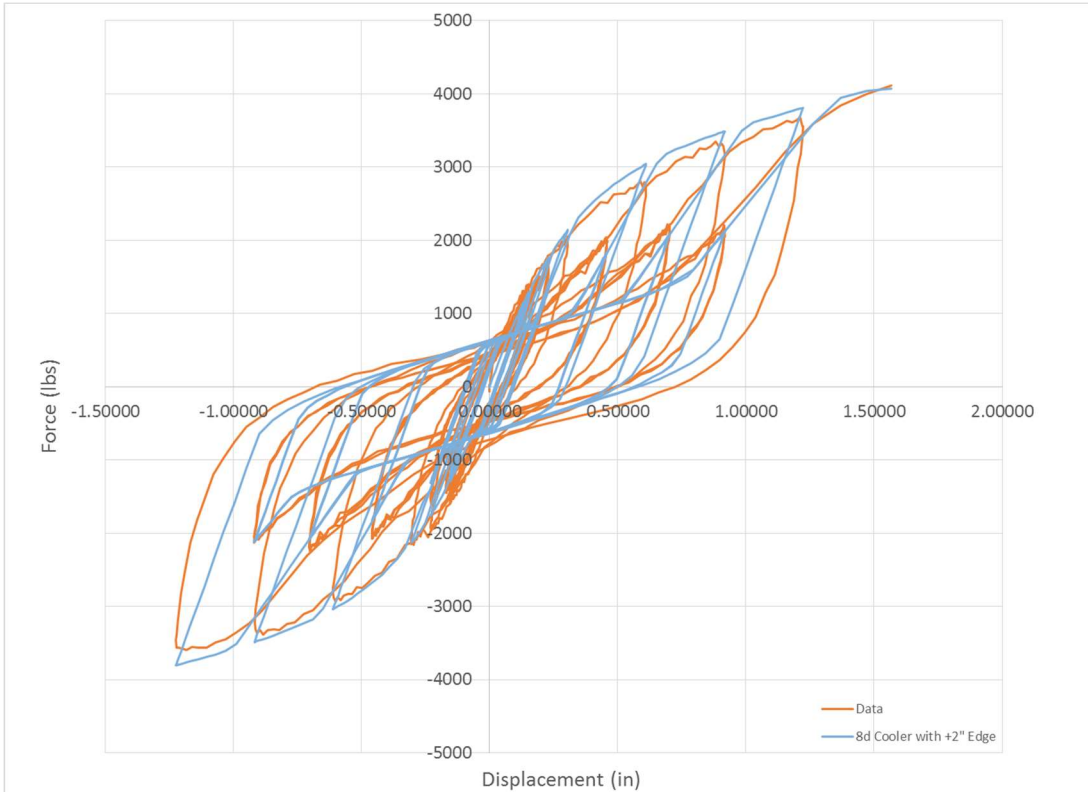


Figure 12. OpenSees Model with 8d Cooler Nail and +2” Edge Nailing - Expanded View

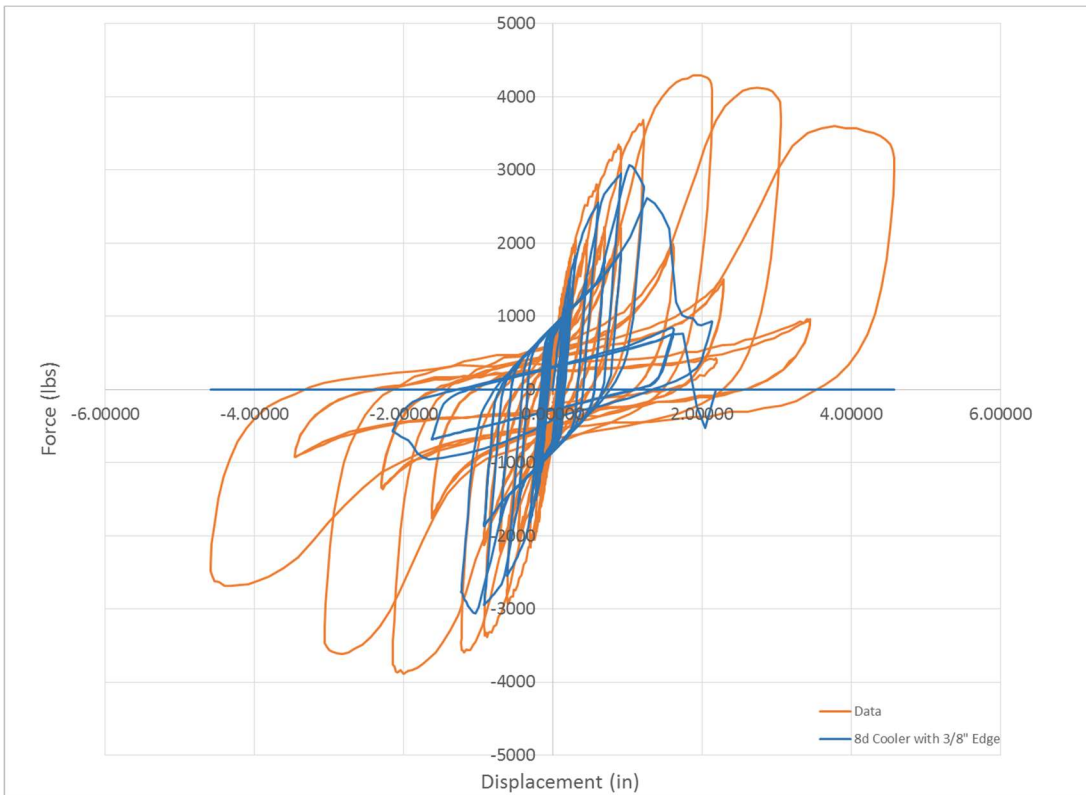


Figure 13. OpenSees Model with 8d Cooler Nail and 3/8” Edge Nailing

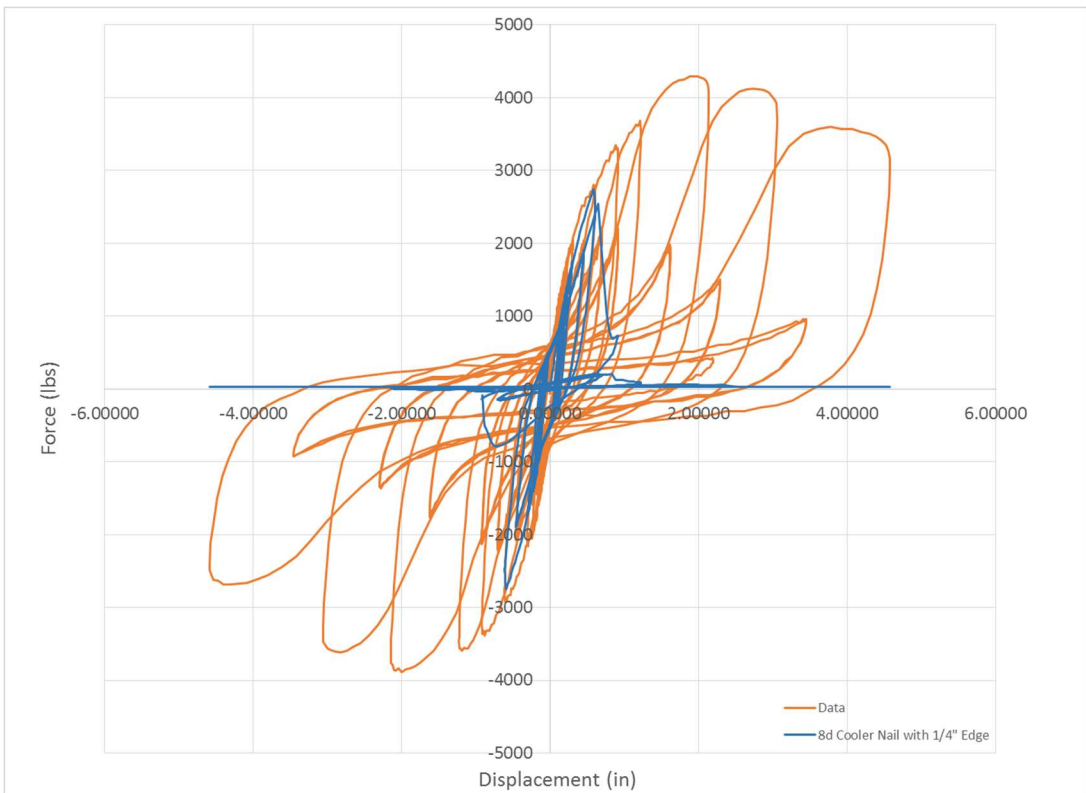


Figure 14. OpenSees Model with 8d Cooler Nail and 1/4” Edge Nailing

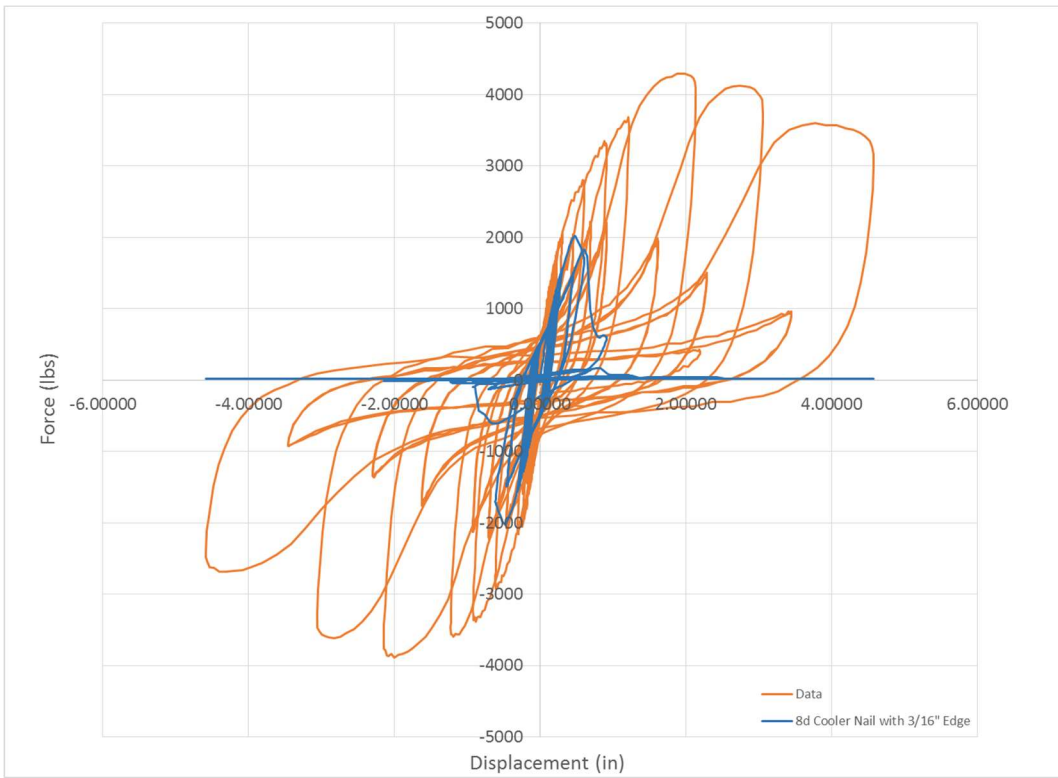


Figure 15. OpenSees Model with 8d Cooler Nail and 3/16" Edge Nailing

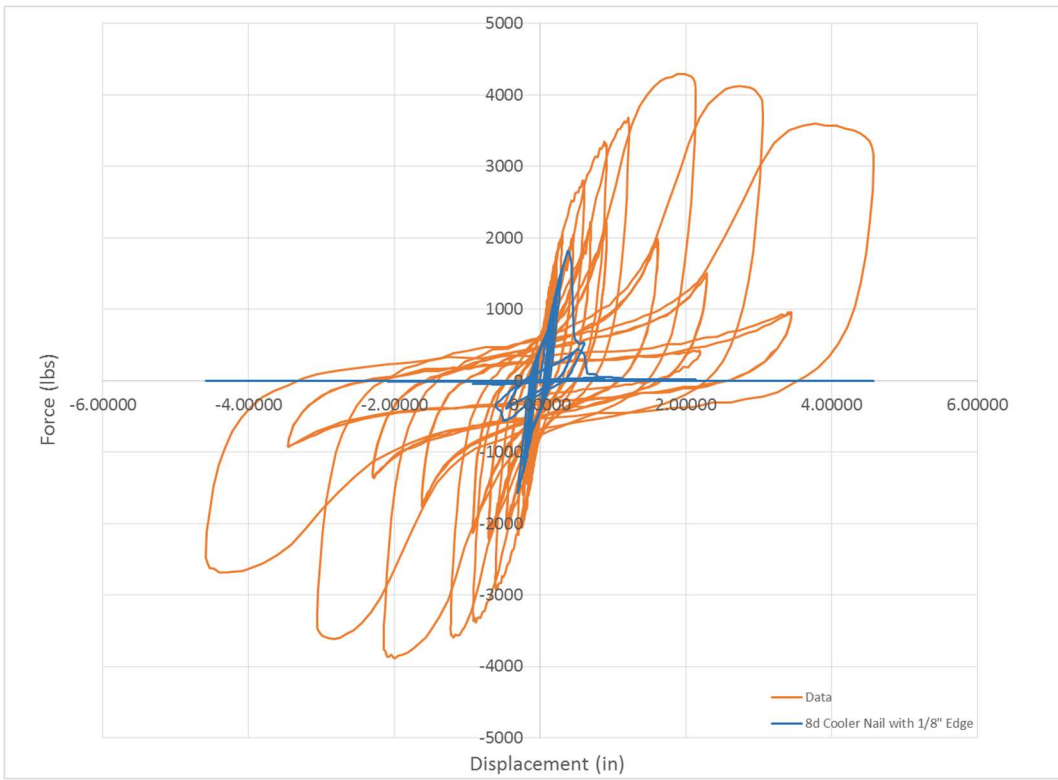


Figure 16. OpenSees Model with 8d Cooler Nail and 1/8" Edge Nailing

CHAPTER 3

Thermal Modeling Setup and Results

This section evaluates the R-values THERM modeling results of four 2x6 wall types including the Conventional Stud Wall, Staggered Stud Wall (2x4 alternating studs with 2x6 sill and header), Rigid External Insulation (Wood Structural Panel Siding over Foam Insulation), and Pressboard I-Beam 2x6 Wall. This work is a preliminary comparison of the framing options with simplified assumptions.

Thermal Modeling Setup

To determine the R-Values for the different types of wall assemblies, THERM, a software program created by Lawrence Berkeley National Laboratories (LBNL 2012) was used. It models heat transfer in two dimensions (in a cross section) through building components such as fenestrations, walls, roofs, and floors where thermal bridging may be an issue.

THERM Parameters

The idealized length of the walls generated was equal to the distance between the adjacent wood studs. Generation of a precise model in THERM requires either importing a *.dxf or *.bmp file into THERM (Mitchell et al 2011). AutoCAD 2013 was used to generate the *.dxf (Drawing eXchange Format) file. In order to properly create a *.dxf file for AutoCAD, the shapes needed for THERM have to be closed polylines for the program to define the material property. An example of a conventional 2x4 wall generated in THERM is illustrated in Figure 17.

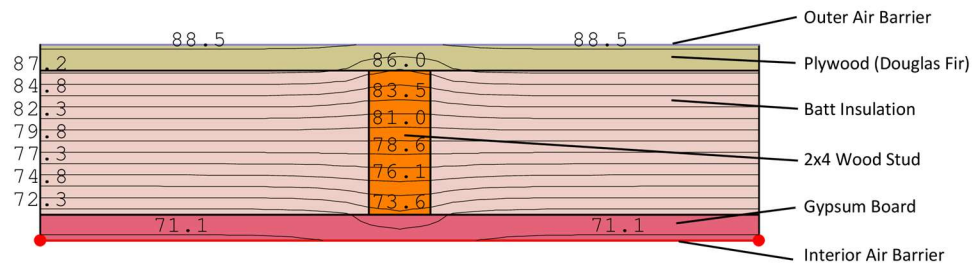


Figure 17. Conventional 2x4 Stud Wall in THERM

Once the *.dxf file is completed in AutoCAD, it needs to be imported into THERM. A new file should be generated first in THERM before importing the AutoCAD *.dxf file. The “common framing” property setting was specified for the cross section. There is an underlay function located in the file tab where the *.dxf gets imported. Once the *.dxf file is imported, the cross-sections have to be traced. Once the cross-section has been traced, a material color becomes populated in the model. On the upper right hand corner, a drop-down menu enables the user to change the material property. As shown in Figure 17, material properties such as plywood, batt insulation, wood stud, and gypsum board are defined. Default material properties in THERM have been used for the thermal models. However, additional material properties can be easily added in THERM.

Once the interior materials are defined, the exterior boundary edges need to be defined. An exterior summer condition of 89.0°F is introduced as part of the heat source as part of the Outer Air Barrier boundary condition. The heat flow travels perpendicular to the cross section of the wall. The numbers as displayed in Figure 17 represent the temperature gradient in °F. The interior wall (Interior Air Barrier) is defined with a temperature of 70.0°F. Those temperatures were chosen to be representative of a summer in Los Angeles. The side boundary conditions are defined as adiabatic where there is no cooling or heating occurring at the boundary. Once the boundaries are defined, the non-

adiabatic boundaries need a U-Factor surface parameter which can be selected by double clicking on the “Outer Air Barrier” and “Interior Air Barrier” respectively. There is a drop down menu that will enable the user to change the U-Factor surface parameter. The Outer Air Barrier is defined with a U-Factor surface parameter of an exterior wall while the Interior Air Barrier is defined with a U-Factor surface parameter of an interior wall.

Once the parameters of the wall assembly are specified, the program can calculate the U-value for the wall assembly. The U-value for the wall assembly can be converted into an R-value by Equation 2. By calculating the R or U value of the assembly, a determination can be made about relative thermal efficiencies of various wall assemblies.

THERM Modeling Results

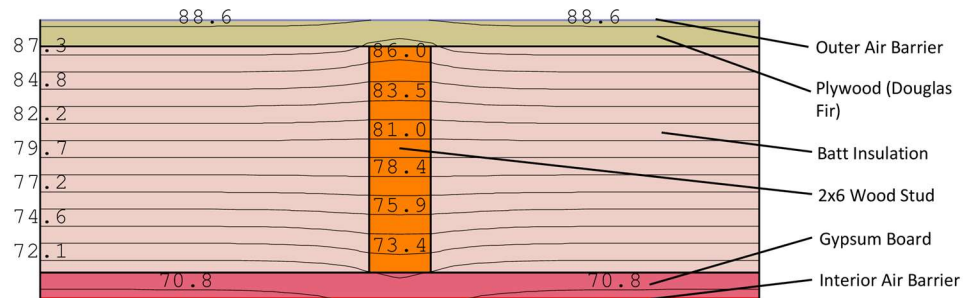


Figure 18. Conventional 2x6 Stud Wall (Temperature Gradient Values in °F)
R-Value=18.0

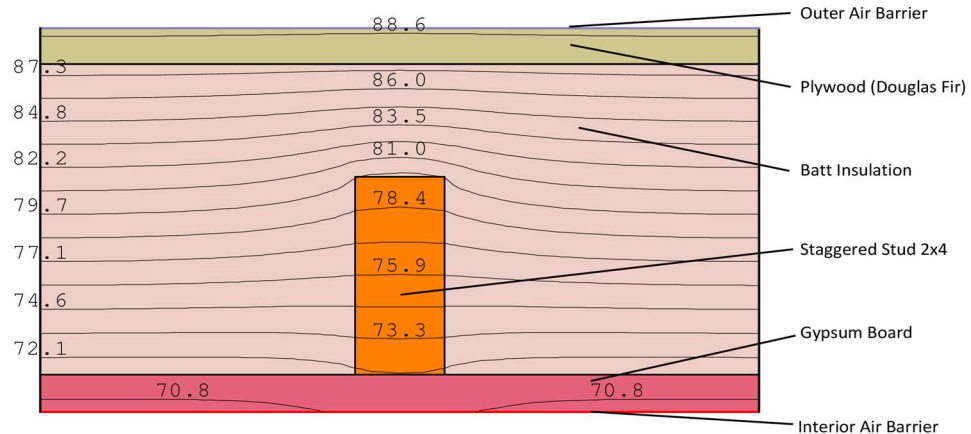


Figure 19. Staggered Stud Wall with 2x4 Alternating Studs and 2x6 Sill and Header
R-Value=18.6

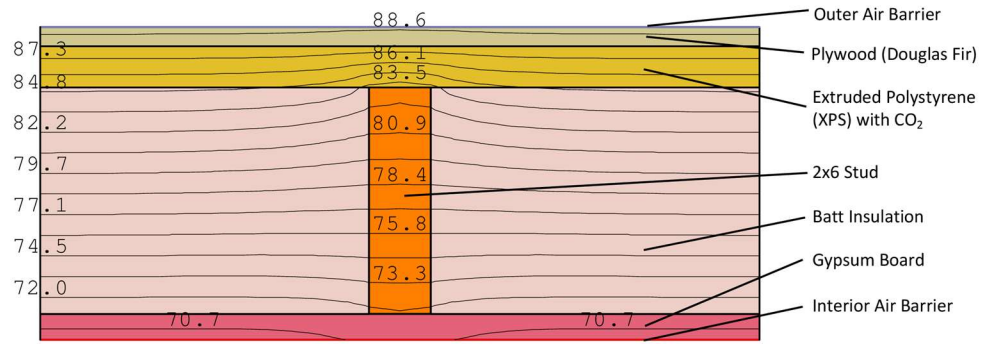


Figure 20. Rigid External Insulation: Wood Structural Panel Siding over Foam Insulation
R-Value 22.2

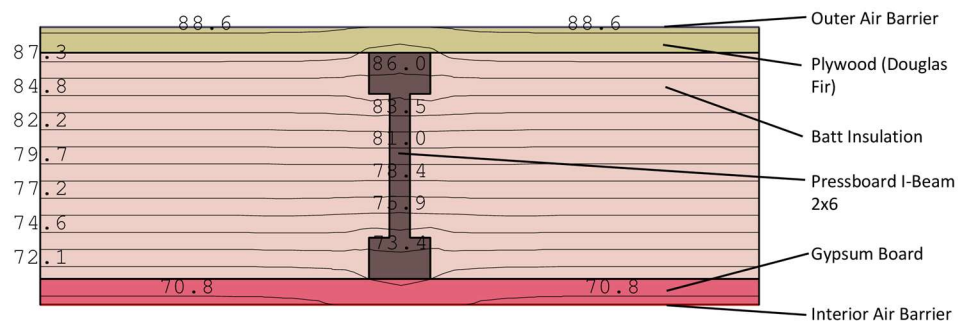


Figure 21. Pressboard I-Beam 2x6 Wall
R-Value 18.1

Table 9. Comparison of R and U Values for 2x6 Wall Framing Types

Framing	U-Value (Btu/hr·ft ² ·°F)	R-Value (hr·ft ² ·°F/Btu)
Conventional 2x4 Stud	0.0806452	12.4
Conventional 2x6 Stud	0.0554949	18.0
Staggered Stud	0.0536213	18.6
Rigid External Insulation	0.0450377	22.2
Pressboard I-Beam 2x6	0.0552847	18.1

Table 9 and Figure 18 through Figure 21 summarize the U and R-Values for each of the 2x6 green wall framing types. As the R-value becomes larger numerically and/or the lower the U-value, the better the building envelope in terms of insulative properties. With green framing wall types that range in R-values from 18.0 to 22.2, the extra 2 in (50.8 mm) of batt insulation increases the thermal efficiency of the wall.

When comparing R-value of the 2x6 conventional wall to that of the 2x4 conventional wall, there is a 45% increase in thermal efficiency.

When comparing the R-values of the I-beam, rigid insulation, and staggered stud 2x6 walls against the 2x6 conventional wall as shown in Table 9, the I-beam's thermal efficiency increase of 0.55% is negligible while the rigid insulation and staggered stud conditionals have a significant thermal efficiency increase of 23.33% and 3.33% respectively. The rigid external insulation is the most thermally efficient out of all the wall types presented.

CHAPTER 4

Discussion and Conclusion

The primary purpose of this investigation was to examine whether OpenSees could accurately predict the load-displacement behavior using sheathing-to-framing connector parameters (*SAWSMaterial*) and using THERM to compare the thermal conductivity (R-value) of various idealized green framing wall arrangements. Using the nail parameters that were originally specified for CASHEW, the OpenSees hysteresis plot visually fits the load-displacement plots from both CASHEW and the physical test results as shown in Figure 9. This infers that OpenSees can be used to model other framing arrangements.

Once the OpenSees model was calibrated to produce load-displacement results using the original nail parameters, nail parameters were modified to obtain a closer fit to the physical testing load-displacement plot as shown in Figure 10. Existing parameters in the literature (CUREE-Caltech nailing parameters) were also assessed. For each respective CUREE-Caltech nailing parameter, the OpenSees model failed after reaching its ultimate strength as shown in Figure 11 through Figure 16.

Thermal performance was studied for a conventional 2x6 stud wall, staggered stud wall, rigid externally insulated wall, and a pressboard I-beam wall. It was shown through THERM that the rigid externally insulated wall showed the most promise with an R-value of 22.2. This was expected due to the additional external insulation.

The validity of OpenSees model was affirmed when the model yielded a similar load-displacement plot to the previous physical model. However, expectations were not met when using the CUREE-Caltech nail parameters (Fonseca et al 2002). The specimen

failure of the OpenSees when applying the CUREE-Caltech nail parameters indicate that the nail parameters are inadequate.

Table 10. Comparison Matrix of Wall Types

Wall Type	Mechanical Performance	Thermal Performance
Conventional 2x6 Stud Wall	Proven in seismic performance	Moderate: Wood studs create thermal bridging
Staggered Stud Wall	Proven in seismic performance	Slight improvement over conventional wall
Rigid External Insulated Wall (Sawn Lumber) Insulation attached in front of Plywood	Proven in seismic performance	Excellent due to elimination of thermal bridging
Rigid External Insulated Wall (Sawn Lumber) Insulation attached behind Plywood	Unknown	Excellent due to elimination of thermal bridging
Pressboard I-Beam Wall	Weaker in seismic performance due to pressboard material	Slight improvement over conventional wall

By understanding how the wall performs both mechanically and thermally, the designer can specify a wall system that is structurally safe and energy efficient.

Table 10 summarizes the mechanical and thermal performance expectations of the different wall types tested in THERM. Expectations fell short with the staggered stud wall and the pressboard I-beam wall as they both have similar thermal resistance values to the conventional 2x6 wall. Since the constructability of these framing types require additional training and labor time, it is not advantageous for the builder and homeowner in terms of cost savings.

Recommended Future Work

Further refinement of the OpenSees model is recommended to take into consideration actual nailing edge conditions, anchor bolts, and hold downs. Shell elements will be required for framing in staggered studs due to eccentricity of the wall. A sensitivity study would be useful to examine how the OpenSees model reacts to each of the individual *SAWSMaterial* parameters. Additional green wall framing techniques and materials should be explored beyond the framing types explored in this thesis. Examples of additional green framing techniques can be found in Straube and Smegal (2011).

Correlation of experimental failure mode to nail forces could be useful for design proposes. Each individual nail could be measured to ascertain which nail yields first.

Since THERM predicted that the idealized rigid external insulated wall was much more energy efficient than a conventional wood shear wall, the entire wall assembly can be constructed taking into consideration all hardware, framing materials, and corner conditions utilizing THERM. Since the framing arrangement with the rigid external insulation yielded the highest R-value, further investigation into how this framing arrangement works with local building codes can help with the design of this wall type.

New fasteners for external rigid insulation and rain screen cladding have been proposed to minimize temporary fastener holes, eliminate blind nailing when attaching to battens, and increased thermal efficiency (Deress and Martin 2015). A suggestion would be to model this system in THERM for thermal performance and OpenSees to model lateral load performance.

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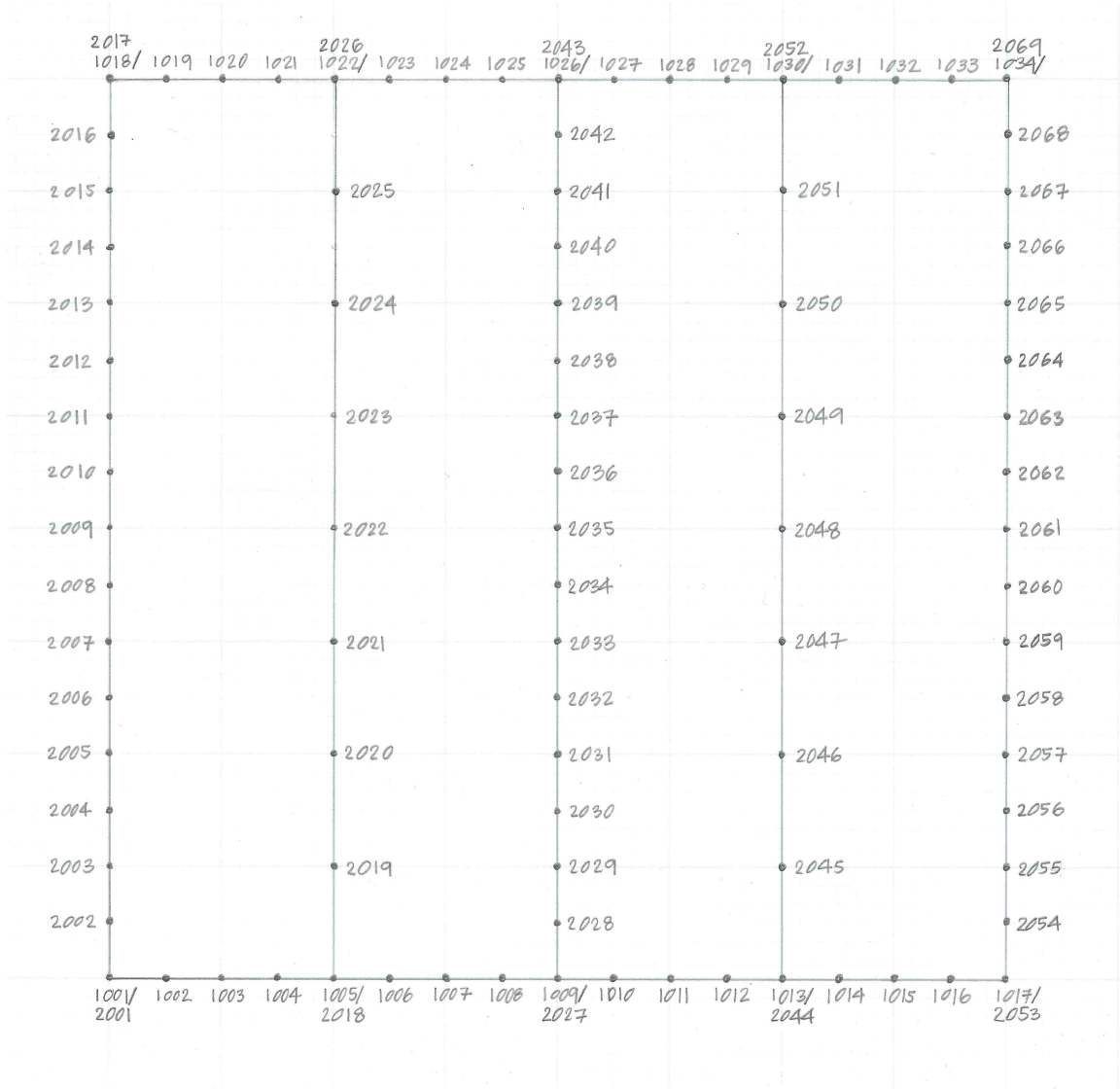
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APPENDIX A

Framing Nodes for 2'x6' Wood Studs in OpenSees



NODES 1001 - 1034 HORIZONTAL FRAMING
 NODES 2001 - 2069 VERTICAL FRAMING

APPENDIX B

OSB Sheathing Nodes and Shells

APPENDIX C

Opensees Code

```
# -----
# Model generation
# -----

# Dimensions are assumed to be in kips (Forces) and inches (dimensions)
# Remove existing model, clears memory for Opensees Interpreter
wipe

# Create ModelBuilder (with three-dimensions and 6 DOF/node-recently
modified)
model BasicBuilder -ndm 3 -ndf 6

# Define GLOBAL XYZ Axis
# X is horizontal (left,right)
# Y is vertical (up, down)
# Z is depth (goes in and out of plane)

# -----
# Create nodes
# -----

# MASTER NODES
#
# -----
# Nodes for establishing beam elements and connections
# Create nodes & add to Domain - command: node nodeId xCrd yCrd zCrd
# Framing based on centerline dimensions
# Horizontal Framing Numbered 1000's
# Vertical Framing Number 2000's
# See Appendix for diagram of master nodes

# Dimensions are in inches and actual dimensions (not nominal)for
lumber
# Double end and header posts are combined into one post for modeling
purposes

#
# -----
# Sheathing Nodes 3000's for left side OSB 4000's for right side OSB
# Left OSB Nodes
set x 1.5
set y 0.75
set z -2.625
set nodeId 3001

while {$y < 90.76} {
  node $nodeId $x $y $z
  puts "$nodeId $x $y $z"
  set x [expr {$x + 4.5}]
  set nodeId [expr {$nodeId + 1}]

  while {$x < 48.01} {
    node $nodeId $x $y $z
```

```

        puts "$nodeId $x $y $z"
        set x [expr {$x + 6}]
        set nodeId [expr {$nodeId + 1}]
    }
    set y [expr {$y + 6}]
    set x 1.5}

set x 1.5
set y 94.5
node $nodeId $x $y $z
puts "$nodeId $x $y $z"
set x [expr {$x + 4.5}]
set nodeId [expr {$nodeId + 1}]
    while {$x < 48.01} {
        node $nodeId $x $y $z
        puts "$nodeId $x $y $z"
        set x [expr {$x + 6}]
        set nodeId [expr {$nodeId + 1}]
    }

#Right OSB Nodes 4000's
set x 48.0
set y 0.75
set z -2.625
set nodeId 4001

while {$y < 90.76} {
    node $nodeId $x $y $z
    puts "$nodeId $x $y $z"
    while {$x < 84.01} {
        set x [expr {$x + 6}]
        set nodeId [expr {$nodeId + 1}]
        node $nodeId $x $y $z
        puts "$nodeId $x $y $z"
    }
    set x [expr {$x + 4.5}]
    set nodeId [expr {$nodeId + 1}]
    node $nodeId $x $y $z
    puts "$nodeId $x $y $z"
    set y [expr {$y + 6}]
    set x 48.0
    set nodeId [expr {$nodeId + 1}]}

set x 48.0
set y 94.5

node $nodeId $x $y $z
puts "$nodeId $x $y $z"
while {$x < 84.01} {
    set x [expr {$x + 6}]
        set nodeId [expr {$nodeId + 1}]
        node $nodeId $x $y $z
        puts "$nodeId $x $y $z"
    }
    set x [expr {$x + 4.5}]
    set nodeId [expr {$nodeId + 1}]
    node $nodeId $x $y $z
    puts "$nodeId $x $y $z"

```

```

# Define OSB/Ply Sheathing Nodes
# Left OSB ID 5000's, Right OSB ID 6000's

# create ElasticMembranePlateSection object which is an isotropic
section for plate and shell analysis
# section ElasticMembranePlateSection $unique section tag $Young's
Modulus $Poisson's Ratio $depth of section $mass density
section ElasticMembranePlateSection 1 494 0.3 0.375 0.00000001499

# create ShellMITC4 element object for sheathing
# element ShellMITC4 $unique element tag $iNode $jNode $kNode $lNode
(for nodes defining
#with the 4 nodes defining element boundaries, input in counter-
clockwise order around the element
# Left OSB
set ID 5001
set iNode 3001

while {$ID < 5127} {
  for {set i 0} {$i < 8} {incr i} {
    element ShellMITC4 $ID $iNode [expr {$iNode + 1}] [expr {$iNode
+ 10}] [expr {$iNode + 9}] 1
    puts "element ShellMITC4 $ID $iNode [expr {$iNode + 1}] [expr
{$iNode + 10}] [expr {$iNode + 9}] 1"
    set ID [expr {$ID + 1}]
    set iNode [expr {$iNode + 1}]
    set iNode [expr {$iNode + 1}]
  }

#Right OSB

set ID 6001
set iNode 4001

while {$ID < 6127} {
  for {set i 0} {$i < 8} {incr i} {
    element ShellMITC4 $ID $iNode [expr {$iNode + 1}] [expr {$iNode
+ 10}] [expr {$iNode + 9}] 1
    puts "element ShellMITC4 $ID $iNode [expr {$iNode + 1}] [expr
{$iNode + 10}] [expr {$iNode + 9}] 1"
    set ID [expr {$ID + 1}]
    set iNode [expr {$iNode + 1}]
    set iNode [expr {$iNode + 1}]
  }

# Master Sill Nodes-Horizontal Framing

# define first nail on sill framing
node 1001 1.5 0.75 -2.625
puts "node 1001 1.5 0.75 -2.625"

set x 6
set nodeId 1002

```

```

node $nodeId $x 0.75 -2.625
puts "node $nodeId $x 0.75 -2.625"
while {$x < 90} {
  node [expr {$nodeId + 1}] [expr {$x + 6}] 0.75 -2.625
  puts "node [expr {$nodeId + 1}] [expr {$x + 6}] 0.75 -2.625"
  set x [expr {$x + 6}]
  set nodeId [expr {$nodeId + 1}]
}

# define last nail on sill framing
set nodeId [expr {$nodeId + 1}]
node $nodeId 94.5 0.75 -2.625
puts "node $nodeId 94.5 0.75 -2.625"
puts "Read Nodes 1001-1017"

#
# Master Header Nodes-Horizontal Framing
set nodeId [expr {$nodeId + 1}]

# define first nail on header framing
node $nodeId 1.5 94.5 -2.625
puts "node $nodeId 1.5 94.5 -2.625"

set x 6
set nodeId [expr {$nodeId + 1}]

node $nodeId $x 94.5 -2.625
puts "node $nodeId $x 94.5 -2.625"
while {$x < 90} {
  node [expr {$nodeId + 1}] [expr {$x + 6}] 94.5 -2.625
  puts "node [expr {$nodeId + 1}] [expr {$x + 6}] 94.5 -2.625"
  set x [expr {$x + 6}]
  set nodeId [expr {$nodeId + 1}]
}

# define last nail on header framing
set nodeId [expr {$nodeId + 1}]
node $nodeId 94.5 94.5 -2.625
puts "node $nodeId 94.5 94.5 -2.625"
puts "Read Nodes 1018-1034"

#
# Master End Double Post Nodes-Left Vertical Framing
set x 1.5
set y 0.75
set z -2.625
set nodeId 2001

while {$y < 90.76} {
  node $nodeId $x $y $z
  puts "node $nodeId $x $y $z"
  set y [expr {$y + 6}]
  set nodeId [expr {$nodeId + 1}]
}

# define last nail on left post vertical framing
node $nodeId $x 94.5 $z
puts "node $nodeId $x 94.5 $z"
puts "Read Nodes 2001-2017"

```



```

#
# Master Center Vertical Post Nodes @24" O.C.
set x 24.0
set y 0.75
set z -2.625
set nodeId [expr {$nodeId + 1}]

while {$y < 84.76} {
    node $nodeId $x $y $z
    puts "node $nodeId $x $y $z"
    set y [expr {$y + 12}]
    set nodeId [expr {$nodeId + 1}]}

# define last nail on left post vertical framing
node $nodeId $x 94.5 $z
puts "node $nodeId $x 94.5 $z"
puts "Read Nodes 2018-2026"

#
# Master Center Vertical Post Nodes @48" O.C.
set x 48.0
set y 0.75
set z -2.625
set nodeId [expr {$nodeId + 1}]

while {$y < 90.76} {
    node $nodeId $x $y $z
    puts "node $nodeId $x $y $z"
    set y [expr {$y + 6}]
    set nodeId [expr {$nodeId + 1}]}

# define last nail on left post vertical framing
node $nodeId $x 94.5 $z
puts "node $nodeId $x 94.5 $z"
puts "Read Nodes 2027-2043"

#
# Master Center Vertical Post Nodes @72" O.C.
set x 72.0
set y 0.75
set z -2.625
set nodeId [expr {$nodeId + 1}]

while {$y < 84.76} {
    node $nodeId $x $y $z
    puts "node $nodeId $x $y $z"
    set y [expr {$y + 12}]
    set nodeId [expr {$nodeId + 1}]}

# define last nail on left post vertical framing
node $nodeId $x 94.5 $z
puts "node $nodeId $x 94.5 $z"
puts "Read Nodes 2044-2052"

```

```

#
# Master End Double Post Nodes-Right Vertical Framing
set x 94.5
set y 0.75
set z -2.625
set nodeId [expr {$nodeId + 1}]

while {$y < 90.76} {
    node $nodeId $x $y $z
    puts "node $nodeId $x $y $z"
    set y [expr {$y + 6}]
    set nodeId [expr {$nodeId + 1}]
}

# define last nail on left post vertical framing
node $nodeId $x 94.5 $z
puts "node $nodeId $x 94.5 $z"
puts "Read Nodes 2053-2069"

#
# Define beam elements

# Add geomTranf
#geomTransf Linear $transfTag $vecxzX $vecxzY $vecxzZ <-jntOffset $dXi
$dYi $dZi $dXj $dYj $dZj>
# The numbers below represent the local axis vs the global axis.
# Vertical Element "2"
geomTransf Linear 2 0 0 -1
# Horizontal Element 1
geomTransf Linear 1 0 1 0

# Assume 2"x6" Wood Beam
# Iz and Iy, Iz= bh3/12, Iy=hb3/12

# Create beam elements - command:
#element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag <-mass $massDens>
# Shear Modulus for Douglas Fir 600 ksi
# Modulus of Elasticity 1600 ksi TYP Wood
# Assume no Torsion "J"

#
# Horizontal Elements (Sill)
# Beam and Column Elements are all numbered 3000, etc.
#

set iNode 1001
set jNode [expr {$iNode + 1}]
set eleTag [expr {( $iNode * 10000)+ $jNode}]

set A 7.875
set E 1600
set G 600
set J 0
set Iy 1.48
set Iz 18.09
set transfTag 1

```

```

while {$iNode < 1017} {
#element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag <-mass $massDens>
  element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag
  puts "element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J
$Iy $Iz $transfTag"
  set iNode [expr {$iNode + 1}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {($iNode * 10000)+ $jNode}]
}

puts "Beam Elements 10011002 through 10161017 Complete"

# Horizontal Elements (Header)
#


---


set iNode [expr {$iNode + 1}]
set jNode [expr {$iNode + 1}]
set eleTag [expr {($iNode * 10000)+ $jNode}]

set A 15.75
set E 1600
set G 600
set J 0
set Iy 11.81
set Iz 36.18
set transfTag 1

while {$iNode < 1034} {
#element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag <-mass $massDens>
  element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag
  puts "element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J
$Iy $Iz $transfTag"
  set iNode [expr {$iNode + 1}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {($iNode * 10000)+ $jNode}]
}

puts "Beam Elements 10181019 through 10331034 Complete"

#End Post Left
#


---


set iNode 2001
set jNode [expr {$iNode + 1}]
set eleTag [expr {($iNode * 10000)+ $jNode}]

set A 15.75
set E 1600
set G 600
set J 0
set Iy 36.18
set Iz 11.81
set transfTag 2

while {$iNode < 2017} {

```

```

#element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag <-mass $massDens>
  element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag
  puts "element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J
$Iy $Iz $transfTag"
  set iNode [expr {$iNode + 1}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {($iNode * 10000)+ $jNode}]

puts "Column Elements 20012002 through 20162017 Complete"

#
# Vertical Post @24" O.C. Column Elements
set iNode [expr {$iNode + 1}]
set jNode [expr {$iNode + 1}]
set eleTag [expr {($iNode * 10000)+ $jNode}]

set A 7.875
set E 1600
set G 600
set J 0
set Iy 18.09
set Iz 1.48
set transfTag 2

while {$iNode < 2026} {
#element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag <-mass $massDens>
  element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag
  puts "element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J
$Iy $Iz $transfTag"
  set iNode [expr {$iNode + 1}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {($iNode * 10000)+ $jNode}]

puts "Column Elements 20182019 through 20252026 Complete"

# Center Vertical Post @48" O.C. Column Elements
set iNode [expr {$iNode + 1}]
set jNode [expr {$iNode + 1}]
set eleTag [expr {($iNode * 10000)+ $jNode}]

set A 7.875
set E 1600
set G 600
set J 0
set Iy 18.09
set Iz 1.48
set transfTag 2

while {$iNode < 2043} {
#element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag <-mass $massDens>
  element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag

```

```

    puts "element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J
$Iy $Iz $transfTag"
    set iNode [expr {$iNode + 1}]
    set jNode [expr {$jNode + 1}]
    set eleTag [expr {($iNode * 10000)+ $jNode}]

puts "Column Elements 20272028 through 20422043 Complete"

#
# Vertical Post @72" O.C. Column Elements

set iNode [expr {$iNode + 1}]
set jNode [expr {$iNode + 1}]
set eleTag [expr {($iNode * 10000)+ $jNode}]

set A 7.875
set E 1600
set G 600
set J 0
set Iy 18.09
set Iz 1.48
set transfTag 2

while {$iNode < 2052} {
#element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag <-mass $massDens>
    element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag
    puts "element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J
$Iy $Iz $transfTag"
    set iNode [expr {$iNode + 1}]
    set jNode [expr {$jNode + 1}]
    set eleTag [expr {($iNode * 10000)+ $jNode}]

puts "Column Elements 20442045 through 20512052 Complete"

#
#Vertical Columns
#End Post Right

set iNode [expr {$iNode + 1}]
set jNode [expr {$iNode + 1}]
set eleTag [expr {($iNode * 10000)+ $jNode}]

set A 15.75
set E 1600
set G 600
set J 0
set Iy 36.18
set Iz 11.81
set transfTag 2

while {$iNode < 2069} {
#element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag <-mass $massDens>
    element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J $Iy $Iz
$transfTag

```

```

puts "element elasticBeamColumn $eleTag $iNode $jNode $A $E $G $J
$Iy $Iz $transfTag"
set iNode [expr {$iNode + 1}]
set jNode [expr {$jNode + 1}]
set eleTag [expr {(($iNode * 10000)+ $jNode)}]

```

```

puts "Column Elements 20532054 through 20682069 Complete"

```

```

#
# -----
# Create hinges to connect the framing together
# Creating hinges isolates the issue to only the nailing at the
# sheathing
# equalDOF master slave DOF(elements that move together)

```

```

equalDOF 1001 2001 1 2 3 4 5
equalDOF 1005 2018 1 2 3 4 5
equalDOF 1009 2027 1 2 3 4 5
equalDOF 1013 2044 1 2 3 4 5
equalDOF 1017 2053 1 2 3 4 5
equalDOF 1018 2017 1 2 3 4 5
equalDOF 1022 2026 1 2 3 4 5
equalDOF 1026 2043 1 2 3 4 5
equalDOF 1030 2052 1 2 3 4 5
equalDOF 1034 2069 1 2 3 4 5

```

```

puts "Hinges for framing established"

```

```

#
# -----
# define SAWS material
# Materials
set F0 0.145 ;# kip
set FI 0.028 ;# kip
set DU 0.42 ;# in
set S0 5.5 ;# kip/in
set R1 0.050
set R2 -0.025
set R3 0.75
set R4 0.006
set alph 0.70
set bet 1.10

# zeroLength material is the actual nail material command
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag -dir
$dir1 $dir2
#$ 1,2,3 -translation along local x,y,z axes, respectively
#$ 4,5,6 -rotation about local x,y,z axes, respectively
# element zeroLength 11 3 5 -mat 2 2 -dir 4 5
# uniaxialMaterial Elastic $matTag $E

# create zerolength materials with SAWS Material

uniaxialMaterial SAWS 999 $F0 $FI $DU $S0 $R1 $R2 $R3 $R4 $alph $bet

```

```

# Nailing of left OSB

```

```

#
# Nails have element tags of 7000' LEFT OSB
# Sill

set iNode 3001
set jNode 1001
set eleTag 7001

while {$eleTag < 7010} {
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
equalDOF $jNode $iNode 3 4 5
puts "equalDOF $jNode $iNode 3 4 5"
set iNode [expr {$iNode + 1}]
set jNode [expr {$jNode + 1}]
set eleTag [expr {$eleTag + 1}]}

puts "Nails 7001 to 7009"

#
# Header
set iNode 3145
set jNode 1018

while {$eleTag < 7019} {
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
equalDOF $jNode $iNode 3 4 5
puts "equalDOF $jNode $iNode 3 4 5"
set iNode [expr {$iNode + 1}]
set jNode [expr {$jNode + 1}]
set eleTag [expr {$eleTag + 1}]}

puts "Nails 7010 to 7018"

# at 1.5" post
set iNode 3010
set jNode 2002

while {$eleTag < 7034} {
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
equalDOF $jNode $iNode 3 4 5
puts "equalDOF $jNode $iNode 3 4 5"
set iNode [expr {$iNode + 9}]
set jNode [expr {$jNode + 1}]
set eleTag [expr {$eleTag + 1}]}

puts "Nails 7019 to 7033"

```

```

# at 24" post
set iNode 3023
set jNode 2019

while {$eleTag < 7041} {
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
  element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
  puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
  equalDOF $jNode $iNode 3 4 5
  puts "equalDOF $jNode $iNode 3 4 5"
  set iNode [expr {$iNode + 18}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {$eleTag + 1}]
}

puts "Nails 7034 to 7040"

#at 48" post
set iNode 3018
set jNode 2028

while {$eleTag < 7056} {
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
  element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
  puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
  equalDOF $jNode $iNode 3 4 5
  puts "equalDOF $jNode $iNode 3 4 5"
  set iNode [expr {$iNode + 9}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {$eleTag + 1}]
}

puts "Nails 7041 to 7055"

# Nailing of RIGHT OSB
#
# Nails have element tags of 8000's RIGHT OSB
# Sill

set iNode 4001
set jNode 1009
set eleTag 8001

while {$eleTag < 8010} {
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
  element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
  puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
  equalDOF $jNode $iNode 3 4 5
  puts "equalDOF $jNode $iNode 3 4 5"
  set iNode [expr {$iNode + 1}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {$eleTag + 1}]
}

puts "Nails 8001 to 8009"

#

```



```

# Header

set iNode 4145
set jNode 1026

while {$eleTag < 8019} {
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
  element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
  puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
  equalDOF $jNode $iNode 3 4 5
  puts "equalDOF $jNode $iNode 3 4 5"
  set iNode [expr {$iNode + 1}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {$eleTag + 1}]
}

puts "Nails 8010 to 8018"

#at 48" post right side
set iNode 4010
set jNode 2028

while {$eleTag < 8034} {
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
  element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
  puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
  equalDOF $jNode $iNode 3 4 5
  puts "equalDOF $jNode $iNode 3 4 5"
  set iNode [expr {$iNode + 9}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {$eleTag + 1}]
}

puts "Nails 8019 to 8033"

# at 72" post
set iNode 4023
set jNode 2045

while {$eleTag < 8041} {
# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
  element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
  puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
  equalDOF $jNode $iNode 3 4 5
  puts "equalDOF $jNode $iNode 3 4 5"
  set iNode [expr {$iNode + 18}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {$eleTag + 1}]
}

puts "Nails 8034 to 8040"

#at 94.5" post
set iNode 4018
set jNode 2054

while {$eleTag < 8056} {

```

```

# element zeroLength $eleTag $iNode $jNode -mat $matTag1 $matTag
  element zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2
  puts "zeroLength $eleTag $iNode $jNode -mat 999 999 -dir 1 2"
# equalDOF master slave DOFconstraint
  equalDOF $jNode $iNode 3 4 5
  puts "equalDOF $jNode $iNode 3 4 5"
  set iNode [expr {$iNode + 9}]
  set jNode [expr {$jNode + 1}]
  set eleTag [expr {$eleTag + 1}]

puts "Nails 8041 to 8055"

```

```

#Boundary Conditions
#fix $nodetag $constvalues 1 constrained 0 not constrained (free)

```

```

fix 1001 1 1 1 0 0 0
fix 1002 0 1 1 0 0 0
fix 1003 0 1 1 0 0 0
fix 1004 0 1 1 0 0 0
fix 1005 0 1 1 0 0 0
fix 1006 0 1 1 0 0 0
fix 1007 0 1 1 0 0 0
fix 1008 0 1 1 0 0 0
fix 1009 0 1 1 0 0 0
fix 1010 0 1 1 0 0 0
fix 1011 0 1 1 0 0 0
fix 1012 0 1 1 0 0 0
fix 1013 0 1 1 0 0 0
fix 1014 0 1 1 0 0 0
fix 1015 0 1 1 0 0 0
fix 1016 0 1 1 0 0 0
fix 1017 0 1 1 0 0 0
fix 1018 0 0 1 0 0 0
fix 1034 0 0 1 0 0 0

```

```

# master slave top nodes

```

```

equalDOF 1018 1019 1
equalDOF 1018 1020 1
equalDOF 1018 1021 1
equalDOF 1018 1022 1
equalDOF 1018 1023 1
equalDOF 1018 1024 1
equalDOF 1018 1025 1
equalDOF 1018 1026 1
equalDOF 1018 1027 1
equalDOF 1018 1028 1
equalDOF 1018 1029 1
equalDOF 1018 1030 1
equalDOF 1018 1031 1
equalDOF 1018 1032 1
equalDOF 1018 1033 1
equalDOF 1018 1034 1

```

```

# -----

```

```

# Recorders
# -----

# Create a recorder for all element forces (local coordinates)
recorder Element -file Element2.txt -ele 10011002 force

# -----
# Analysis parameters
# -----

# -----
# STATIC REVERSE CYCLIC ANALYSIS
# -----
#
#create a Linear TimeSeries (load factor varies linearly with time):
command timeSeries Linear $tag
timeSeries Linear 1

# Create a Plain load pattern with a linear TimeSeries:
# command pattern Plain $tag $timeSeriesTag { $loads }
pattern Plain 1 1 {
#   # Create the nodal load - command: load nodeID xForce yForce
zForce xRot yRot zRot
#   # 1 kip on node 1018
    load 1018 1 0 0 0 0 0}

    # we need to set up parameters that are particular to the model.

set fl [open "datapoints5.txt" r]
set data [read $fl]
close $fl
set lines [split $data \n]

foreach Dincr $lines {
set IDctrlNode 1018;
# node where displacement is read for displacement control
set IDctrlDOF 1;
# degree of freedom of displacement read for displacement control
set Dmax $Dincr;
# maximum displacement of pushover. push to 10% drift

# ----- set up analysis parameters
# CONSTRAINTS handler -- Determines how the constraint equations are
enforced in the analysis
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/617.htm)
#   Plain Constraints -- Removes constrained degrees of freedom
from the system of equations (only for homogeneous equations)

constraints Plain;

# DOF NUMBERER (number the degrees of freedom in the domain):
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/366.htm)

```

```

# determines the mapping between equation numbers and degrees-of-
freedom
#           Plain -- Uses the numbering provided by the user
numberer Plain

# SYSTEM
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/371.htm)
# Linear Equation Solvers (how to store and solve the system of
equations in the analysis)
# -- provide the solution of the linear system of equations  $Ku = P$ .
Each solver is tailored to a specific matrix topology.
#           ProfileSPD -- Direct profile solver for symmetric positive
definite matrices
#           BandGeneral -- Direct solver for banded unsymmetric matrices
#           BandSPD -- Direct solver for banded symmetric positive
definite matrices
#           SparseGeneral -- Direct solver for unsymmetric sparse
matrices
#           SparseSPD -- Direct solver for symmetric sparse matrices
#           UmfPack -- Direct UmfPack solver for unsymmetric matrices

system BandGeneral

# TEST: # convergence test to
# Convergence TEST
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/360.htm)
# -- Accept the current state of the domain as being on the converged
solution path
# -- determine if convergence has been achieved at the end of an
iteration step
#           NormUnbalance -- Specifies a tolerance on the norm of the
unbalanced load at the current iteration
#           NormDispIncr -- Specifies a tolerance on the norm of the
displacement increments at the current iteration
#           EnergyIncr-- Specifies a tolerance on the inner product of
the unbalanced load and displacement increments at the current
iteration

set Tol 0.1;
# Convergence Test: tolerance
set maxNumIter 100;
# Convergence Test: maximum number of iterations that will be performed
before "failure to converge" is returned
set printFlag 0;
# Convergence Test: flag used to print information on convergence
(optional)
# 1: print information on each step;
set TestType EnergyIncr ;
# Convergence-test type
test $TestType $Tol $maxNumIter $printFlag;

# Solution ALGORITHM: -- Iterate from the last time step to the current
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/682.htm)
#           Linear -- Uses the solution at the first iteration and
continues
#           Newton -- Uses the tangent at the current iteration to
iterate to convergence

```

```

#           ModifiedNewton -- Uses the tangent at the first iteration to
iterate to convergence
set algorithmType Newton
algorithm $algorithmType;

# Static INTEGRATOR: -- determine the next time step for an analysis
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/689.htm)
#           LoadControl -- Specifies the incremental load factor to be
applied to the loads in the domain
#           DisplacementControl -- Specifies the incremental
displacement at a specified DOF in the domain
#           Minimum Unbalanced Displacement Norm -- Specifies the
incremental load factor such that the residual displacement norm is
minimized
#           Arc Length -- Specifies the incremental arc-length of the
load-displacement path
# Transient INTEGRATOR: -- determine the next time step for an analysis
including inertial effects
#           Newmark -- The two parameter time-stepping method developed
by Newmark
#           HHT -- The three parameter Hilbert-Hughes-Taylor time-
stepping method
#           Central Difference -- Approximates velocity and acceleration
by centered finite differences of displacement
integrator DisplacementControl $IDctrlNode $IDctrlDOF $Dincr

# ANALYSIS -- defines what type of analysis is to be performed
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/324.htm)
#           Static Analysis -- solves the KU=R problem, without the mass
or damping matrices.
#           Transient Analysis -- solves the time-dependent analysis.
The time step in this type of analysis is constant. The time step in
the output is also constant.
#           variableTransient Analysis -- performs the same analysis
type as the Transient Analysis object. The time step, however, is
variable. This method is used when
#           there are convergence problems with the Transient Analysis
object at a peak or when the time step is too small. The time step in
the output is also variable.

analysis Static

# -----
perform Static Pushover Analysis
# -----

set Nsteps [expr int($Dmax/$Dincr)];
# number of pushover analysis steps
set ok [analyze $Nsteps];
# this will return zero if no convergence problems were encountered

# ----- in case of convergence problems
if {$ok != 0} {
# change some analysis parameters to achieve convergence
# performance is slower inside this loop
    set ok 0;
    set controlDisp 0.0;          # start from zero

```

```

set D0 0.0;      # start from zero
set Dstep [expr ($controlDisp-$D0)/($Dmax-$D0)]
while {$Dstep < 1.0 && $ok == 0} {
  set controlDisp [nodeDisp $IDctrlNode $IDctrlDOF ]
  set Dstep [expr ($controlDisp-$D0)/($Dmax-$D0)]
  set ok [analyze 1 ]
  if {$ok != 0} {
    puts "Trying Newton with Initial Tangent .."
    test NormDispIncr $Tol 2000 0
    algorithm Newton -initial
    set ok [analyze 1 ]
    test $TestType $Tol $maxNumIter 0
    algorithm $algorithmType
  }
  if {$ok != 0} {
    puts "Trying Broyden .."
    algorithm Broyden 8
    set ok [analyze 1 ]
    algorithm $algorithmType
  }
  if {$ok != 0} {
    puts "Trying NewtonWithLineSearch .."
    algorithm NewtonLineSearch .8
    set ok [analyze 1 ]
    algorithm $algorithmType
  }
}
};      # end if ok !0
}

puts "DonePushover"

```