Chapter 3 Methods and Materials

3.1 – General

This study entailed the experimental investigation of two hundred and thirteen single-shear bolted timber connections loaded parallel to grain both monotonically and cyclically. Secondary testing included moisture content, specific gravity and dowel embedment strength of timber members and dowel bending strength of fasteners. All materials, testing and associated parameters used in this research were selected based on the needs and goals outlined in the objectives (Section 1.2). The member variations and number of bolt patterns evaluated are shown in Table 3.1.

Table 3.1: Details of joint assemblies tested.

Bolt Type	Materials	Direction of Loading	Predicted Yield Mode	No. of Rows	No. of Bolts per Row	Replication	Load Type
.5-in bolt	2x6 lumber 2x6 lumber	Parallel	II	1	1	10	Cyclic
					1	3	Monotonic
					3	10	Cyclic
					5	10	Cyclic
					5	3	Monotonic
.5-in bolt	2x6 lumber 2x6 lumber	Parallel	II	2	3	10	Cyclic
					5	10	Cyclic
					5	3	Monotonic
.375-in bolt	.25-in Steel Plate 4x6 lumber	Parallel	III	1	1	10	Cyclic
					1	3	Monotonic
					3	10	Cyclic
					5	10	Cyclic
					5	3	Monotonic
.375-in bolt	.25-in Steel Plate 4x6 lumber	Parallel	III	2	3	10	Cyclic
					5	10	Cyclic
					5	3	Monotonic
.375-in bolt	4x6 lumber 4x6 lumber	Parallel	IV	1	1	10	Cyclic
					1	3	Monotonic
					3	10	Cyclic
					5	10	Cyclic
					5	3	Monotonic
.375-in bolt	4x6 lumber 4x6 lumber	Parallel	IV	2	3	10	Cyclic
					5	3	Monotonic
					5	10	Cyclic
.5-in bolt	4x6 lumber 4x6 lumber	Parallel	IV	1	1	10	Cyclic
					1	3	Monotonic
					3	10	Cyclic
					5	10	Cyclic
					5	3	Monotonic

Cyclic testing is utilized in order to simulate seismic loading conditions and investigate the bolted timber connection response to these conditions. Because the group action factor is a safety parameter the influence on capacity strengths under cyclic loading will yield valuable design information to improve the safety and reliability of bolted timber connections.

A specimen reference was developed according to Figure 3.1. For example, all specimens within a population are referred to as the 2X2R3C Series. A reference to all specimens within a group is designated as the 2X Series. Groups are distinguished by expected yield mode and bolt diameter shown in Table 3.1.

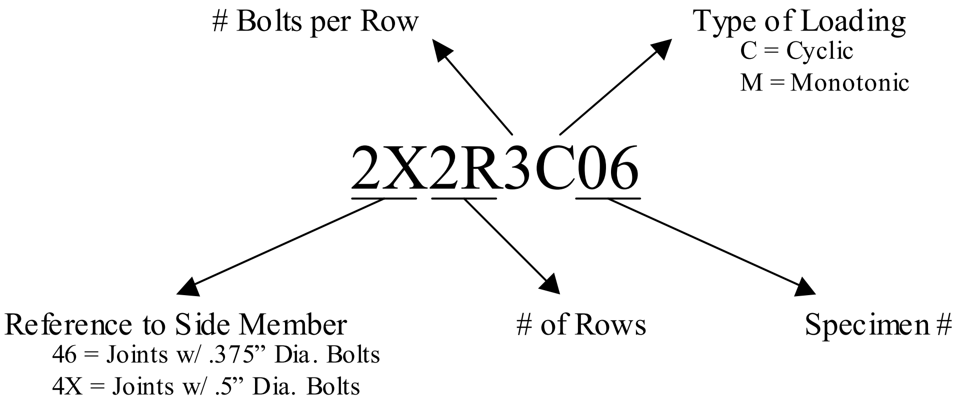


Figure 3.1: Description of test labeling.

3.1.1 – Sample Size Determination

The number of replications per cyclically loaded configuration was determined according to Equation (3.1), (from Heine, 2001).

$$n = \frac{2z^2{}_{\alpha/2}COV^2}{e^2} \tag{3.1}$$

where:

$$COV = \frac{\sigma}{\mu} \tag{3.2}$$

$$e = \frac{\Delta}{\mu} \tag{3.3}$$

and: COV = coefficient of variation, %,

σ = standard deviation, same as μ,

μ = population mean of any variable, any,

e = relative error, %,

Δ = absolute error, same as μ,

$z_{\alpha/2}$ = area under normal curve associated with a 100(1-α)% confidence interval.

Heine (2001) showed how to determine the number of replications, n, based on an estimate of COV from test results reported by Gutshall (1994). Gutshall tested single bolt, single-shear joints subjected to Sequential Phased Displacement loading. The highest COV for maximum load was reported to be 16.4 percent for a joint with a 1/2 in. bolt with a 4 in. x 4 in. member and 1/4 in. steel plate member. Using this data, a sample size of ten assures with 90 percent confidence that the estimated mean is within 12 percent of the true mean of the maximum load parameter (Heine, 2001).

The number of replications per monotonically loaded configuration was not based on any statistical evaluation of previous experiments. In this case monotonic data was primarily used to determine a relevant displacement history for cyclic tests per Section 3.5.1.

3.2 – Materials

The timber material used in each of the connection assemblies was kiln dried Southern Yellow Pine, a species widely used in the Eastern United States, and was purchased from local suppliers. All 2 in. x 6 in. material was grade stamped No. 1. All 4 in. x 6 in. material was grade stamped No. 2. The specimens were cut to avoid localized defects, knots, checks, etc., in the wood as much as possible. Timber specimens were planed to simplify drilling and alignment within the test fixture such that a 2 in. x 6 in. nominal was 1.4 in. x 5.4 in. actual and a 4 in. x 6 in. nominal was 3.4 in. x 5.4 in. actual. Bolt holes were drilled 1/16 in. oversized with either a drill press or a milling machine (for efficiency, not alignment, reasons) with good accuracy; the intention was not to create perfectly aligned joints. A large portion of the 4 in. x 6 in. material was manufactured such that the pith and significant volumes of juvenile material had a direct effect on joint performance. Economically it was not feasible to exclude this material from the study and it is felt that utilizing this material was a more accurate representation of the material used in current construction practice. See Figure 3.2.

Figure 3.2: Photograph of typical 4 in. x 6 in. material end view.

Mild carbon steel plates with an assumed yield stress of 36 ksi were used in one of the bolted connection geometries All steel side plates were 1/4 in. thick and had the same hole placement geometry as their timber counterparts. It should be noted that bolt holes in the steel side plates were not oversized.

The bolts used throughout this study were either SAE Grade 2 or 307A mild carbon steel. In certain instances it was required to use SAE Grade 2 bolts because of the lack of availability of 307A bolts with specific shank lengths.

3.3 – Joint Geometry

All joint fabrication took place at the Brooks Forest Products Center at Virginia Polytechnic Institute and State University. The 1997 NDS recommended distances for end (7D), edge (1.5D) and spacing between bolts in a row (4D) for full design value were met or exceeded on all assemblies. The spacing between rows of bolts was maintained at 2 in. for all applicable assemblies. Other aspects of joint geometry were selected with consideration of the limits of the hydraulic actuator and test fixture.

In general, the initial cutting of boards to ensure uniform thickness and width allowed for accurate placement within the test fixture. Typical specimen dimensions are shown in Figure 3.3 and actual test dimensions are cross-referenced from Table 3.2.

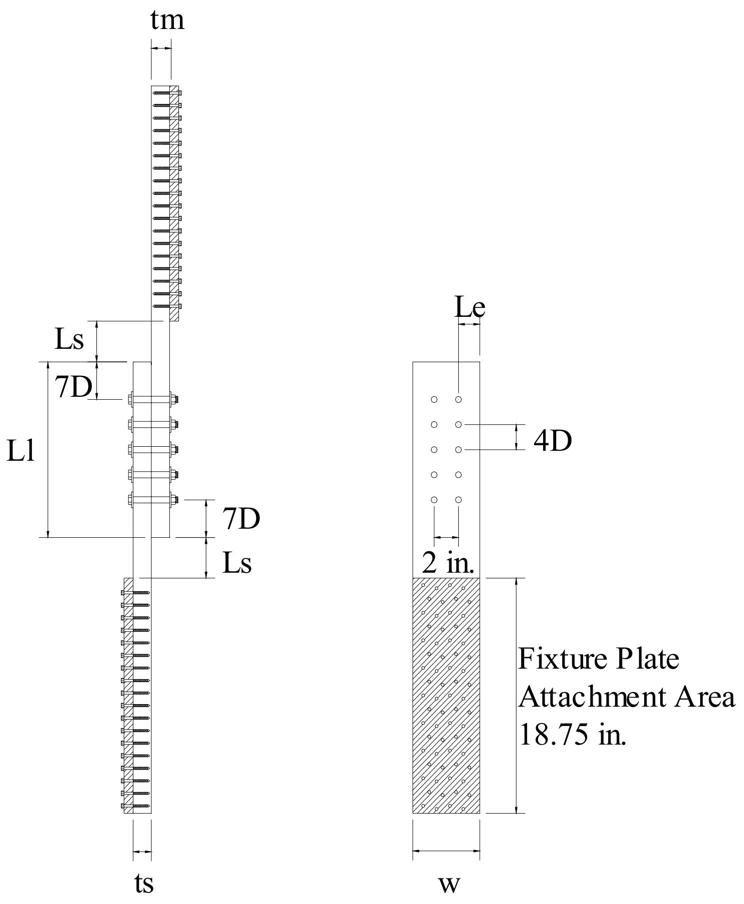


Figure 3.3: Typical dimensioning of joint configurations.

Table 3.2: Associative dimensions of tested configurations.

	Bolt Diameter (in)	No. of Bolts per Row	No. of Rows	Predicted Yield Mode	Member Dimensions					
					tm (in)	ts (in)	w (in)	Le (in)	Ll (in)	Ls (in)
2X Series	0.5	1	1	II	1.4	1.4	5.4	2.7	7	3.5
	0.5	3	1	II	1.4	1.4	5.4	2.7	11	3.5
	0.5	5	1	II	1.4	1.4	5.4	2.7	15	2
	0.5	3	2	II	1.4	1.4	5.4	1.7	11	3.5
	0.5	5	2	II	1.4	1.4	5.4	1.7	15	2
ST Series	0.375	1	1	III	3.4	0.25	5.4	2.7	5.25	6
	0.375	3	1	III	3.4	0.25	5.4	2.7	8.25	3
	0.375	5	1	III	3.4	0.25	5.4	2.7	11.25	3
	0.375	3	2	III	3.4	0.25	5.4	1.7	8.25	3
	0.375	5	2	III	3.4	0.25	5.4	1.7	11.25	3
46 Series	0.375	1	1	IV	3.4	3.4	5.4	2.7	5.25	6
	0.375	3	1	IV	3.4	3.4	5.4	2.7	8.25	3
	0.375	5	1	IV	3.4	3.4	5.4	2.7	11.25	3
	0.375	3	2	IV	3.4	3.4	5.4	1.7	8.25	3
	0.375	5	2	IV	3.4	3.4	5.4	1.7	11.25	3
4X Series	0.5	1	1	IV	3.4	3.4	5.4	2.7	7	3.5
	0.5	3	1	IV	3.4	3.4	5.4	2.7	11	3.5
	0.5	5	1	IV	3.4	3.4	5.4	2.7	15	2

3.4 – Test Equipment

All tests were conducted in the Wood Engineering Laboratory of the Brooks Forest Products Center at Virginia Polytechnic Institute and State University. Testing conducted for this study included single-shear bolted connection tests, dowel embedment tests, bolt bending tests, and moisture content/specific gravity determinations.

Single-shear bolted connection tests were tested on a 55,000 pound capacity servo-hydraulic Material Testing System (MTS) testing machine with a ± 50,000 pound load range card and a ± 2.5 inch displacement range card. Additionally, a potentiometer with a displacement range of ± 2.5 inches was attached to each member of the connection in the direction of loading so that the actual slip at the connection could be determined as shown in Figure 3.4. This setup eliminates the inclusion of fixture deformation and wood to fixture slip in the displacement measurement.

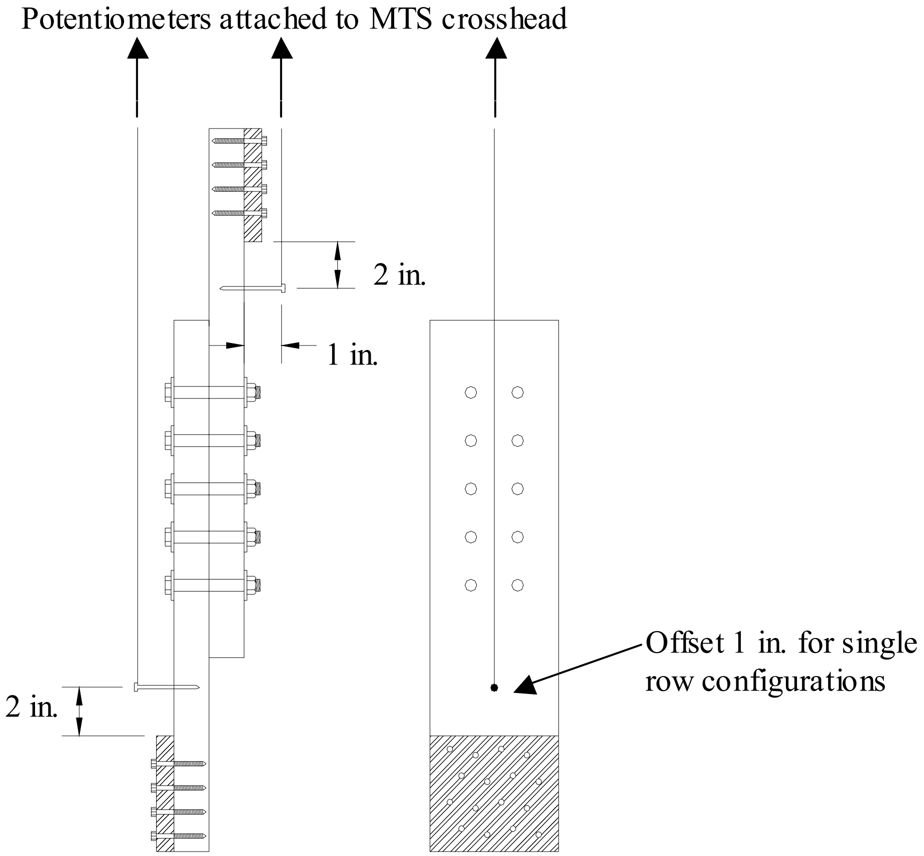


Figure 3.4: Typical placement of potentiometer anchors.

The test fixture shown in Figure 3.5 was designed to allow efficient testing and test observation by minimizing assembly time and by utilizing a side bracing system (as opposed to bracing the front and back faces) to reduce thrust forces on the load cell caused by joint eccentricity. In this case bracing the faces of a connection was not feasible due to the large deflections imposed, the large loads expected, and the fact that whatever was used as bracing (i.e., rollers) would interfere with bolt heads, washers, or nuts because of the multiple-bolt configurations.

Wood members were fastened to a 1/2 in. thick steel plate, which had sixty-four predrilled holes, with 1/4 in. diameter wood screws (see Figure 3.6). Simpson Strong-Tie Co., Inc. provided self-tapping Strong Drive “S” Series screws (SDS 1/4x3) for use with the assemblies utilizing 4 in. x 6 in. material. The steel plates with attached wood members were then secured to the upper and lower portions of the fixture with 5/8 in. diameter Grade 8 bolts (see Figure 3.7). Spacers were used to minimize crushing between the steel plates and fixture during the set-up process. In the case of joints tested with 1/4 in. thick steel side plate, spacers were left out and static friction between the fixture, the side plate, and the 1/2 in. thick fixture plate provided the restraining action.

The side bracing system consisted of 1 in. steel plate and L4x4x3/4 steel angles as shown in Figure 3.7. The extended leg had a slot milled in the direction of loading to guide a pin attached to the movable portion of the fixture. The pin was greased and sheathed by a steel tube and meant to role along the slot, acting like a roller bearing, during testing. Because of the difficulty of milling a perfectly circular steel tube to ensure a rolling action, the slot was greased so the steel tube and pin could slide with as little friction as possible. The bracing system greatly reduced the thrust on the load cell and hydraulic ram seals due to joint eccentricity, thus limiting the chances of equipment damage.

Figure 3.5: Photograph of single shear connection test and fixture.

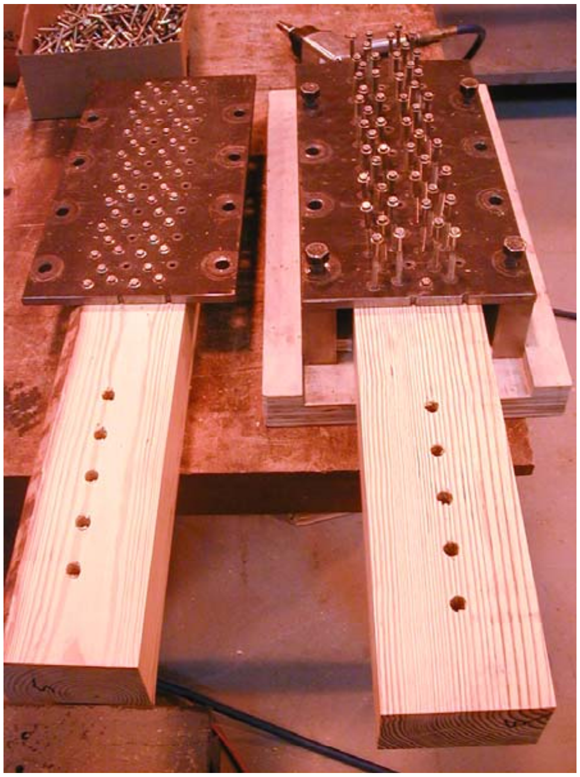


Figure 3.6: Photograph of fixture plate to wood attachment.

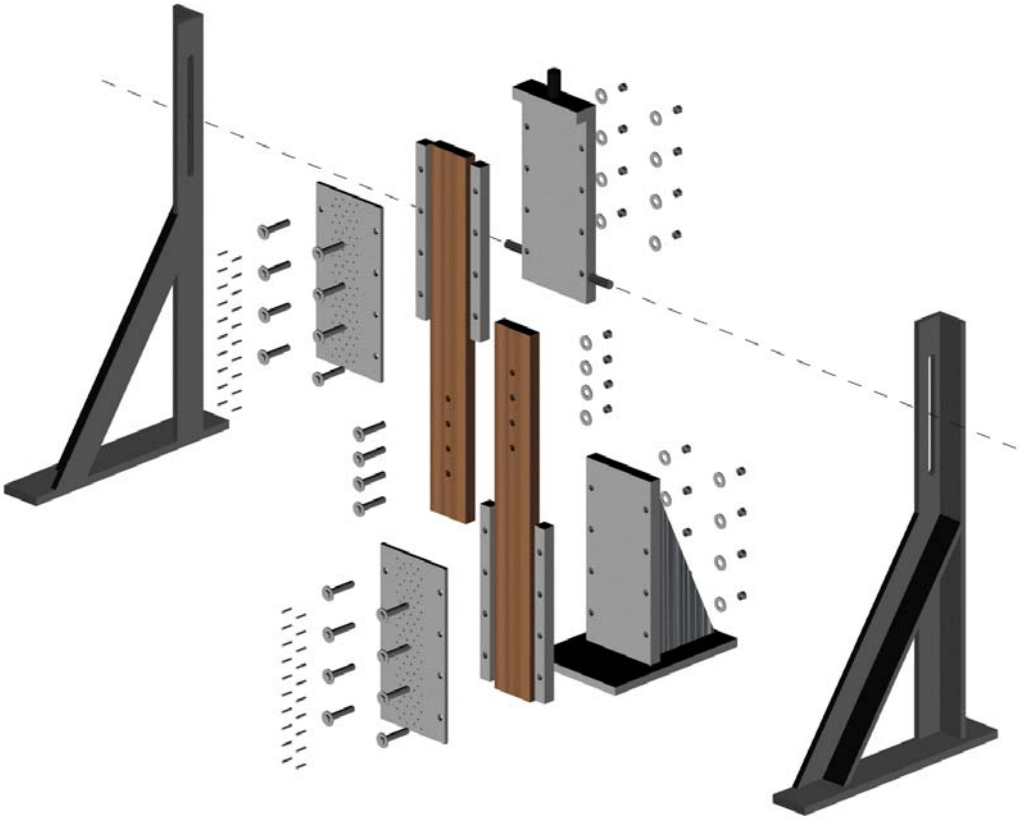


Figure 3.7: Rendering of joint to test fixture assembly (from Heine, 2001).

3.5 – Testing Procedures

In this section, testing procedures will be described including joint tests, dowel embedment tests, bolt bending tests, and moisture content/specific gravity determinations. In the case of connection tests a thorough review will be given for the development of a displacement controlled test protocol based on monotonic connection performance. An overview of dowel embedment and bolt bending tests will be presented as well as how embedment and moisture content/ specific gravity samples were taken from individual pieces of a connection assembly.

3.5.1 – CUREE Deformation Controlled Quasi-Static Cyclic Protocol

Development of a testing protocol for deformation controlled cyclic tests based on procedures outlined for the Consortium of Universities for Research in Earthquake Engineering (CUREE) – Caltech Woodframe Project (Krawinkler et. al., 2001), requires a reference deformation (Δ) based on monotonic performance; specifically, a fraction of the monotonic deformation capacity is recommended. The monotonic deformation capacity, Δ_m, is defined as "the deformation at which the applied load drops, for the first time after peak load, to 80% of the maximum load applied to the specimen," (Krawinkler et. al., 2001). The reference deformation, Δ, is then suggested as being equal to $0.6\Delta_m$ to account for the potential difference in deformation capacity between monotonic and cyclic tests, due to deterioration of strength from cumulative damage. The protocol is comprised of initiation cycles, primary cycles, and trailing cycles and is a function of the expected deformation capacity, $\Delta = 0.6\Delta_m$.

Construction of the CUREE Deformation Controlled Quasi-Static Protocol is defined in the following sequence and illustrated in Figure 3.8.

- Six initiation cycles. Amplitude equal to 0.05Δ.
- Primary Cycle 1. Amplitude equal to 0.075Δ.
- Trailing Cycles 1.1 thru 1.6. Amplitude equal to 0.75(0.075Δ).
- Primary Cycle 2. Amplitude equal to 0.1Δ.
- Trailing Cycles 2.1 thru 2.6. Amplitude equal to 0.75(0.1Δ).
- Primary Cycle 3. Amplitude equal to 0.2Δ.
- Trailing Cycles 3.1 thru 3.3. Amplitude equal to 0.75(0.2Δ).
- Primary Cycle 4. Amplitude equal to 0.3Δ.
- Trailing Cycles 4.1 thru 4.3. Amplitude equal to 0.75(0.3Δ).
- Primary Cycle 5. Amplitude equal to 0.4Δ.
- Trailing Cycles 5.1 and 5.2. Amplitude equal to 0.75(0.4Δ).
- Primary Cycle 6. Amplitude equal to 0.7Δ.
- Trailing Cycle 6.1 and 6.2. Amplitude equal to 0.75(0.7Δ).
- Primary Cycle 7. Amplitude equal to 1.0Δ.
- Trailing Cycles 7.1 and 7.2. Amplitude equal to 0.75(1.0Δ).
- Primary Cycle i. Amplitude equal to amplitude of primary cycle (i-1)+0.5Δ.
- Trailing Cycles i.1 and i.2. Amplitude equal to 0.75(amplitude of primary cycle i).

Generally, this study utilized a protocol with ten primary cycles, or three primary cycles beyond the expected cyclic deformation capacity, to ensure a complete loading history up to and beyond capacity.

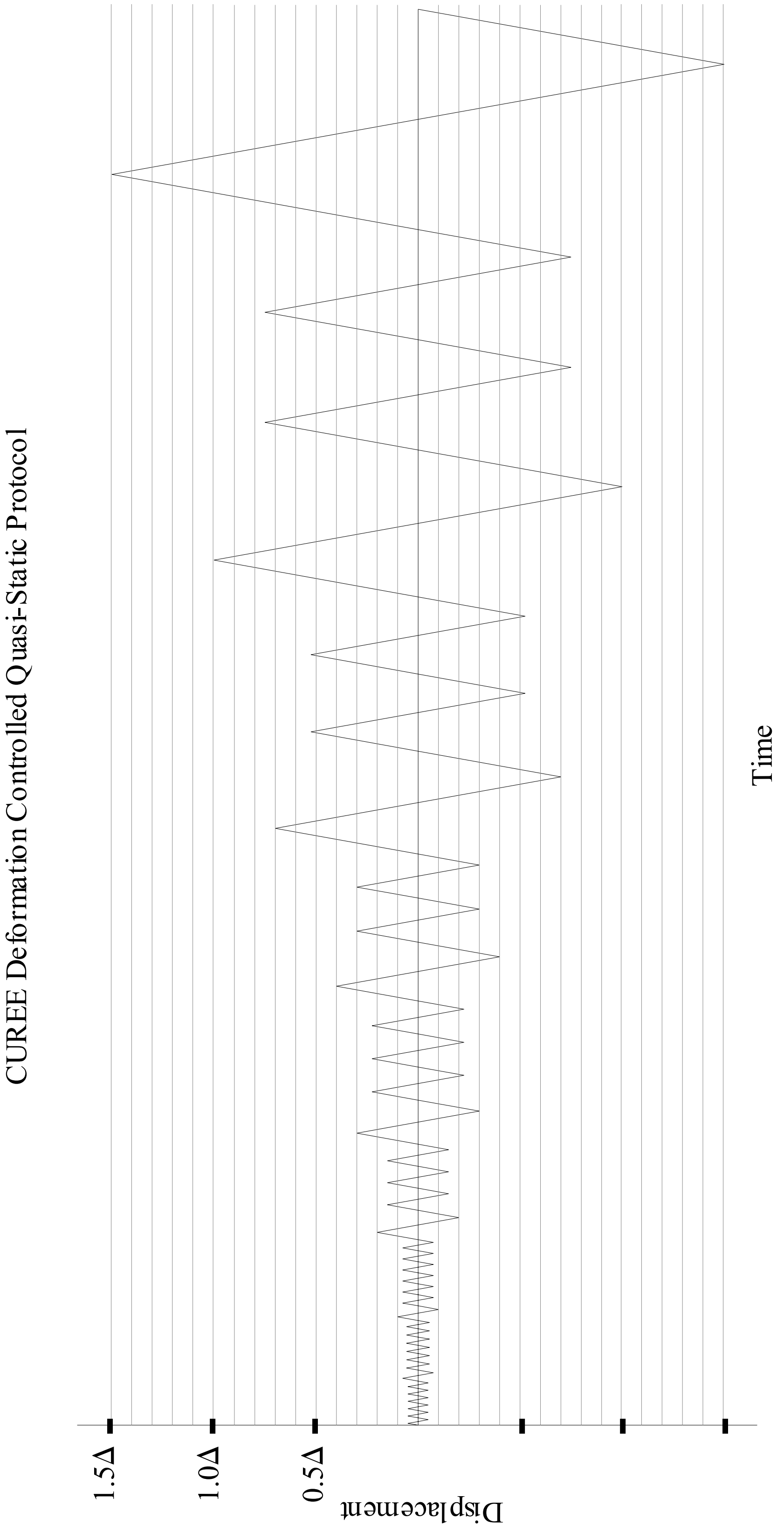


Figure 3.8: Abbreviated CUREE Deformation Controlled Quasi-Static Protocol (after Krawinkler et. al., 2001).

3.5.2 – Monotonic Connection Tests

Development of the CUREE Displacement protocol required an input displacement from which the protocol could be scaled. As previously stated, the expected deformation capacity of a joint tested cyclically is based on the factored deformation capacity of a joint tested monotonically. For this study, an average deformation capacity for three monotonic tests was determined and scaled for joint configurations noted in Table 3.1. Joint configurations containing three bolts per row were not tested monotonically. Instead monotonic deformation capacity was estimated based on linear interpolation of the data obtained from the monotonic test results for single-bolt and five-bolt per row configurations.

Monotonic testing of bolted joints conformed to ASTM D 1761-88 with the addition of two potentiometers as illustrated in Figure 3.4. Joints were tested at a speed of .0714 in./min. so that a displacement of 1/2 in. was reached in 7 minutes. The data acquisition-sampling rate was set at 3 Hz.

3.5.3 – Cyclic Connection Tests

Cyclic connection tests were displacement controlled using the CUREE deformation controlled quasi-static cyclic protocol based on the loading history for ordinary ground motions. Protocols were digitized based on a load rate of 4.724 in./min., and sampled for the digital control of the test machine at 100 Hz. The data acquisition-sampling rate was set at 20 Hz.

3.5.4 – Dowel Embedment Tests

Dowel embedment test samples were obtained from the two respective members of all connection tests. Samples were cut from the tested joints near bolt locations and excluded any material damage such as cracked or crushed wood (See Figure 3.9). This practice was easily accomplished with single row configurations because failure usually occurred through the centerline of the members. Two row configurations presented a challenge because failures tended to involve the entire cross section. In general it was possible, and a matter of practice, to save the end cut-offs from each connection assembly piece so that if necessary, dowel embedment samples could be taken from them.

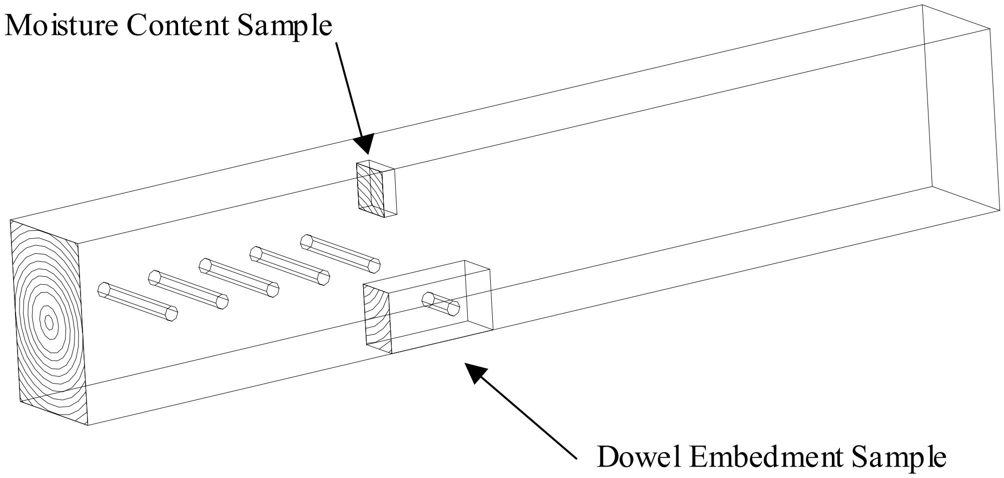


Figure 3.9: Property test sampling of bolted connection members.

Dowel embedment specimen testing conformed to ASTM D 5764-97a, Standard Test Method for Evaluating Dowel Bearing Strength of Wood and Wood-Based Products (ASTM, 2001). The specimens were tested in the full-hole configuration. Because of the nature of sampling from bolted connection members, the specimen thickness was a function of the width of undamaged material. For all tests, specimen dimensions were 2 in. wide by 1.5 in. thick with a loaded length of 2.5 in., and an unloaded length of 1.5 in.. Speed of testing was 0.08 in./min. so that capacity was reached in 1 to 3 minutes.

Specimens were tested in the full-hole configuration to ensure that splitting did not occur before an accurate value of embedment capacity could be attained. One of the difficulties of full-hole testing has historically been the validity of assuming that the loading pin remains perfectly rigid. In reality the pin will bend and cause a non-uniform stress distribution during loading. In an attempt to provide the most uniform distribution of load possible for full-hole testing, a fixture was fabricated so that the loading pin had rigid supports such that rotation was minimized and bending reduced (See Figure 3.10).

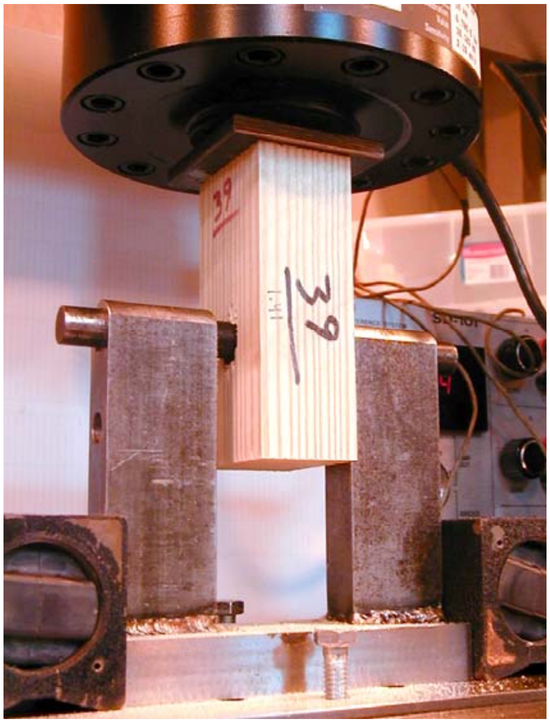


Figure 3.10: Photograph of full hole dowel embedment test.

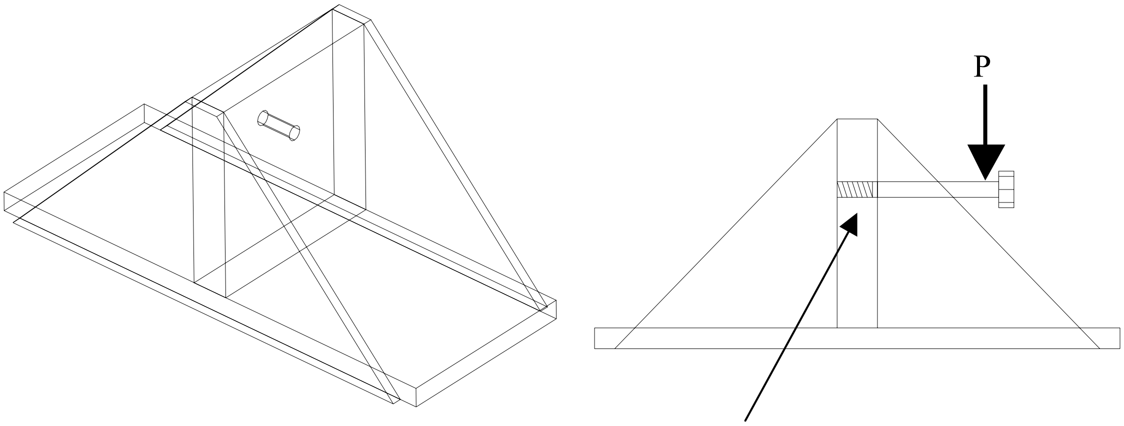
3.5.5 – Moisture Content and Specific Gravity Measurements

Moisture content and specific gravity measurements were made for all wood connection pieces. Samples were obtained as illustrated in Figure 3.9 and tested in accordance with ASTM D4442-92 and ASTM D2395-93.

3.5.6 – Bolt Bending Tests

Bolt bending tests were conducted on all bolt sizes used to satisfy the material property requirements of the Yield Limit Model in the determination of probable yield modes, 5% offset yield strength, and connection capacity. A total of fifteen replications per bolt size were tested according to the basic requirements and procedures outlined in ASTM F1575-95. A three point loading configuration was used on bolts with adequate shank length (See Figure 3.11). Bolts with small shank lengths were tested in the cantilever method illustrated in Figure 3.12.

Figure 3.11: Photograph of bolt bending test: three-point loading.



Countersink hole to exclude threads from M_{max} location.

Figure 3.12: Bolt bending test: cantilever method.

3.5.7 – Test Data Analysis

Data evaluation of monotonic and cyclic testing conformed to “Standard Test Method for Cyclic Properties of Connections Assembled with Mechanical Fasteners”, a draft ASTM standard (ASTM, 1999). This method was used to obtain consistency in the evaluation of strength parameters of monotonic and cyclic tests. Figure 3.9 shows a typical load-deflection plot for monotonic test, which is also analogous to a backbone or envelope curve generated from cyclic tests. Backbone and/or an envelope curve typically define the approximate cyclic test response by connecting successive hysteretic peaks.

Specific definitions of connection parameters are as follows (ASTM, 1999):

- The equivalent elastic-plastic curve is drawn so that the area under the two line segments is equal to the area under the actual data curve up to the failure displacement, $\Delta_{failure}$.
- The yield load is defined so that $F_{Peak} \geq F_{yield} \geq 0.8F_{Peak}$.
- The ductility ratio is defined as $D = \dfrac{\Delta_{failure}}{\Delta_{yield}}$.

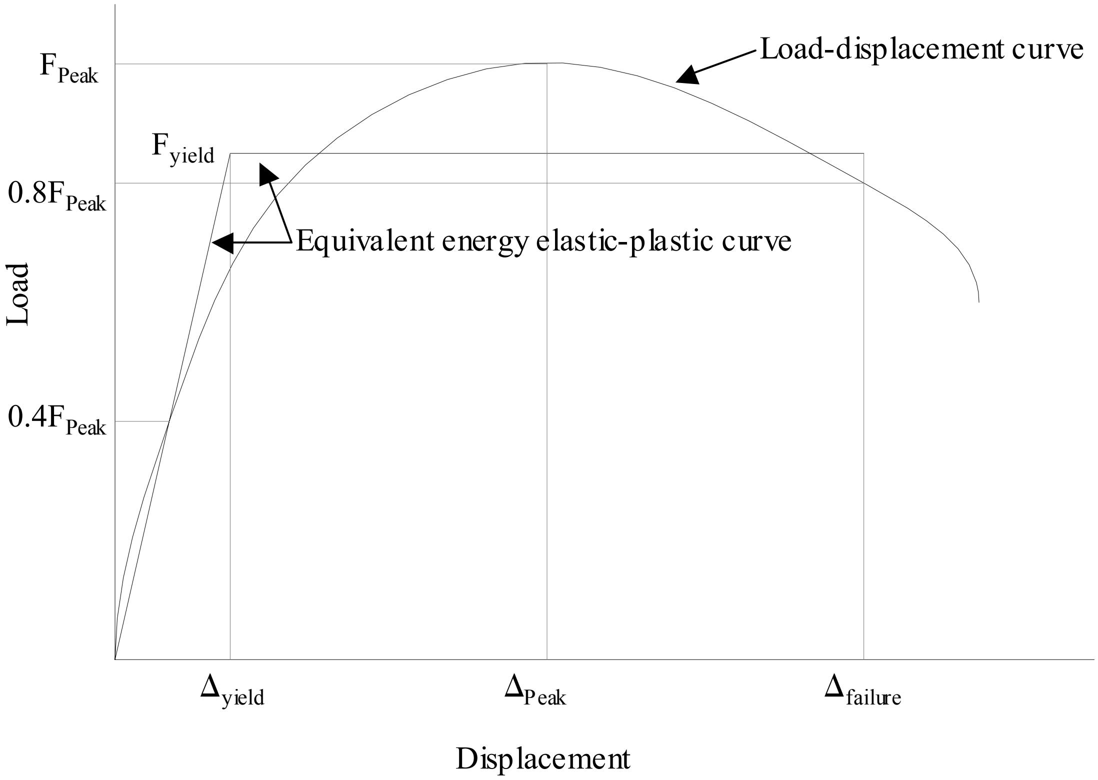


Figure 3.13: Equivalent energy elastic-plastic system (after ASTM, 1999).

When analyzing cyclic data, there are several energy-based properties that are determined on a cycle-by-cycle basis. These properties are illustrated in Figure 3.14 and are defined as follows (ASTM, 1999):

- Strain energy for a given cycle is the sum of the area enclosed by triangles GTA and GLO.
- Hysteretic Energy for a given cycle is the area enclosed by the actual load-deflection curve (hatched area in Figure 3.14).
- Cyclic stiffness for a given cycle is the slope of line OT.
- The equivalent viscous damping ratio, $\zeta = \dfrac{Hysteretic.Energy}{2\pi.Strain.Energy}$

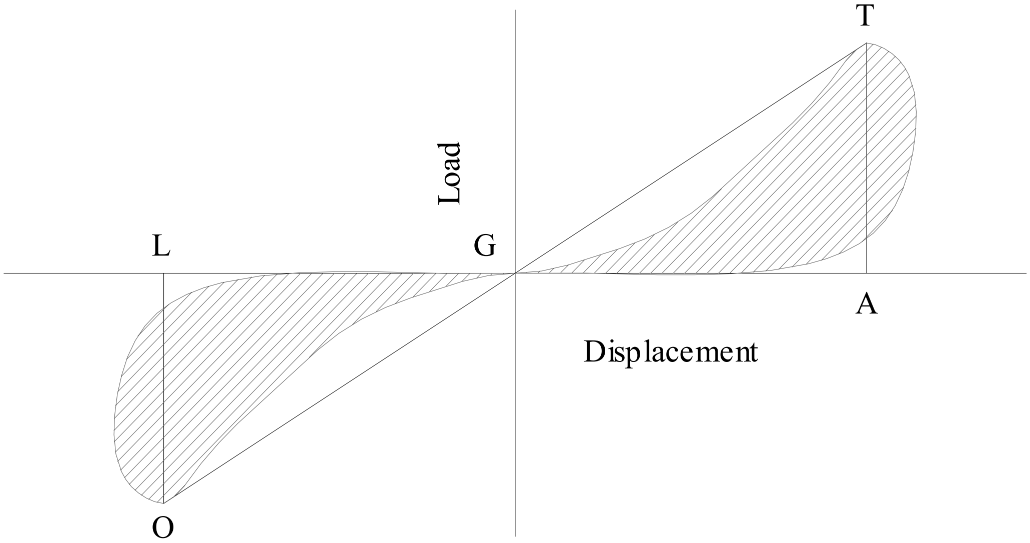


Figure 3.14: Illustration of Hysteretic Energy and Strain Energy definitions from force-deflection hysteresis.

3.6 – Summary

Displacement controlled monotonic and CUREE cyclic procedures were employed to determine the influence of the fastener group action in multiple bolt connections at capacity. Cyclic test data was also used to determine connection properties.

Tested joint configurations tested were designed to provide a broad range of data that may be used to determine relations between yield modes, number of bolts, and side member material. Material property tests from respective assembly pieces were obtained as carefully as possible and as closely as possible to the actual connection location. This will provide a direct, traceable link between mechanical and physical material properties and the connection performance properties.