Chapter 3 – Materials and Methods

3.1 – Introduction

Again, the objectives of this research were to 1) measure strength and stiffness performance of cyclic moisture conditioned connections, 2) develop conclusions related to trends in connection performance as exposure time increases, and 3) verify the accuracy of the general dowel equations for estimating yields of connections and failure mode.

The experimental phase of the research work involved monotonic tests of six hundred thirty single-shear laterally-loaded connections. The specific sequence of each connection specimen's actual testing to failure was relative to each connection's specified exposure to periods of high and low relative humidity. Each connection group received a different amount of exposure to cyclic moisture conditioning. Connection specimens involved a solid wood stud member and a panel member connected by a single common nail. For the purposes of comparison, general dowel equations were used to compute predicted values of the lateral resistance for each connection type. Because of the input parameters of these specific formulas, supplemental material tests were required. These include embedment testing on the wood materials, in addition to simple bending tests on the fasteners themselves. All fabrication, conditioning, and testing was performed at the Brooks Forest Products Center. The Department of Wood Science and Forest Products, an academic branch within the College of Natural Resources, manages this facility on the main campus of Virginia Tech in Blacksburg, Virginia.

The experimental design matrix includes connection configurations typically found in modern light-frame residential construction. A total of six different connection configurations, of one-hundred five specimens each, were divided into seven separate treatment groups to assign the prescribed dose of moisture exposure prior to testing. A generalized randomized complete block design was employed, which included fifteen replications per connection configuration. Additional materials for each connection configuration type were prepared in order to insure error-free data from each specimen batch.

The blocking factor in this design was caused by the different connection configurations tested. Six different types of side member materials, each produced at a different location or mill, were used in the connection specimens. Even though all six types of sheathing products were similar in structure and composition, the performance of a particular panel product cannot be directly compared to that of another panel product. This is simply because each panel was manufactured under unknown manufacturing parameters, such as the resin and wax content, hot-press schedule, and compaction ratio. In terms of OSB and plywood manufacturing, these processing parameters are influential in determining the final material performance of a structural sheathing product. A blocking factor was appropriated to each group by an affiliation to either 'Mill A', 'B', 'C', 'D', 'E', or 'Mill F'. The designations refer to the specific side member materials utilized in each connection group. These references will be used throughout the thesis when referring to a particular specimen group affiliated with any of the six side member materials.

The treatment factor was related to the varying degrees of exposure to cyclic moisture conditioning received by the connections specimens. There were seven treatment groups differentiated by receiving either zero cycles (control group), one, five, ten, fifteen, twenty-five, or forty cycles in a cyclic wet/dry environment. The experimental design matrix includes connection material types, sizes, and number of replications for each block/treatment group (Table 3.1).

Additional tests included main and side member embedment testing, fastener bending testing, vertical density profile evaluations, and moisture content measurements. Embedment testing of the main and side member materials provided bearing strength information for each material. Fastener bending tests allowed for the determination of the bending yield of each nail type used in the connection specimens. The moisture content testing of the main and side members of each specimen within each connection/treatment batch provided validation of consistency among the specimens. Significantly high or low moisture contents within a specific connection will cause the related data to be invalid. Vertical density profile evaluations were necessary to examine the process of de-densification of each particular panel product used as the side members of the connection specimens. Material embedment and fastener yield distributions are inputs for the general dowel equations and are used to calculate predictions of connection behaviors based on the yield model. The specific test procedures are further described in this chapter.

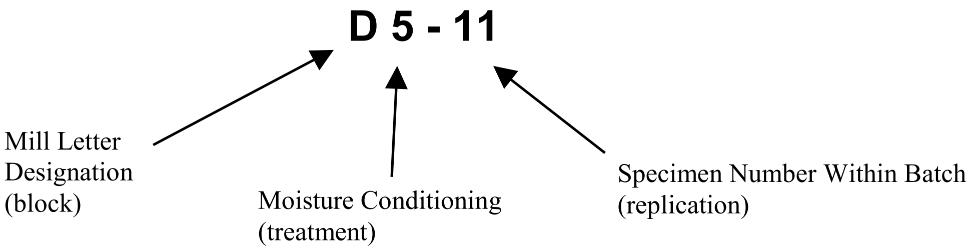
Throughout this chapter the terms *main* and *side member* are used extensively. This terminology is used to describe the two major components of each connection specimen. The main member represents the solid wood framing stud upon which the sheathing (i.e., the side member) is attached with a specific size smooth-shank wire nail. In other words, the side member first receives the fastener and then it passes into the main member where the nail point remains embedded. The nail type and size used in the specimens was determined by the thickness of the side member material. In addition, it should be noted that all samples comprising a main member (both connection and embedment specimens) were fabricated so that loading was applied parallel to the orientation of the grain in the solid wood component.

Table 3.1: Connection sample components and replications per treatment.

Mill (Block)	**Main member**	**Side member**	**Nail type**	**Treatment Assignment** *(Corresponding number of cycles received)*							**Totals**
				1 *(0)*	**2** *(1)*	**3** *(5)*	**4** *(10)*	**5** *(15)*	**6** *(25)*	**7** *(40)*	
A	SF 2 x 4"	7/16" OSB	6d Common	15	15	15	15	15	15	15	**105**
B	SF 2 x 4"	7/16" OSB	6d Common	15	15	15	15	15	15	15	**105**
C	SF 2 x 4"	7/16" OSB	6d Common	15	15	15	15	15	15	15	**105**
D	SF 2 x 4"	7/16" OSB	6d Common	15	15	15	15	15	15	15	**105**
E	SF 2 x 4"	19/32" OSB	8d Common	15	15	15	15	15	15	15	**105**
F	SF 2 x 4"	15/32" CD 4-ply plywood	6d Common	15	15	15	15	15	15	15	**105**
Totals				**90**	**90**	**90**	**90**	**90**	**90**	**90**	**630**

3.1.1 – Specimen Identification System

An alphanumeric system was employed to identify each individual connection specimen. The illustration below describes the classification scheme.



In this system, the first letter identifies the mill which inherently also describes the side member material and nail type used. The second character denotes the treatment group assignment, which directly represents the number of moisture cycles the specimen will receive. The last number indicates the replication number within that particular batch. For example, the above illustration can then be identified, using Table 3.1, as a specimen using 7/16 in. OSB sheathing from 'Mill D' as the side member with a 6d common nail to connect with the main member. Note that the same 2 in. by 4 in. stud material was used in all specimens with a randomization process used for assigning to the experimental units. This sample is the eleventh replication of this connection configuration and is assigned to treatment group '5', which is a code for exposure to fifteen cycles of cyclic moisture conditioning, as shown in Table 3.1.

3.1.2 – Sample Size Determination

The sample size is the minimum number of specimens fabricated, conditioned, and tested per connection/treatment batch. This value was chosen in a manner so that the sample average was within plus or minus eight percent of the population mean at a ninety percent confidence level (CI) according to the equation (Ott and Longnecker 2001):

$$n = \frac{(z_{\alpha/2})^2 \sigma^2}{E^2}$$

Where:

n = minimum required sample size

$z_{\alpha/2}$ = quantile related with a p-value of 1 - α/2 under a normal curve

σ = population standard deviation

E = ½ the width of a 100(1 - α) % confidence interval

Note:

$$\mathrm{CI}_{(1-\alpha)\%} = \mu \pm E$$

$$\sigma = \delta\mu$$

$$E = e\mu$$

Where:

e = coefficient of allowable error (8%)

δ = predicted coefficient of variation (COV), %

μ = population mean

Simplification and substitution modifies the original equation to become:

$$n = \frac{(z_{\alpha/2})^2 \delta^2}{e^2}$$

Therefore, the population mean, μ, is not needed for calculation. The predicted coefficient of variation (COV) is determined by investigating similar connection research and using the highest observed COV from that study. The COV for this work was based on work by Smart (2002), which reported a maximum COV of 19% among connections employing 7/16 in. OSB side members and 8d common nails.

Using the last equation, the calculated value of the required sample size for this population is fifteen based on a ninety percent CI where $z_{\alpha/2} = 1.645$.

3.2 – Materials

All materials used for the connection specimens were readily available at local home improvement stores and lumberyards. Samples were fabricated to simulate actual sheathing to framing connections typically used in light-frame residential construction. Components of each specimen involved one main member and one side member attached by a wire nail. The main members for all connections were solid softwood framing studs while the side members consisted of six panel products. Two types of non-coated, smooth shank, common wire nails were used as fasteners.

3.2.1 – Main Member – Framing Lumber

Each specimen used in this research involved a nailed connection between lumber and panel products. All main members were made from 2x4 nominal dimension lumber grade stamped by the Northeastern Lumber Manufacturers Association (NeLMA), as STUD grade and surfaced dry (i.e., the lumber was surfaced at MC of 19% or less). In addition, the grade stamp, shown in Figure 3.1a, indicated the use of Balsam Fir (*Abies balsamea*) and the Eastern Spruce species group, which includes Red Spruce (*Picea rubens)*, White Spruce (*Picea glauca)*, and Black Spruce (*Picea mariana*). Another stamp indicated that heat treatment (HT) was applied by the manufacturer (Figure 3.1b). This is a practice required by several international organizations (i.e., European Union and United Nations) involving all imported wood products, including composite panels, boxes, and pallets. The purpose of the regulation is to guard against forest disease agents, namely the pinewood nematode.

The framing material used in each sample had actual dimensions of 1.5 in. in thickness by 3.5 in. in width by 6.0 in. in length. The main members were cut to 6 in. lengths from approximately forty 10 ft. studs. All studs were taken from the same pack and were chosen based on the following criteria: no loose knots, no obvious decay or shake, no encased knots larger than 1 in. diameter, and only one encased knot smaller than 1 in. in diameter was allowed per 6 in. length. In addition, the stud ends were trimmed prior to cutting. Seven hundred eighty main members were obtained and numbered sequentially as cut. The additional one hundred fifty main members were cut for embedment test samples and for replacements if needed at time of connection fabrication.

(a) *(b)*

Figure 3.1: (a) Grade stamps and (b) heat treatment mark on main member materials.

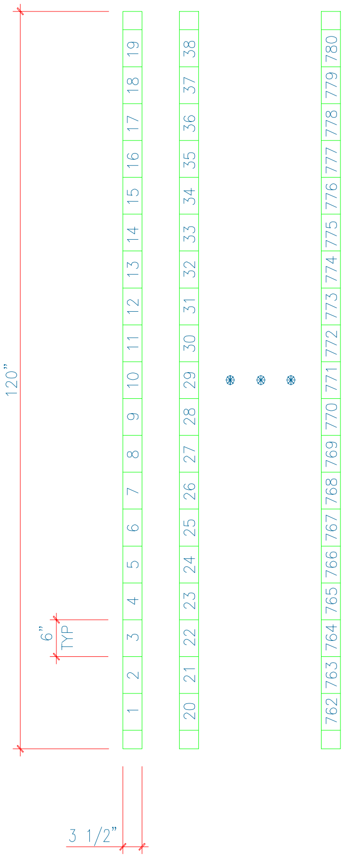


Figure 3.2: Cutting and sequential numbering diagram of main member components.

3.2.2 – Side Member – Structural-Grade Sheathing

The side member materials for each connection/treatment batch varied because this research was primarily focused on the effect of cyclic moisture conditions and sheathing materials on connection rigidity. Side member materials consisted of four types of 7/16 in. OSB (each from a different manufacturer), one type of 19/32 in. OSB, or a 15/32 in. plywood product (Figure 3.3). All the panel products were specified as Exposure 1 per APA or TECO policies for structural grade wood panels. Additionally, each sheathing type was span rated at 24/16, except for the thickest panel product, which was designed for flooring applications with supports spaced at 20 in. on center. Mill letter designations were used to differentiate between the side member types as seen in Table 3.1. This was especially important with respect to specimen labeling.

Figure 3.3: The six different side member materials.

Regardless of panel thickness, each side member was cut to a final size of 3.5 in. by 16 in. Two 4 ft. by 8 ft. panels of each side member type were needed to produce enough samples for the replications required. Each panel was first trimmed on all edges and then cut into thirteen 3.5 in. wide stripes along the length of the panel using a fenced table-saw with supporting rollers to insure stability. Each strip was then cut to 16 in. lengths on a radial-arm saw. Care was taken to preserve each side member's specific placement within the entire 4 ft. by 8 ft. panel. Side members were numbered sequentially as cut. Figure 3.4 shows the cutting schedule and subsequent number assignments used to produce 130 side members per panel type.

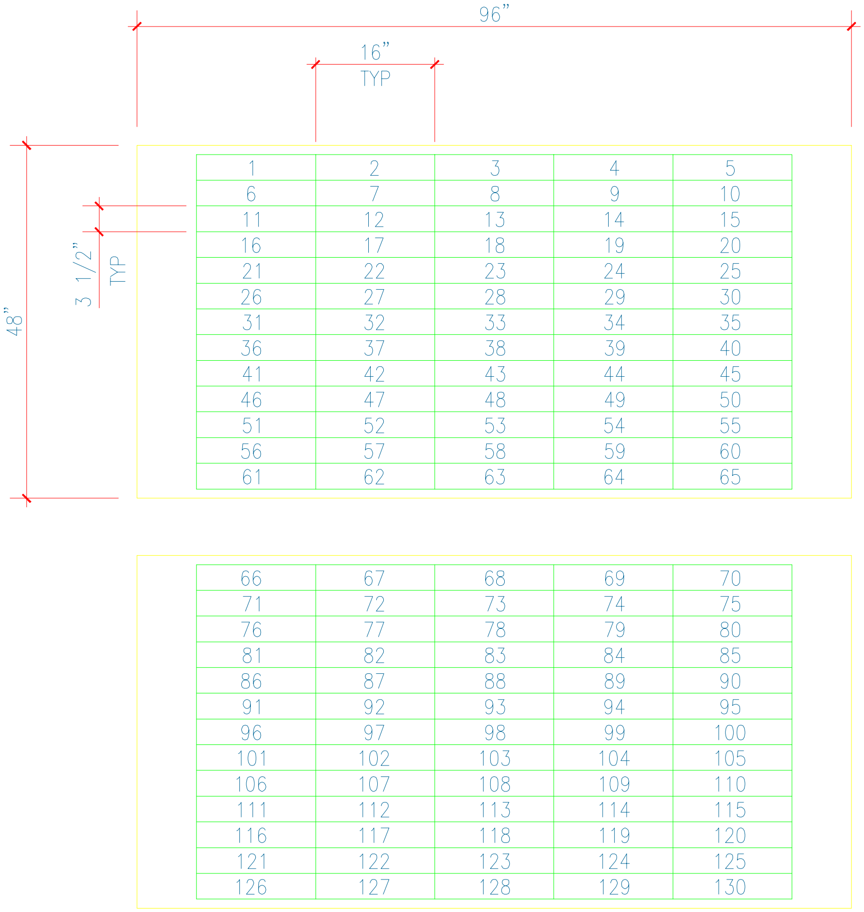


Figure 3.4: Cutting schedule and numbering system for side member components.

3.2.3 – Fastener – Common Wire Nails

All fasteners used in the connection specimen meet the ASTM F 1667: *Standard specification for driven fasteners: nails, spikes, and staples* (ASTM 2003c). The two types of fasteners used were 6d and 8d common wire nails. All nails were checked with calipers for proper length and visually inspected for defects prior to use. ASTM F 1667 classifications for each nail type used are shown in Table 3.2

Table 3.2: Sheathing and fastener assingments, nail dimensions, and classifications.

Mill (Block)	Side Member	Nail type	Length (in)	Shank Diameter (in)	Head Diameter (in)	ASTM Classification
A	7/16" OSB	6d Common	2	0.113	0.266	F1667 NL CM S 05 B
B	7/16" OSB					
C	7/16" OSB					
D	7/16" OSB					
F	15/32" CD 4-ply plywood					
E	19/32" OSB	8d Common	2 1/2	0.131	0.281	F1667 NL CM S 07 B

The ASTM F 1667 standard assigns an appropriate categorization to each specific fastener type as provided in Table 3.2. The classification indicates fastener type, metal, a number, and finish. For example, 6d common wire nails are designated as F1667 NL CM S-05B. This code specifies the ASTM standard (F1667), a nail type fastener (NL), common (CM), steel (S) with a bright finish (B) and a reference number (05) to lookup the dimensional information in the ASTM F 1667 standard. Table 3.2 provides nail length, shank diameter, and head diameter as listed in the standard. The terms 6d and 8d are simply trade designations in reference to the penny weight (1/20 oz). This facilitates the process of counting individual nails when buying or selling large amounts.

As previously stated, the nail type used in the connection specimens was determined by the thickness of the side member material in each particular sample. This standardization is based on configurations provided in an APA - The Engineered Wood Association publication, *PRP-108: Performance Standards and Qualification Policy for Structural-Use Panels* (APA 2001). The standard provides the testing protocol, identified as APA Test Method S-4, for evaluating fastener holding performance in laterally-loaded sheathing to stud connections that have been subjected to water submersion followed by drying. According to this standard, all side members with thicknesses of 0.5 in. and less receive a 6d box nail, while panels greater than 0.5 in. in thickness are fastened by an 8d common nail. Only specimens with side members from

‘Mill E’ required the application of the larger 8d nail. Common nails were used instead of box nails because of availability issues.

All of the nails of each type were from the same producer and all nails were purchased from a local hardware store at the same time. Only non-coated metal fasteners were used in an effort to allow the process of galvanic corrosion. This was done in order to simulate worst-case scenarios for connections in the presence of cyclic moisture conditions. Typically, the majority of light-frame residential construction makes use of cheaper, non-coated nails for securing sheathing when an exterior siding material is intended. As discussed in an earlier chapter, moisture is able to move through porous materials and attack unprotected metals.

3.3 – Specimen Fabrication

One main member, one side member, and one nail composed each of the six hundred thirty connection specimens. The edge of the main member was attached to the face of the side member and a nail was inserted by hammer so that its major axis was perpendicular to the plane of interface between the two wood materials. Density profile samples representative of each of the side member types were analyzed at the end of each cycle using an x-ray density profilometer. Half-hole embedment samples representing the main member material and all side member types were also prepared. Fastener bending tests were preformed on two types of wire nails in the ‘new/unused’ condition. Following fabrication, the connection samples and density samples were placed into the climate chamber for exposure to cyclic moisture conditioning prior to testing.

3.3.1 – Connection Specimens

As stated previously, each connection sample includes one main and side member and a single wire nail. The dimensional details in regards to specific placement of each element in respect to each other are provided in Figure 3.5.

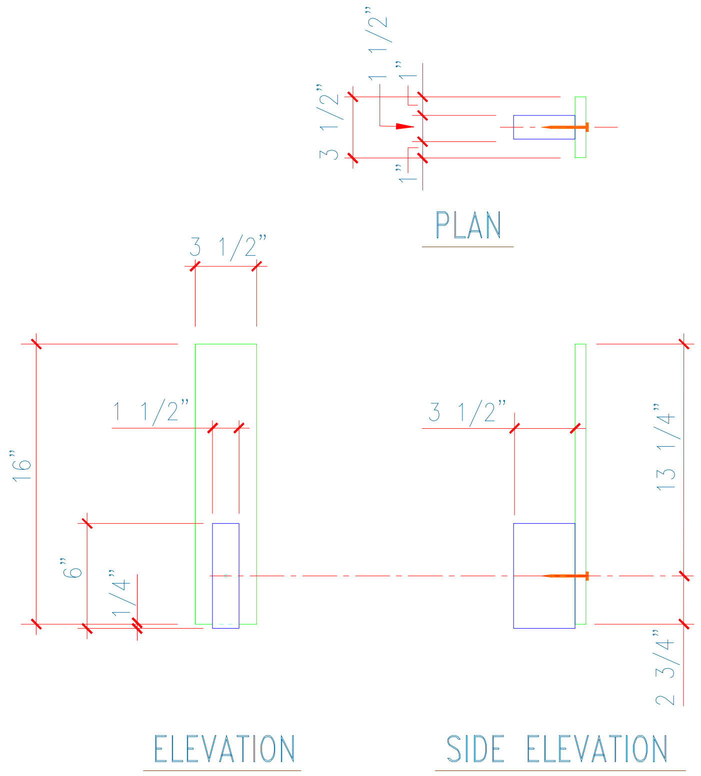


Figure 3.5: Sizing and configuration of connection specimens.

Each sample was sequentially numbered upon cutting the individual pieces from the full-sized panels and studs. Specific assignment to each particular connection/treatment batch was determined by a random number generating program using SAS version 8.0, a statistical software package produced by the SAS Institute Incorporated of Cary, North Carolina. This program provided randomized matching of a single main member to a single side member. Assignments to each treatment group within a particular block were also randomized with this method.

Prior to assembly, the two cut ends of the main members and all four cut edges of the side member pieces were coated with a wax and water elusion called Anchorseal® made by UC Coatings Corporation of Buffalo, New York (Figure 3.6). This sealant has the same viscosity as latex paint, a specific gravity of 0.95, and can be applied by spray or brush. Normally this product is used to seal the ends of freshly sawn logs in order to prevent checking and degrading resulting from rapid moisture loss while awaiting further processing. For this project the purpose of the end sealer was similar – to prevent moisture transfer from occurring at the cut ends and edges of the prepared connection components. This allows for simulating the characteristics of a full-sized panel of OSB or a full-length stud. Sealing the cut ends and edges minimizes the amount of moisture transfer in and out of the undressed areas and causes the dressed faces of the sheathing and studs to become primary sites for moisture transfer into and out of the materials as surrounding conditions change. This effect is similar to what is experienced in a full-scale scenario where the ratio of cut, or exposed edges, to the total surface area is greatly minimized by using full-size 4 by 8 ft. panels and slender 2 by 4 in. studs. Smaller wood samples adsorb and desorb moisture at higher rate than their larger-sized counterparts, which they are intended to simulate. Figure 3.7 and Figure 3.8 are photos of the stacked main and side members after the application and drying of the end coating, but prior to connection fabrication and conditioning.

Figure 3.6: One-gallon bucket of Anchorseal® end sealer.

Figure 3.7: Main members with dry coat of Anchorseal® end sealer.

Figure 3.8: Side members with dry coat of Anchorseal® end sealer.

A jig was constructed and used as a template to maintain consistency among all connection specimens (Figure 3.9). First, a main member was put into the jig and then the side member was placed on top. The nail location was shown as the intersection of two carefully measured lines scribed onto the jig. Nails were driven with a handheld hammer into the side member and then main member to complete a connection specimen. The nails were driven so the underside of the head was flush with the face of the side member.

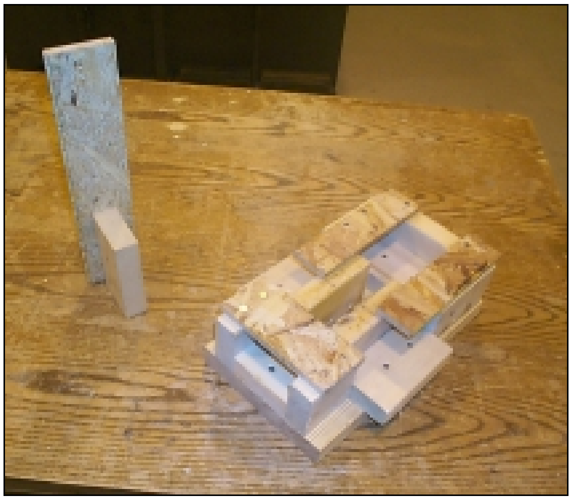


Figure 3.9: Connection specimen and nailing jig.

Prior to use, each nail was inspected for defects and checked for the proper dimensions according to ASTM F 1667 as shown in Table 3.2. In addition, care was taken to insure that the side member face labeled 'This Side Down' was facing the main member upon nailing the two components together. This was done to maintain consistency among the samples, but is not necessarily indicative of the practices used on a construction site. In fact, the panel labeling only applies to flooring applications. Because composite panels are manufactured with a rough and a smooth side, it is important for the rough surface to be installed facing upwards as a safety precaution. The smooth side can be slippery when wet and become a hazard for workers.

3.3.2 – Embedment Specimens

Embedment specimens were prepared from main and side member materials identical to those used in the connection fabrication process. The purpose of the embedment tests was to produce data concerning the bearing resistance of each type of wood material and fastener utilized in this project. This information, in conjunction with fastener bending data, was used in the general dowel equations for calculating the predicted lateral resistance of each connection configuration tested. The predictions do not include the effect of moisture cycling and therefore are likely to be analogous to the resistance afforded by the connection samples that received no exposure inside the climate chamber, but were conditioned to a 12% EMC prior to testing.

Fabrication of the embedment samples followed ASTM D 5764, which relates to testing for bearing resistance in wood products (ASTM 2003e). Procedures for preparing half-hole embedment specimens were used instead of the full-hole alternative because small diameter nails were used. Twenty specimens were made for testing the main member material and all six types of side member materials with both the 6d and 8d common nails. The main member embedment specimen dimensions were as follows: 1.5 in. (tangential direction) by 1.75 in. (loaded dimension, radial direction) by 3 in. (longitudinal direction). The side member counterparts were cut to 3.5 in. in width by 2.5 in. in length and the loaded dimension was dependent on the specific side member material, which varied among 7/16 in., 15/32 in., and 19/32 in. thickness. Prior to testing, the specimens received exposure inside a conditioning chamber allowing the moisture content within the samples to adjust to 12% over a period of 21 days.

3.3.3 – Fastener Bending Specimens

The nails used in the fastener bending tests were selected from the same batches as those used in the connection specimens. Ten wire nails of both types, 6d and 8d common, were randomly sampled, evaluated for defects, and measured to insure they met the specifications outlined in ASTM F 1667: *Standard specification for driven fasteners: nails, spikes, and staples* (ASTM 2003c).

3.3.4 – Density Profile Specimens

Samples of the side member materials were prepared for the purpose of observing the de-densification of the sheathing materials as exposure to cyclic moisture conditioning increased. Representative sets of two specimens from each of the six side member types were cut into 2 in. by 2 in. sizes. The size was determined by the dimensions required to accommodate the specimens within the confines of the sample holding tray used with the vertical-density profilometer.

3.3.5 – Moisture Content & Specific Gravity Specimens

Samples of both main and side member samples were cut from the connection specimens following testing. Moisture content and specific gravity measurements were determined from the same samples and were prepared using ASTM D 1037: *Standard methods for evaluating the properties of wood-based fiber and particle Panel Materials* and ASTM D 2395: *Standard test methods for specific gravity of wood and wood-base materials*, respectively (ASTM 2003f, ASTM 2003h).

3.4 – Specimen Conditioning

A major component of this research involved exposing connection and density samples to various periods of cyclic humidity exposure. An indoor climate chamber was built for this purpose. The moisture conditioning regime involved repeatedly cycling the relative humidity from high to low levels. The relative humidity in the chamber was cycled within a range experienced in a typical in-service wall envelope. The basis for which will be explained later in this section. This section also discusses the methods used to produce the desired conditions within the climate chamber and observations of moisture contents of the main and side members during exposure.

3.4.1 – Conditioning Regime

Within the climate chamber, the connection specimens were subjected to multiple-phase moisture conditioning in the form of cyclic relative humidity with constant temperature. The range of conditions produced inside the chamber were applicable to the general environmental conditions experienced in a wall cavity of a typical light-frame structure in the United States. The MOIST software, developed by Burch and Thomas (1993) at the National Institute of Standards and Technology, is able to simulate heat and moisture transfer for a variety of US cities using integrated weather data and user selected wall layer components. This capability was utilized to estimate the moisture content ranges within the sheathing-to-stud interface. Unfortunately, because of the limitations of the MOIST software, the effect of stud members was ignored. For this reason, only the simulation data relevant to the sheathing material will be analyzed and referenced in the development of the upper and lower limits of the conditioning regime.

A five-year simulation of moisture transfer was performed with MOIST for a wall system in Madison, WI. The configuration of the wall layers from the interior to exterior were as follows: Painted gypsum board (1/2 in.), OSB sheathing (7/16 in.), asphalt-coated fiber-reinforced building paper, and painted lap sugar pine siding. Insulation, vapor barriers, and air spaces are neglected because they are considered non-storage materials (i.e., do not store heat or moisture). The cyclic fluctuation in moisture content of the OSB sheathing was between 4% and 12% (Figure 3.10). Notice that one complete cycle occurs once each calendar year (52 weeks) in response to seasonal climate changes.

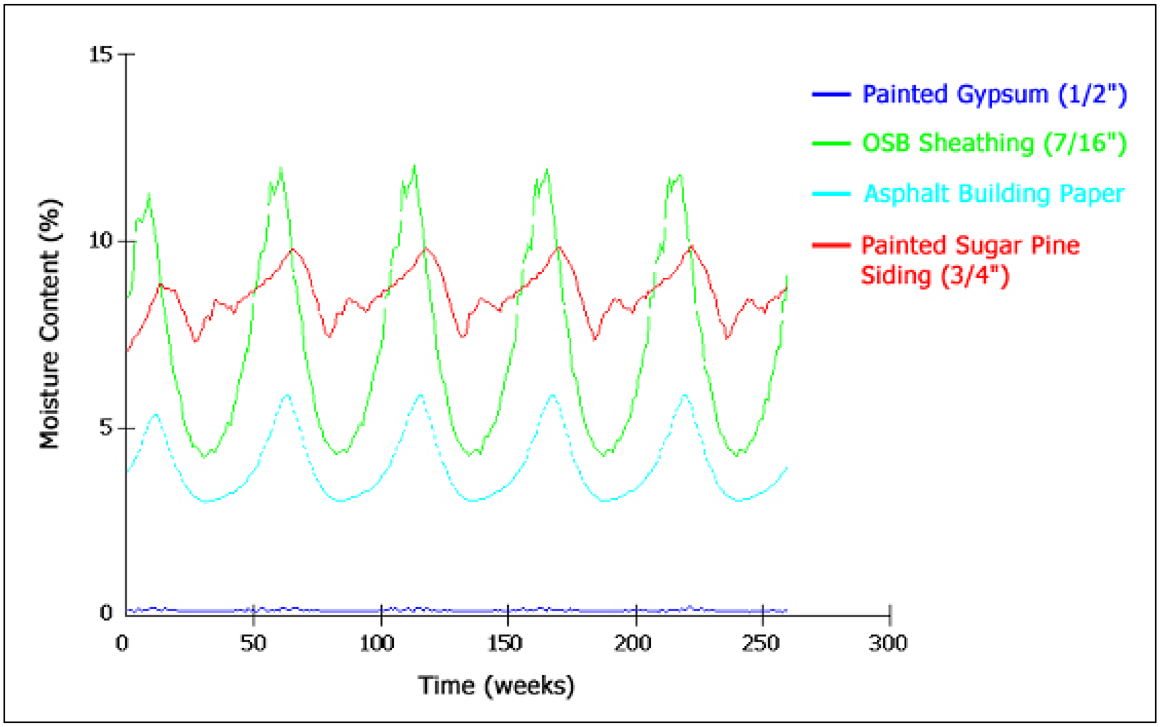


Figure 3.10: Simulated moisture content cycling of OSB sheathing layer within a typical wall construction in Madison, WI.

Predictions of relative humidity cycling on both the interior and exterior surfaces of the OSB sheathing were also performed in the aforementioned MOIST simulation (Figure 3.11). Again, notice the yearly cyclic phenomenon of the relative humidity levels. The conditions of the climate chamber were changed at intervals mimicking this cyclic activity.

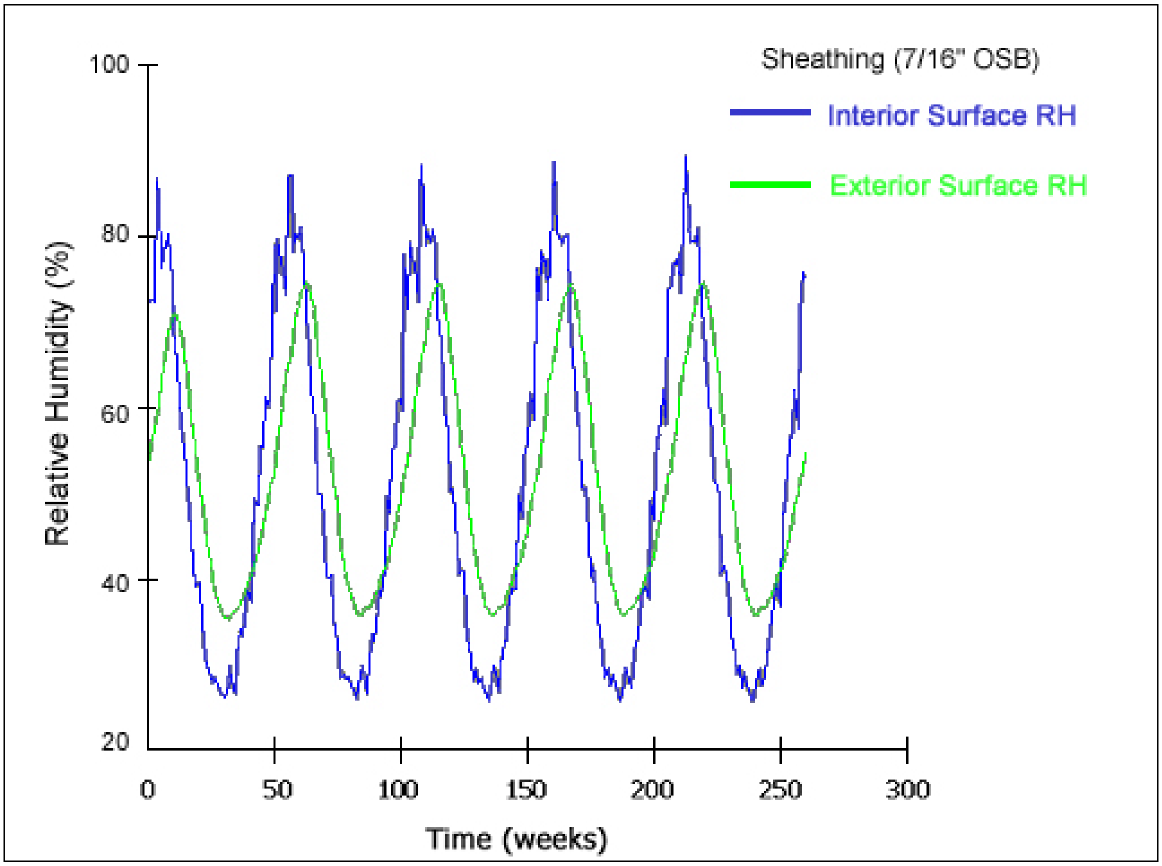


Figure 3.11: Simulated relative humidity cycling on inside and outside surfaces of OSB sheathing layer within a typical wall construction in Madison, WI.

The conditioning regime used in the climate chamber was based on the MOIST computer simulations and a study analyzing the time required for main member samples to closely approach EMC in both high and low humidity environments. At the highest humidity level (95% RH and 25°C), the EMC of wood material is expected to be approximately 23%. The lowest humidity conditions (30% RH and 25°C) will yield an EMC of about 6% (Forest Products Laboratory 1999). Based on these expectations and time allowances, it was determined that four days would allow the wood to closely approach its EMC within both low and high humidity conditions; therefore, one cycle involved four days at high humidity and four days at low humidity. Information conveyed in the next section supports the thought that EMC was closely approached after four days in both wet and dry environments.

Table 3.3 provides information related to the time durations of each of the seven treatments. Some connection specimens were exposed to only one complete cycle while others received as much as forty cycles inside the climate chamber.

The recorded changes in the relative humidity and temperature are presented in Figure 3.12 and Figure 3.13. An extensive listing of the daily measurements used to create these graphs is provided in Appendix A.

Table 3.3: Dates of connection fabrication and testing.

	Moisture exposure at testing (replications per # of cycles)						
	0	1	5	10	15	25	40
Fabricated:	9/27/03	10/5/03	2/10/04	9/27/03	7/16/03	7/17/03	7/18/03
Tested:	10/4/03	10/13/03	3/21/04	12/16/03	11/15/03	2/2/04	6/1/04
Cycling Days:	7 *	8	41	79	119	195	313

* One-week relaxation period at 12% MC

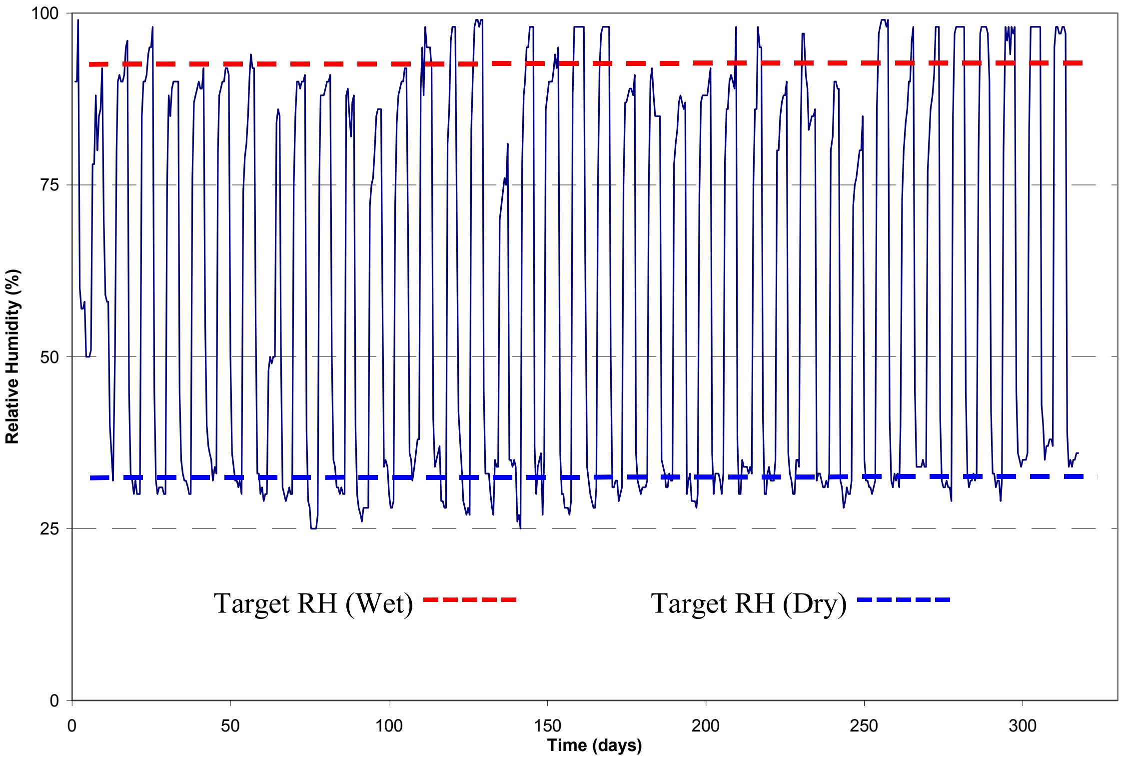


Figure 3.12: Relative humidity recordings inside the climate chamber.

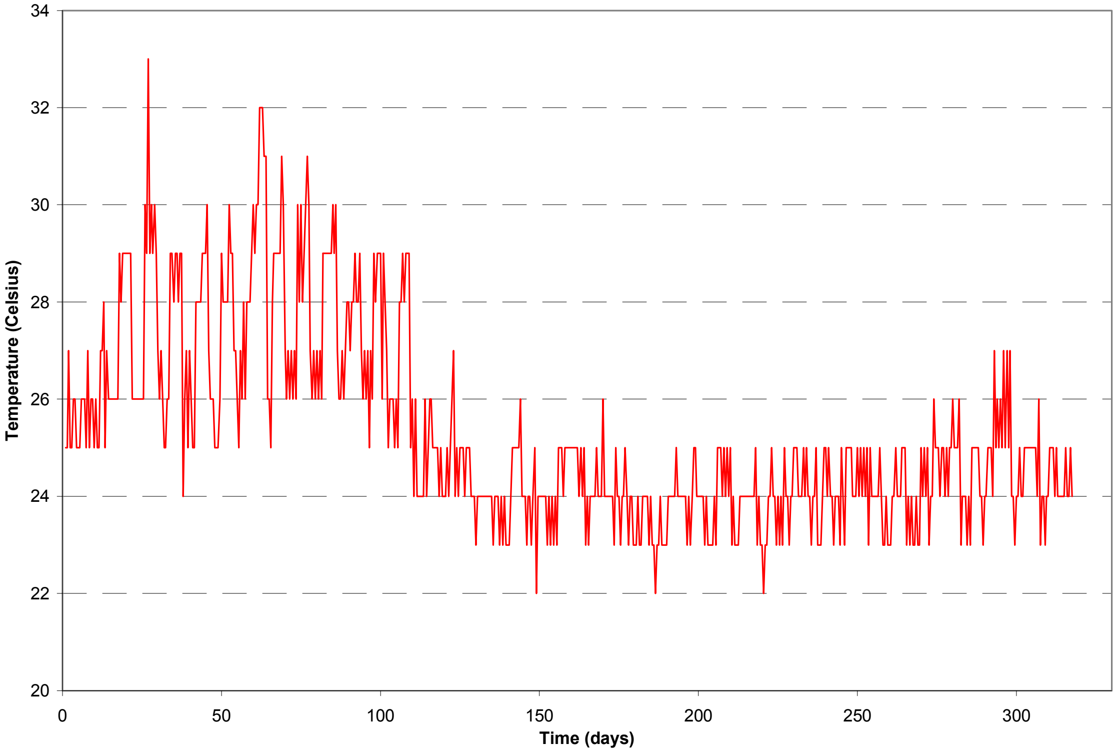


Figure 3.13: Temperature recordings inside the climate chamber.

3.4.2 – Moisture Content Study

A consecutive series of moisture content observations were recorded from connection materials exposed to one complete moisture conditioning cycle. The study involved two sets of matched main and side member samples. One sample of each matched set was coated with the wax emulsion end sealer product, Anchorseal®. The other set remained uncoated. The two groups of samples were first allowed to reach an equilibrium moisture content of about 6.5% to 7.0% while kept indoors in a climate controlled environment for several weeks. The samples were then placed within the climate chamber, which was set to maintain dry conditions (30% RH and 25°C). Only 48 hours were required in the dry conditions as the samples were already very dry. MC stabilized at about 4.5% to 6.0% with the sealed samples achieving the lowest values. Next, conditions were changed to wet conditions (95% RH and 25°C) for 96 hours. The unsealed samples reached MC of 23% and 20% for the main member (stud) and the side member (sheathing), respectively. Conversely, the sealed samples only obtained 11%

and 13% MC in the main and side members, respectively. Following the high humidity exposure, the climate chamber was again set to the dry conditions for 96 hours. Rapid moisture loss was observed in all samples after the first 24 hours and then slowly decreased as cycling ended. MC values in the range of 5.0% to 7.0% were measured in samples, overall. Throughout the conditioning regime, the sealed samples sustained much lower moisture contents than the unsealed group, especially during the wet stage. Figure 3.14 illustrates the trends observed during cycling. This study provided the basis for devising the cycling schedule.

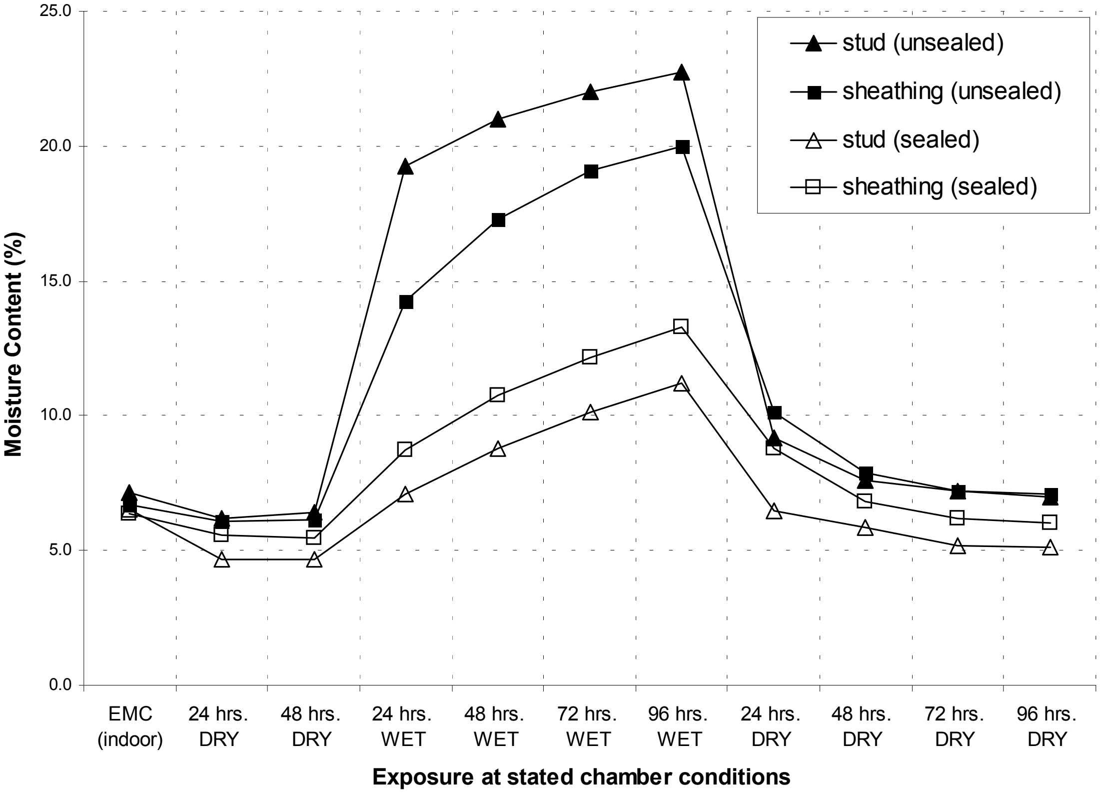


Figure 3.14: Moisture contents of materials during one cycle.

3.4.3 – Climate Chamber

Moisture conditioning of the connection samples required the use of a controlled environment in which the temperature and relative humidity settings were adjustable. A stud-framed structure, measuring eight feet long and eleven feet wide, was constructed inside the Wood Engineering Lab at the Brooks Forest Products Center, where it stood for nearly eleven months during the conditioning phase of the project (Figure 3.15). A center walkway and shelving provided ample space for sample placement, conditioning, and eventual extraction at time of testing (Figure 3.16). Light-weight, clear plastic enclosed the entire chamber and the openings were sealed with duct tape. An access door was installed at the end of the walkway and the door jam was lined with weather stripping to prevent any air leakage. Furthermore, supply and return venting was mounted inside the enclosure as a means of circulating the air.

Figure 3.15: Climate chamber located in the Wood Engneering Laboratory.

Figure 3.16: Shelving system within the climate chamber.

3.4.4 – Conditioning Unit

A conditioning unit provided a continuous flow of conditioned air controlled by user selected dry-bulb and water spray temperatures. This machine was linked to the venting system inside the climate chamber. For high humidity conditions, a fan pulled air from the return venting and through a water spray, causing the air stream to be saturated with water vapor. The air was then heated to the set dry-bulb temperature and returned to the climate chamber via the supply venting. The same process was followed when dry conditions were desired apart from setting the damper in the conditioning unit to an open position so the flow of air was allowed to bypass the water spray and move directly to the heater and then back into the chamber. The air conditioning unit relies on a unique correlation between water spray temperature and dew point to produce the desired climate conditions. A correlation graph was supplied by the manufacturer, Parameter Generation and Control, Inc. of Black Mountain, North Carolina. Near the beginning of this project, observations determined that the conditioning unit had difficulties lowering the relative humidity level in the chamber in a timely manner whenever a dry cycle was started. A dehumidifier rated at forty pints per day was installed and operated during low humidity periods to expedite moisture removal from the air and the specimens inside the climate chamber. As seen below in Figure 3.17, the dehumidifier was positioned so that air could circulate within the chamber since its intake vent was in the front of the machine and the outlet vent was on the back.

Figure 3.17: Dehumidifier positioned inside the climate chamber.

3.4.5 – Temperature and Relative Humidity Recorder

A microprocessor-based circular chart recorder was used to monitor the conditions within the climate chamber. A combination temperature/ relative humidity probe was located inside the chamber and was coupled by a shielded cable with the chart recorder. The actual recording device was placed on the exterior of the chamber structure to avoid any moisture related breakdown of the mechanical and electronic components.

Prior to installation and use of the recorder, the probe was calibrated using saturated salt solutions. According to the manufacturer's instructions, a two-point calibration method was performed. A saturated salt solution of magnesium chloride ($MgCl_2$) produces an environment of 33% relative humidity at 25 degrees Celsius. A saturated salt solution of sodium chloride (NaCl) produces an environment of 75% relative humidity at 25 degrees Celsius. Probe calibration was performed approximately every two months during operation of the chamber and recorder.

Continuous measurements were recorded onto a circular paper chart, which was collected every seven days and replaced. As stated in the Section 4.4.1, which pertains to the conditioning regime, the climate readings taken from the recorder are presented in Appendix A. The readings were taken directly from the paper charts and include two temperature and two relative humidity readings per day at approximately 9AM and 3PM with any conditioning changes (i.e., dry to wet or wet to dry conditions) occurring at 12PM noon.

The temperature and relative humidity conditions are summarized graphically in Figure 3.12 and Figure 3.13 on pages 40 and 41, respectively.

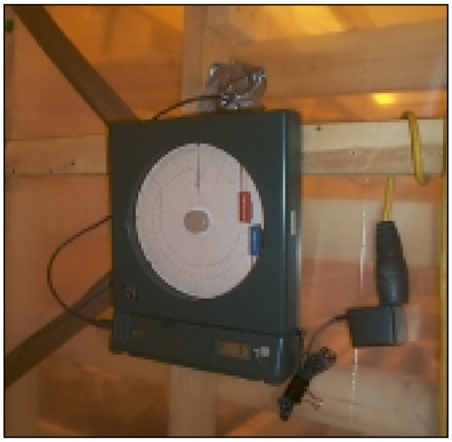


Figure 3.18: Circular recorder mounted outside the climate chamber.

3.5 – Testing Equipment

Specialized testing machinery and tools were used throughout the testing phase. Equipment was needed for testing the connection where lateral resistance of the joint was of interest. Input parameters for calculating the design loads also required testing which involved material testing machines.

Two universal testing machines were used for the loading tests. A servo-hydraulic testing machine was used for testing the connection specimens. This system involved a MTS 810 Material Test System attached to a servo-hydraulic universal testing machine with a capacity of 22,000 pounds. The equipment was connected to a desktop computer with data acquisition software enabling the collection of load and displacement data from the load cell and the built-in LVDT (linear variable differential transformer). Both were directly coupled with the hydraulic actuator on the universal testing machine (Figure 3.19).

Figure 3.19: MTS 810 servo-hydraulic testing machine.

The small specimen dimensions of both the wire nails and embedment samples necessitated the use of a more precise testing machine designed to measure small loads and displacements. The screw-driven MTS 10/GL universal testing machine in combination with a 225-pound load cell was used for the fastener bending tests (Figure 3.20). A 10,000-pound load cell was used during the main and side member embedment testing. Load and displacement data was collected by data acquisition software onboard the adjoining computer.

Figure 3.20: MTS 10/GL screw-drive testing machine

Both testing machines are housed within the Wood Engineering Laboratory at the Brooks Forest Products Center in Blacksburg, Virginia.

3.6 – Testing Procedures

Connection, embedment, nail bending, and moisture content samples were all tested according to the specified standards. Procedures for evaluating the density-profile followed the guidelines provided by the equipment manufacturer. The specifics of each testing process are discussed in detail in this section. Moisture content measurements and vertical-density profiling was executed within the wood-based composites laboratory/wet lab areas of the Brooks Center.

3.6.1 – Connection Tests

Monotonic loading was performed on each connection sample following its prescribed exposure to the cyclic moisture conditioning within the climate chamber. Loading was executed with a lateral resistance test similar to the protocol described in ASTM D 1761: *Standard test methods for mechanical fasteners in wood* (2003g) Unlike the cited ASTM standard, the nails were not cleaned prior to connection fabrication in an effort to replicate the conditions seen on actual construction sites. A more significant diversion from the standard lies in the particular specimen bracing system involved. The apparatus described in ASTM D 1761 for securing the connection during loading is known to contribute to eccentricities in the load path. More precisely, the main and side member components are allowed to rotate laterally in addition to the intended shear movement. A modified device was designed that greatly improved sample bracing within the testing machine (Liu and Soltis 1984). In the revised apparatus, the main member was held stationary to the base of the test machine while the side member was prevented from moving laterally by frictionless rollers. A metal grip was attached to the hydraulic actuator of the universal testing machine and secured the side member. According to ASTM D 1761, ramp loading was applied in the tensile direction at a speed of 0.10 in. per minute using the MTS 810 universal testing machine. A 1,000-pound load cell was used in this procedure. Figure 3.21 illustrates the bracing fixture fully expanded and after securing a connection specimen within the testing apparatus.

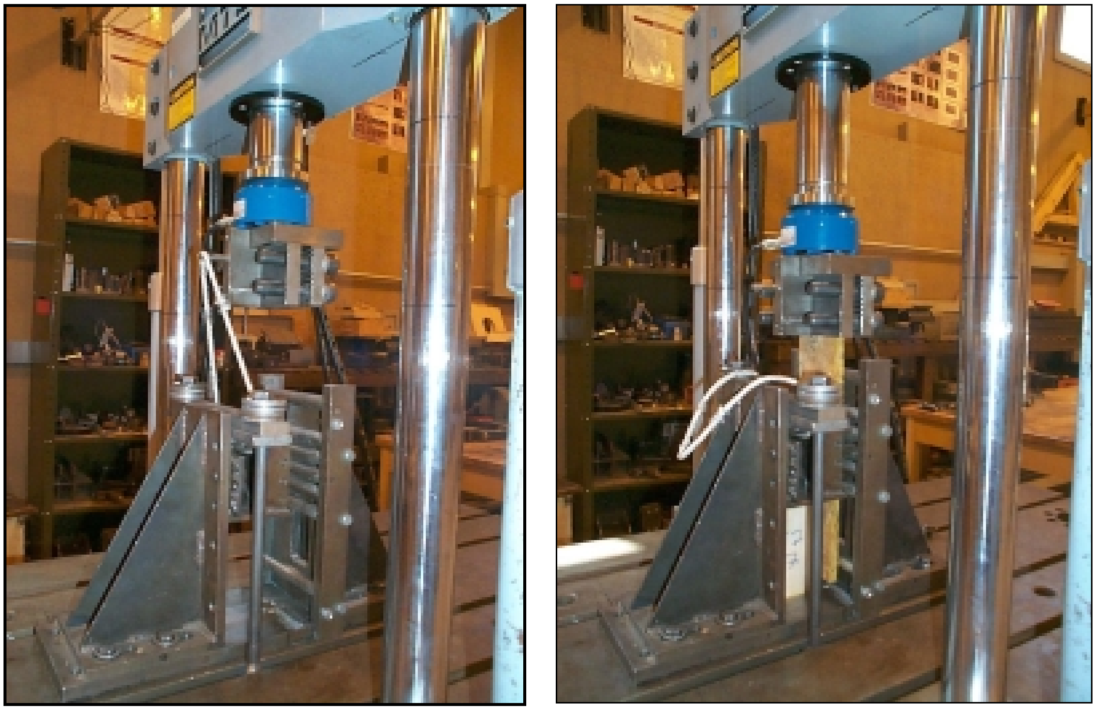

(a) *(b)*

Figure 3.21: (a) Bracing fixture before and (b) after sample insertion.

Concerns about the accuracy of the built-in MTS LVDT and the gripping ability of the fixture were addressed by comparing the recorded displacement by the built-in LVDT to that of a string pot attached between the stationary crosshead of the MTS machine and the side member itself. A string pot, or a cable-extension transducer, is a device used to detect and measure linear position using a flexible cable loaded onto a spring-loaded reel. In theory, the tight coupling between the actuator grip and the side member should have allowed the built-in LVDT to report a displacement value identical on that from the string pot. This was proven by overlaying the two load/displacement plots generated by the two devices (Figure 3.22). There is no difference between the plots lines except at loads much greater than those experienced in actual connection tests. Based on this reasoning, displacement data was collected using the built-in LVDT rather than the labor-intensive task of using sample-mounted string pots for each of the six-hundred thirty connection tests.

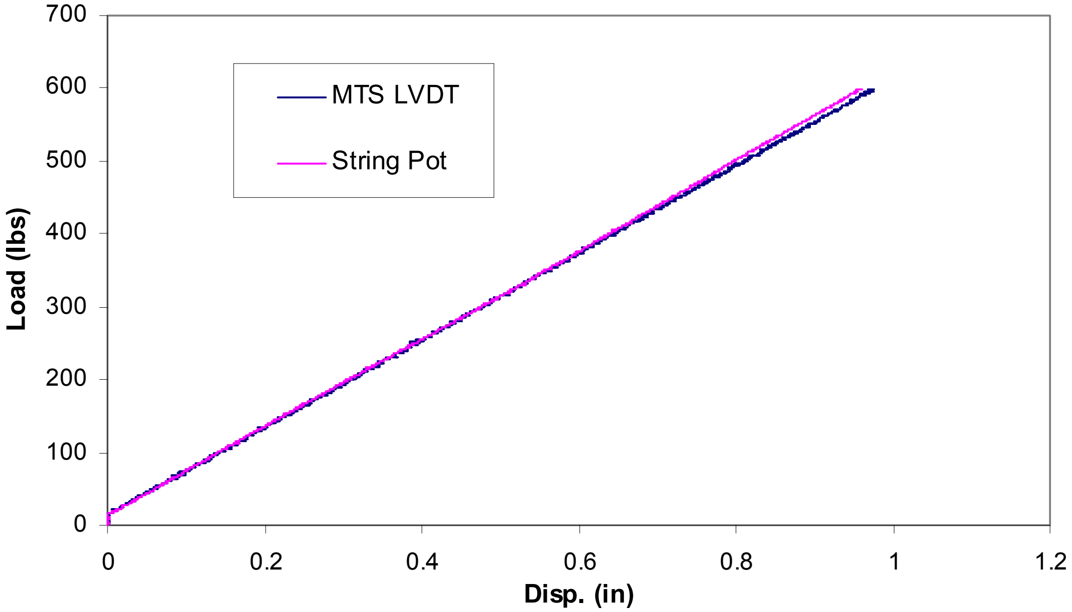


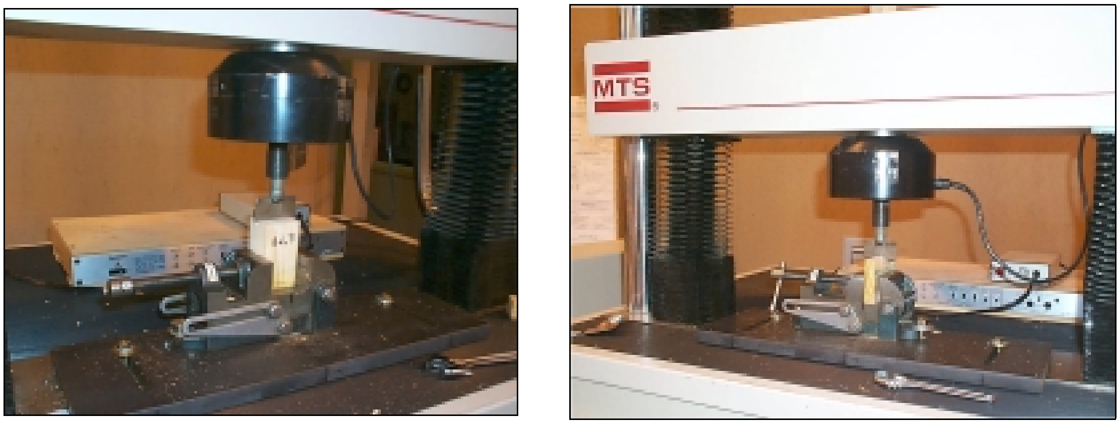
Figure 3.22: MTS displacement vs. string pot displacement.

3.6.2 – Embedment Tests

As previously mentioned in the section about embedment specimen fabrication, the practices for preparing half-hole embedment specimens were used rather than the full-hole alternative. This was due to the use of wire nails which were too weak to resist bending in the testing equipment associated with full-hole embedment testing. Furthermore, this method is commonly used in place of the full-hole test for wood samples that are prone to cracking. During the half-hole embedment test, the nail simulator is forced into the main or side member material requiring complete support of small diameter fasteners such as the nails used in this project. The loading point apparatus simulators for the 6d and 8d common nail incorporated actual nail shanks into the loading apparatus as seen in Figure 3.23.

Figure 3.23: Simulators of 8d and 6d common nails, respectively.

In accordance to ASTM D 5764 test method, ramp loading was applied in the compressive direction at a speed of 0.10 in. per minute until the ultimate load was achieved. The MTS 10/GL universal testing machine and a 10,000-pound load cell were used. Figure 3.24a, below, is a photograph taken during a main member embedment test. A side member embedment test is shown in Figure 3.24b.



(a) *(b)*

Figure 3.24: (a) Main member and (b) side member samples during embedment testing.

3.6.3 – Fastener Bending Tests

This operation involved bending samples of 6d and 8d common wire nails in order to determine their bending yield strength – an input parameter of the general dowel equations. The test method followed the procedure outlined in ASTM F 1575 (ASTM 2003d). The MTS 10/GL universal testing machine with a 225-pound capacity load cell was used for bending the nails. An apparatus was used to support each nail during the center-point loading tests. According to the standard, a 1.3 in. span was used for 6d common nails, while a 1.5 in. span was afforded to the larger 8d common nails. All bearing and loading surfaces where cylindrical in shape with diameters equal to 0.375 in. Figure 3.25 shows a nail during a bending tests supported by the said apparatus. Testing continued until the nail specimen was loaded past the 5% offset limit as specified in ASTM F 1575.

Figure 3.25: Fastener bending test.

3.6.4 – Density Profile Tests

At the end of each moisture cycle, the twelve representative side member samples (two samples per side member type) were weighed and the dimensions measured. In addition, the samples were loaded into a sample tray, as seen in Figure 3.26, and then placed into an x-ray density profilometer. This device measured each set of samples and then reported the density profile of the specimen through its thickness. Specifically, a Quintek QMS Density Profiler, Model QDP-01X was used (Figure 3.27). Prior to gathering density data about each sample, the density-profiler machine performed a calibration operation on each sample set in order to determine the mass absorption coefficient. This procedure insures that each density reading is accurate regardless of a particular material's resistance to the penetration of x-rays.

After scanning, the samples were returned to the climate chamber until the end of the following cycle when density readings were taken again with the same machine. Changes in the density profiles of the side member samples were measured throughout the project at the end of each cycle. Figure 3.28 is a photograph showing how the density samples were placed inside the climate chamber adjacent as the connection samples were.

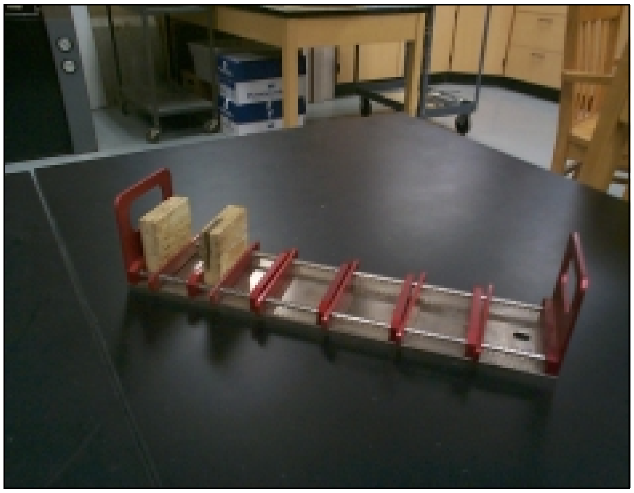


Figure 3.26: Sample tray used with the profilometer.

Figure 3.27: X-ray density profilometer and computer.

Figure 3.28: Representative side member samples positioned inside the climate chamber.

3.6.5 – Moisture Content & Specific Gravity Tests

Samples of both main and side member materials were cut from connection specimens following loading to failure. One-third of each connection/treatment batch was sampled in this manner. Upon cutting with a band saw, the samples of main and side members were initially weighed, recorded, and placed inside an oven to dry for 24 hours at approximately 103°C. Then the corresponding oven dry (OD) weights of the samples were recorded. This process is known as the gravimetric method for determining the moisture content of the initial 'wet' wood sample. The MC test was performed in accordance with ASTM D 1037: *Standard test methods for evaluating the properties of wood-base fiber and particle panel materials* (ASTM 2003f). The percentage of water weight per the OD weight of the wood sample is referred to as the moisture content (MC) and is computed as follows:

$$\text{MC (\%)} \ = \frac{\text{Wet weight - OD weight}}{\text{OD weight}} \times 100$$

The same samples used for moisture content tests were also involved in the specific gravity measurements. The guidelines stated in ASTM D 2395: *Standard test methods for specific gravity of wood and wood-base material*s were followed for each specific gravity approximation (ASTM 2003h). In particular, the procedure involving the water immersion technique was used; also referred to as *Method B*. First, the wood sample is attached to the end of a sharp pick and then dipped into a bath of molten wax. After cooling, the wax provides a watertight coating over the sample's entire surface, which is then placed into a container of water. The water tank sits on a digital scale, which allows for measuring the mass of the displaced water. Specific gravity (SG) is a substance's density divided by the density of water (1 gm/cm^3):

$$\text{SG} = \frac{(\text{substance mass} / \text{substance volume})}{(\text{water mass} / \text{water volume})}$$

Using the submersion method, explained previously, specific gravity is calculated as:

$$\text{SG} = \frac{\text{OD weight of wood sample}}{\text{weight of water displaced by sample}}$$

Therefore, each sample's OD weight at the time of testing was divided by the weight of the water that the wax-coated sample displaced when it was submersed into the water tank. Specific gravity measurements are unitless. Figure 3.29 and Figure 3.30 are photographs of the equipment used to prepare and measure the moisture content and specific gravity samples.

Figure 3.29: Specific gravity determination using water immersion method.

Figure 3.30: Oven, wax bath, and water tank atop scale.

3.7 – Property Definitions

For the purposes of comparison and convention, several performance parameters were determined for each connection, embedment, and fastener bending sample. These values are typically reported in connection tests and provide reference points with which contrasts can be easily made. Primarily, the performance properties of each sample were determined from specific limit state yields along the loading curve. Additional calculations were used to solve for supplementary values. An example of a typical load-slip plot from a connection test is illustrated below in Figure 3.31. Response values of specific interest include the elastic stiffness, 5% offset yield, maximum yield, and failure.

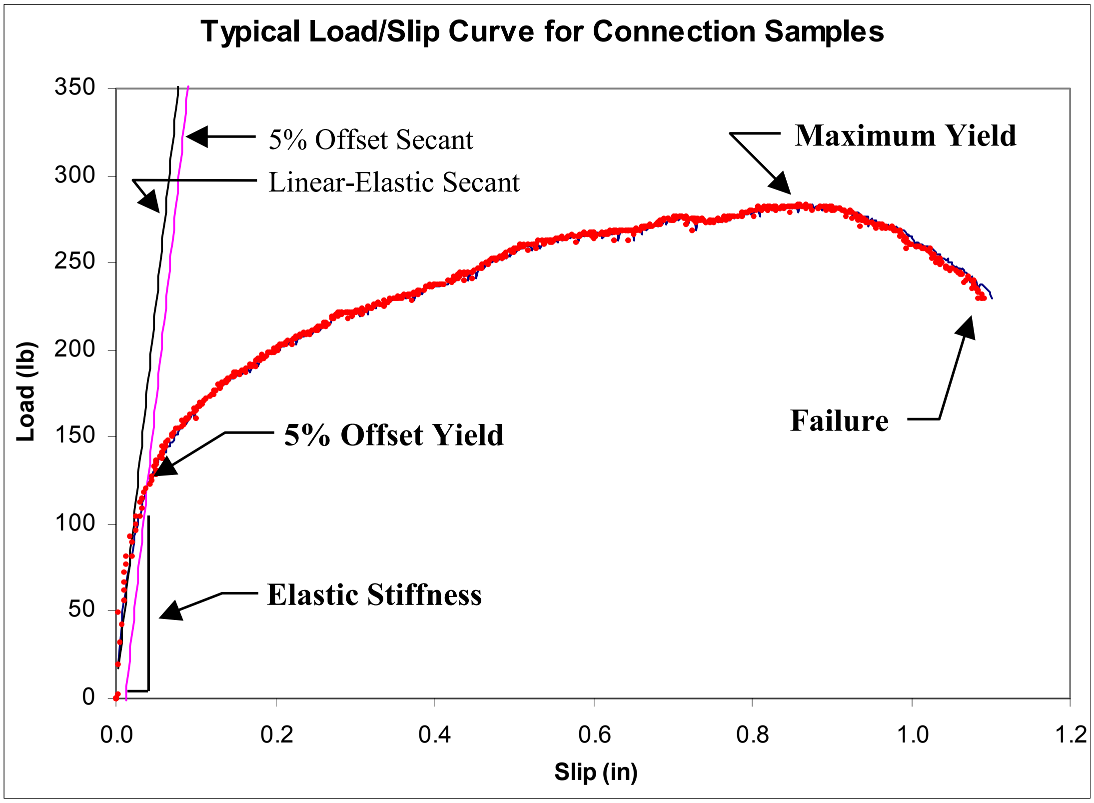


Figure 3.31: Sample plot and associated performace parameters.

Elastic stiffness is the slope of the initial linear portion of the load-deflection curve. This region begins after the specimen 'settles' within the test fixture and ends at the proportional limit where the curve becomes non-linear and continues, at a decreasing rate, toward maximum load and eventually failure. The elastic stiffness parameter provides for standardized comparisons of connections loaded within the linear-elastic region. Measurements are in units of pounds per inch.

The 5% offset yield is a significant limit state whenever a case involves dowel connections in wood. This parameter is found by offsetting the linear-elastic secant by a positive factor equal to 5% of the fastener diameter. The new parallel secant intersects the load-deflection curve between the linear-elastic region and the plastic region prior to maximum capacity. This was the 5% offset yield. The load at this point was reported in pounds while the slip afforded by the test sample is described in units of inches.

Maximum yield refers to the ultimate capacity obtained during loading. This parameter was found on the load-displacement curve between the plastic region and failure yield. The resistance parameter, load, was stated in units of pounds. The associated displacement at the maximum load was described in inches.

Failure yield is straightforward, but was specifically defined as equaling 80% of the maximum load on the unloading side of the load-displacement curve. Load and displacement at failure are reported in units of pounds and inches, respectively.