

**Determination of
Short-Term Duration-of-Load Performance
of Nailed and Bolted Connections Using
Sequential Phased Displacement Tests
Volume I: Summary Report**

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SUMMARY

An experimental study of the cyclic properties of nailed and bolted wood connections is described. The study used a proposed ASTM standard test procedure that is currently being developed by ASTM Subcommittee E06.13, and is titled “Standard Test Method for Dynamic Properties of Connections Assembled with Mechanical Fasteners.

The objectives of this investigation are 1) determine the effects of cyclic loading on the performance and safety of nailed and bolted connections, and 2) determine if the value of 1.6, used as the load duration factor for wind and seismic design in the *1991 National Design Specification for Wood Construction*[®] (NDS[®]), is appropriate. Results presented in this document along with information in a companion document (Dolan et al., 1994a) are used to answer these objectives.

Three typical nailed and three typical bolted connections were constructed to include three of the four possible yield modes for wood connections. Two matched samples of each connection type (15 specimens for nails and 10 specimens for bolts) were tested using the new ASTM standard method to either catastrophic failure or a connection slip of 1.0 inches. One matched sample was subjected to cyclic loads oriented parallel-to-grain, while the other matched sample was tested in the perpendicular-to-grain direction.

Previous results indicate that prior load-controlled cyclic loading to magnitudes as high as 2.0 times the nominal design values published in the 1991 NDS do not have adverse effects on connection capacity, or ductility for nailed and bolted wood connections (Dolan et al., 1994a). This indicates that design seismic events will not significantly lower a wood connection’s ability to resist loads. Apparent factors-of-safety based on the allowable seismic design values and a stabilized¹ connection response, determined with the proposed ASTM standard procedure, ranged from 1.5 to 2.8 for nailed connections, from 2.1 to 3.2 for bolted connections loaded parallel-to-grain, and from 3.2 to 5.9 for bolted connections loaded perpendicular-to-grain. Furthermore, all connections were subjected to more than 50 cycles of loading, yet retained significant resistance to loads and continued to dissipate significant amounts of energy.

High ductilities associated with nailed connections and their ability to dissipate large amounts of energy indicate that an apparent factor-of-safety of 1.5, based on the stabilized response rather than monotonic response, is sufficient to guarantee acceptable seismic and wind performance. Comparable apparent factors-of-safety for bolted connections are greater than 2.1, and are sufficient to provide acceptable seismic and wind performance.

Results presented also quantify several cyclic properties such as equivalent energy elastic-plastic response, ductility, yield load and displacement, hysteretic damping, cyclic stiffness, and equivalent viscous damping. Values of these cyclic properties are based on stabilized connection response, not on optimum or monotonic response, and illustrate the ability of wood connections to dissipate significant quantities of energy during cyclic or dynamic loadings expected during natural hazard events such as earthquakes. The ability to dissipate energy improves a structure’s performance and reliability.

¹Stabilized response is defined by the proposed ASTM standard as having no more than 5 percent decrease in load resistance between two successive cycles to the same displacement.

INTRODUCTION

The load duration factor, C_D , for wood construction under seismic and wind loading increased from 1.33 to 1.6 in the 1991 edition of the *National Design Specification® for Wood Construction* (NDS®). While, this increase does not reflect any change in philosophy from previous design codes, it highlights an area of limited research. Specifically, the lack of research data raised questions about the load duration increase for seismic loading from historic levels. The basis of the questioning relates to previous connection tests used to determine design values for the NDS which were performed with monotonic quasi-static and impact loading, while seismic events produce reversing load effects on the connections.

Equations presented in the 1991 NDS for determining allowable design load include two factors. The first factor adjusts short-term strength to an allowable strength for 10-year load duration. This factor is equal to 1.6 and is based on engineering judgement and results of load duration tests on wood members. The second factor is a factor-of-safety for the particular yield mode considered. The factor-of-safety includes adjustments that account for uncertainty, variability, and calibration to historic performance. In Equations 8.2-1 to 8.2-6 in the 1991 NDS, constants in the denominator of each equation combine the duration-of-load (DOL) and factor-of-safety (FOS). Therefore, the constants of each equation can be broken into two components as follows:

- 4.0 for MODES I_m and I_s becomes 1.6 x 2.5 for DOL and FOS respectively
- 3.6 for MODE II becomes 1.6 x 2.25 for DOL and FOS respectively and
- 3.2 for MODES III_m, III_s, and IV becomes 1.6 x 2.0 for DOL and FOS respectively.

The change from 1.33 to 1.6 for the DOL factor was made for all NDS fastener equations without changing the FOS. The use of the previous value of 1.33 instead of 1.6 essentially increased the factor-of-safety for seismic loads over that used for normal duration loads.

To understand why $C_D = 1.6$ is proposed for short-term loads such as seismic actions, consider the method used to calculate the nominal design values shown in the 1991 NDS. Connection design values are based on experimental yield loads derived from monotonic tests with a rate of loading causing failure of specimens in 5-10 minutes. This short-term load is then indexed to a nominal design value based on a service duration of 10 years. (Normal or 10-year load duration considers that wood structures experience cumulative duration at design load of 10 years over the useful life of the structure.) To adjust short-term values to nominal 10-year loads, values are divided by 1.6. The 1991 NDS readjusts nominal values back to short-term (10-minute) design values for seismic loads by multiplying by the load duration factor of 1.6. ***There are no other factors implied in the use of $C_D = 1.6$ other than indexing back to short-term design capacity.*** The 1.6 load duration factor is conservative since it adjusts nominal design values to a 10-minute design value, whereas an earthquake is a much shorter duration event.

However, monotonic tests are not representative of cyclic loads such as earthquakes. Monotonic tests do not provide information on any effect of prior cyclic load history on connection capacity and/or ductility. There is concern that previous load history may affect connection reserve capacity and/or ductility in subsequent cyclic loading.

This research project was necessary to determine the effects of cyclic load history on nailed and

bolted connections and determine apparent factors-of-safety for cyclicly loaded connections.

The objectives of this study are:

1. Present results of cyclic tests of nailed and bolted connections.
2. Determine the stabilized cyclic response of wood connections and associated capacities and ductilities.
3. Determine if a load duration factor of 1.6 is conservative for laterally loaded nailed and bolted connections in wood if fabricated according to the minimum requirements of the 1991 NDS.
4. Determine apparent factors-of-safety for nailed and bolted connections, subjected to cyclic loading.

These objectives are addressed using the results presented in this report and a companion document on monotonic and cyclic response of nailed and bolted connections (Dolan, et al., 1994a). Monotonic and cyclic test results indicate that prior cyclic loading to magnitudes as high as 2.0 times the nominal 1991 NDS design values do not adversely affect the capacity or ductility of nailed and bolted connections.

From the specific information presented, we cannot directly determine whether the load duration factor presented in the 1991 NDS is scientifically correct since long-term load tests of connections have not been performed. Long-term connection tests are needed to confirm the nominal design values to which all of the other durations are calibrated. This report, however, provides information on whether the seismic design values, calculated according to the 1991 NDS, are appropriate.

Related detailed and summary information on connection tests is presented in companion reports that are available from the Department of Wood Science and Forest Products, Timber Engineering Center, which is located in the Brooks Forest Products Research Center at Virginia Polytechnic Institute and State University. Summary and detailed data for each specimen tested to determine monotonic and load-controlled cyclic performance are presented in Virginia Polytechnic Institute and State University (VPI&SU) Timber Engineering Reports No. TE-1994-001 and TE-1994-002, respectively. The detailed data for each specimen tested under the proposed ASTM standard, Sequential Phased Displacement (SPD), procedure are presented in VPI&SU Timber Engineering Report No. TE-1994-004.

TEST PROCEDURES

Specimen Configurations

Test connection geometries were chosen to represent typical connection details found in construction in the United States, and include three of four yield modes that can occur in dowel type timber connections. Connections had one dowel fastener loaded in single shear. Fifteen specimens of each nail connection type and ten specimens of each bolted connection type were tested in each sample. Table 1 summarizes the types and numbers of replications used for nailed connections in displacement-controlled cyclic tests.

Table 1: Summary of type and number of nailed connection specimens tested under displacement-controlled cyclic loads.

Fastener Type (inches)	Main / Side Member Materials	Load Direction	Expected Yield Mode	Number of Replicates
10d (0.148 x 3.0)	Lumber / 15/32-in Plywood	Parallel-to-Grain	III _s	15
10d (0.148 x 3.0)	Lumber / 15/32-in Plywood	Perpendicular-to-Grain	III _s	15
16d (0.162 x 3.5)	Lumber / Lumber	Parallel-to-Grain	IV	15
16d (0.162 x 3.5)	Lumber / Lumber	Perpendicular-to-Grain	IV	15
10d (0.148 x 3.0)	Lumber / 18-ga. Steel	Parallel-to-Grain	III _s	15
10d (0.148 x 3.0)	Lumber / 18-ga. Steel	Perpendicular-to-Grain	III _s	15

All lumber and plywood used for the tests was purchased at local lumber retailers. Specimens were constructed from southern pine, and were cut so as to avoid localized defects in the wood as much as possible. The wood was conditioned at a temperature of $20 \pm 3^{\circ}$ C and relative humidity of $65 \pm 5\%$ for a minimum of 14 days, or until the equilibrium moisture content was reached. Steel plate used in two connection geometries was also locally purchased and consisted of $\frac{1}{4}$ -inch, ASTM A36 mild carbon steel (ASTM 1989-a) and 18-gauge A446 galvanized sheet steel (ASTM 1989-b). Nails used in two connection geometries were 10 penny (10d) brite common nails with a diameter of 0.148 inches and length of 3 inches. The 16 penny (16d) brite common nails used in the third nailed connection geometry were 0.162 inches in diameter and 3.5 inches long.

Table 1 shows that three types of nailed connections were tested, with each connection type tested in two configurations (parallel-to-grain and perpendicular-to-grain). Two configurations were planned to investigate any effects of grain orientation on connection performance. Since nailed connections are characterized by yielding of the nails as well as the wood, two yield modes that represent fastener yielding (modes III_s and IV) were included. Three types of commonly used connections were included, 1) plywood-to-lumber, which is used in shear walls and diaphragms, 2) lumber-to-lumber, which is typical of light framing connections, and 3) light-gauge sheet steel-to-lumber, which is typical of joist hangers and other light-gauge metal connectors. Fifteen replicates were tested in each configuration to provide some information on the statistical variation in connection performance.

Summary information on type and number of replicates for bolted connection tests is presented in Table 2. Bolted connections were subjected to loading in the parallel- and perpendicular-to-grain orientations to investigate effects of grain orientation on connection performance.

Table 2: Summary of type and number of bolted connection specimens tested under displacement-control cyclic loads.

Fastener Type	Main / Side Member Materials	Load Direction	Expected Yield Mode	Number of Replicates
3/4-in Bolt	2-in / 2-in Nominal Lumber	Parallel-to-Grain	II	10
		Perpendicular-to-Grain	II	10
3/4-in Bolt	4-in / 4-in Nominal Lumber	Parallel-to-Grain	IV	10
		Perpendicular-to-Grain	III _M	10
1/2-in Bolt	1/4-in Steel Plate / 4-in Nominal Lumber	Parallel-to-Grain	III _S	10
		Perpendicular-to-Grain	III _S	10

Three types of bolted connection geometries were tested in an effort to include three of four yield modes possible for bolted connections. Connection geometries were chosen to simulate those typically used in wood structures. The 2-inch-to-2-inch nominal lumber connection with a 3/4-inch bolt represents typical diaphragm chord connections. The 4-inch-to-4-inch nominal lumber connections with a 3/4-inch bolt represents the yield mode expected in a concrete to wood connection such as a sill plate to concrete wall anchorage. Finally, 4-inch nominal-to-1/4-inch steel plate connections represent typical hardware used in glulam and post-frame connections.

The stationary member for all bolted connections was defined as the member that was clamped in a fixed position in the testing fixture, and was located on the nut side of all bolted connections. For all nailed connections, the stationary member was the penetrated or main member of the connection. The active member for all connections was defined as the member that was moved by the MTS hydraulic actuator in a cyclic displacement pattern. All bolted connections tested with the load acting perpendicular-to-grain to the stationary member required that the stationary members be wider than the active members in order to meet edge distance requirements for the full 1991 NDS design values.

Specimen Fabrication

The full test program required five samples of matched specimens. Matched samples were obtained by cutting five replicates of each component from adjacent locations in a single board of southern pine lumber. This matching technique provided specimens in each sample with as close to identical physical characteristics as possible. Obvious local variations such as knots or splits were avoided in choosing the locations of each set of four components. Matched components were then marked so that sets of five "identical" specimens produced five samples, each with 15 or 10 matched specimens depending on whether the fasteners were nails or bolts, respectively. Summary results of tests on three of the five matched samples are presented in a companion report (Dolan, et al., 1994a). Two matched samples were tested using the new ASTM procedure, and the results are presented in this report. Detailed results for each specimen tested using the SPD protocol are available in a companion report (Dolan and Gutshall, 1994b).

Nailed Connections

Nailed connections were fabricated and then placed in an environmental chamber (at 20⁰ C (68⁰ F) and 65% relative humidity) for a minimum of 14 days to allow for relaxation of wood fibers around the nail and to achieve approximate equilibrium moisture content. This conditioning time provided a more accurate representation of a nailed connection that has been in service for a period of time. Nailed connections usually have a higher initial stiffness immediately after assembly because wood fibers in contact with the nail shank have not relaxed.

Pre-drilled nail holes, meeting the guidelines established in the 1991 NDS, were used to guide the nails and prevent splitting of the wood members during driving with a hand-held hammer. The 1991 NDS allows a pre-drilled hole no more than 75% of nail diameter for wood with a specific gravity less than 0.60. Therefore, connections using 10d common nails were pre-drilled with a 1/16-inch hole, or 42% of nail diameter, and connections using 16d common nails were pre-drilled with a 3/32-inch hole, or 58% of nail diameter. For 18-gauge steel plate-to-2x4 connections, a 9/64-inch hole (95% of nail diameter) was pre-drilled in the steel plate. Members used in the testing had actual average specific gravities ranging from 0.48 to 0.62 depending upon the grade and size of lumber used. An additional sample of lumber-to-lumber nailed connections, constructed with 16d common nails were fabricated without pre-drilled pilot holes to investigate the effect of the pilot holes on the connection performance

Bolted Connections

Bolted connections were fabricated immediately prior to testing. A bolt hole that was 1/16-inch larger than the bolt was used for both wood and steel members of all bolted connections. This was in accordance with assembly tolerances given in the 1991 NDS and *1989 Manual of Steel Construction, Allowable Stress Design* published by the American Institute of Steel Construction. All bolt holes were centered between the edges of members and drilled with high speed steel drill bits to ensure smoothness and uniformity. In all connection configurations, end distances exceeded minimum requirements given in the 1991 NDS for use of full design values, and standard A307 mild carbon steel bolts or their equivalent were used.

Active members of connections were held by a gripping fixture attached to the testing machine. A SAE grade 8 bolt was inserted through the gripping fixture into a pre-drilled hole of the same diameter to prevent any slipping between the wood or steel member and the grip. Stationary members of the connections were blocked to prevent any movement.

Test Equipment

All tests were conducted in the Wood Engineering Laboratory of the Brooks Forest Products Research Center at Virginia Polytechnic Institute and State University. Two MTS servohydraulic test machines were used to conduct displacement-controlled cyclic tests. Displacements were measured using two linear variable differential transformers (LVDT) that were attached to the sides of specimens to measure connection slip, and loads were measured using load cells attached to the MTS actuators. Data was acquired using commercial data acquisition software on a micro computer in the engineering laboratory. Acquired data was analyzed using commercial spreadsheet software.

Test specimens were held in place and guided by a steel fixture to prevent rotation that would have resulted in forces other than pure shear being applied to the specimen. Figure 1 shows a

diagram of the test fixture. One important aspect of the fixture alignment is that the center of the load cell is aligned with the connection shear plane. This minimizes any moment introduced into the specimen. Rollers are included in the fixture to minimize the effects of friction between the fixture and the moving side of the specimen.

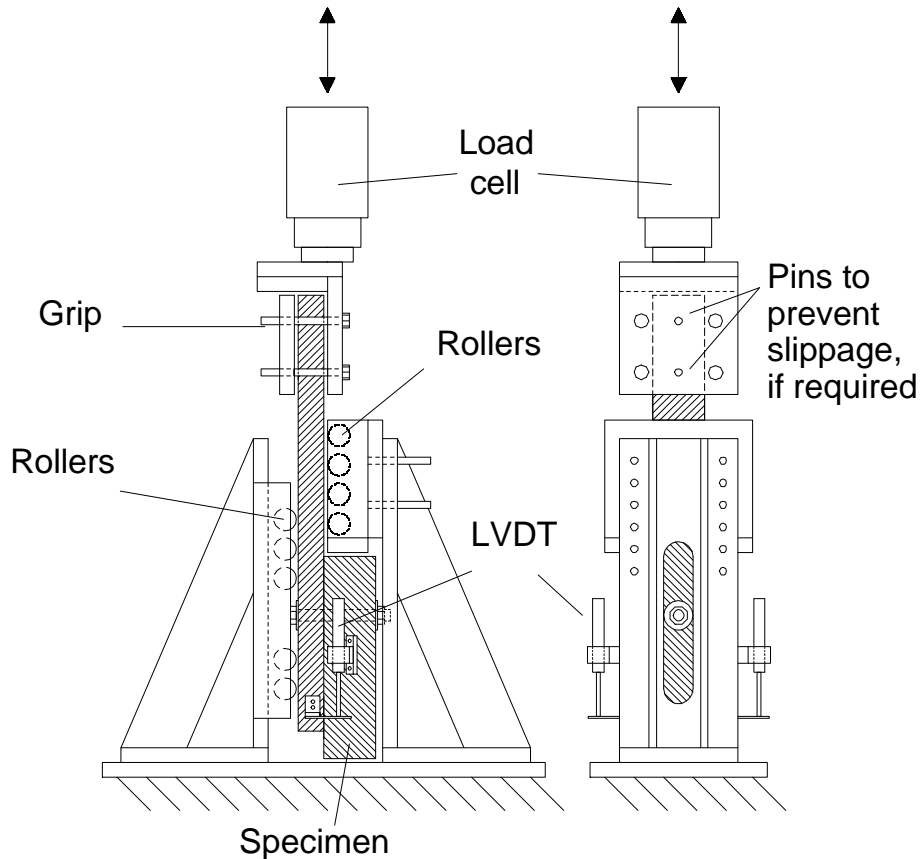


Figure 1: Test fixture used for connection lateral load tests.

Proposed ASTM Test Procedure

The method used in this study is a proposed ASTM standard that is being developed by ASTM Subcommittee E06.13, and is a modification of the "Sequential Phased Displacement" (SPD) procedure used by the Joint Technical Coordinating Committee on Masonry Research (TCCMAR) for the United States-Japan Coordinated Earthquake Research Program. This procedure is used by TCCMAR to serve as a uniform basis for comparing components not subjected to real-time earthquake loading. The procedure entails reversed-cyclic displacements

of progressively increasing magnitude until a first major event² (FME) occurs. The loading is then followed by degradation and stabilization cycles before progressing to the next higher increment of displacements. This process is repeated until failure occurs.

For this study, failure was defined as catastrophic failure, when the specimen was physically unable to carry any load, or when a connection slip of 1.0 inch was obtained. A maximum displacement of 1.0 inch was used as a failure criteria for two reasons. First, if a connection in a real structure were to slip as much as 1.0 inch, load would most likely be transferred to other locations in the structure due to load sharing. Second, the 1.0 inch displacement was close to the maximum displacement that the test fixture could tolerate and continue to maintain the specimen's correct alignment.

The SPD procedure, described by Porter (1987), was modified from a quasi-static to pseudo-dynamic displacement rate to account for the fact that response of wood connections is dependent on load rate. Therefore, a cyclic frequency of 1.0 Hz was specified so that connection response would approximate the frequency range expected in low-rise wood buildings during an earthquake or high-wind event. The displacement pattern was a fully reversing, triangular ramp function which was cycled between varying displacement amplitudes. Characteristic points on the experimental load-slip traces provided data for calculating the dynamic properties of the connections.

The loading procedure for nailed connections involved ordinary reversed-cyclic displacements for three cycles at each incremental level below the displacement associated with the 1991 NDS nominal design loads². Three increments of three cycles each were performed prior to reaching the estimated NDS nominal design displacement. The displacement where the expected load would equal the 1991 NDS nominal design value was estimated from previous monotonic tests of matched samples (Dolan et al., 1994a). The initial displacement set was 0.25 of anticipated nominal design value displacement, followed by 0.50 and 0.75 of nominal design value displacement. The initial three sets of three cycles are shown in Figure 2, the schematic of the complete displacement pattern followed during testing.

Once nominal design value displacement was reached, a sequential phased displacement (SPD) loading procedure was employed. The displacements of each set of cycles, or phase, built upon the preceding phase, and in each incremental phase after the nominal design value displacement, three decay cycles are added. These decay cycles began at the particular incremental displacement, and decayed at a rate of 0.25 times the maximum displacement of the phase. These decay cycles were followed by three additional cycles at the previous maximum displacement magnitude, as is shown in Figure 2. These three cycles were required to obtain a stabilized response and were followed by one cycle at the next increment of displacement. Thus, the procedure included phases of displacement history consisting of an initial displacement increment, followed by three decay cycles, followed by three stabilizing cycles at the initial displacement.

²The first major event (FME) for this investigation is defined as the displacement associated with the 1991 NDS allowable design load. This displacement was estimated from monotonic test results which are reported on the companion report, TE-1994-001 (Dolan, et. al., 1994A).

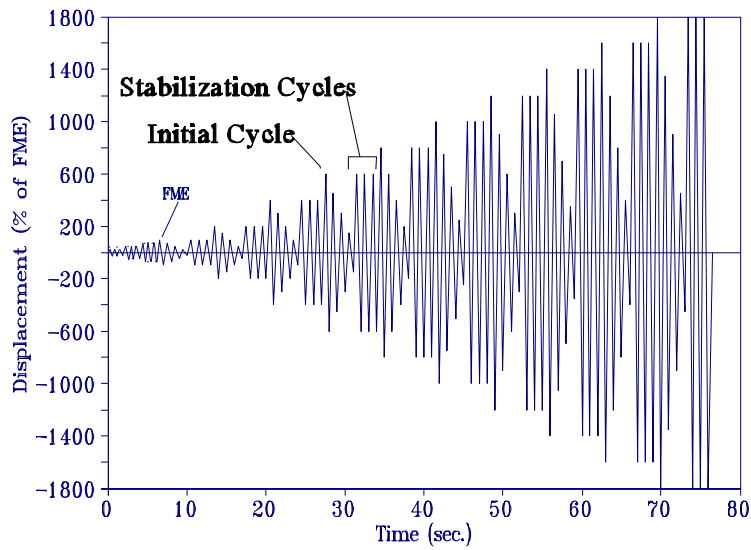


Figure 2: Displacement pattern used in the Sequential Phased Displacement tests.

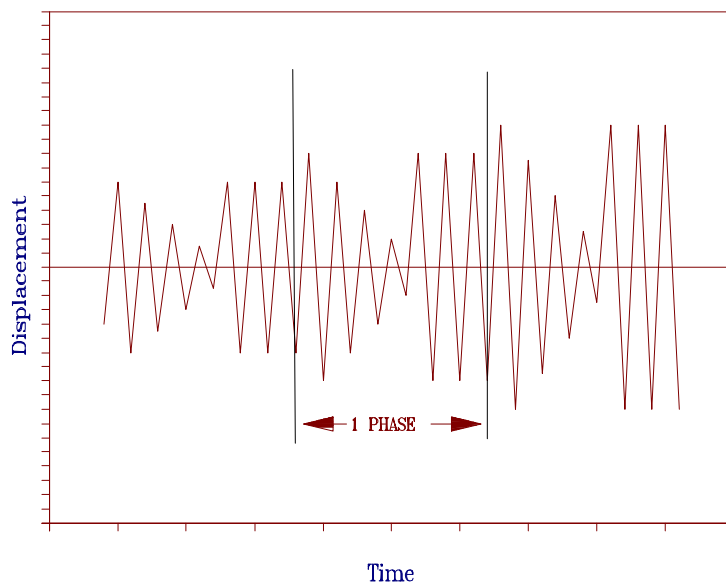


Figure 3: Displacement pattern of a single phase of cycles.

Figure 3 shows one set of cycles that constitutes a single phase in the displacement pattern. The

three cycles following the decaying cycles were used to determine a stabilized hysteretic response. In order for connections to be considered stabilized, a load degradation of no more than 5% was allowed between successive cycles. Three stabilization cycles was determined to be sufficient from preliminary tests cycled under displacement-controlled and results of load-controlled cyclic tests of matched samples (Dolan et al., 1994a). The stabilized hysteresis curve was used to calculate the stabilized energy dissipation of connections, and provided conservative estimates of performance properties expected in structures previously loaded or subjected to a large number of cycles during a loading event.

The displacement pattern used for bolts was determined differently than that used for nails. This was necessary because of the effects of oversized bolt holes in the wood and steel members. Due to the slip associated with the oversized holes, too few phases were required to reach the maximum allowable connection slip. Therefore, the initial phase of the test pattern for bolted connections was set to allow 14 phases to reach a connection slip of 1.0 inch. This allowed properties of interest to be determined with reasonable accuracy from test data.

The SPD procedure more accurately represents an earthquake or wind loading patterns than do the usual monotonic or simple reversed cyclic loading patterns used for previous tests. The rationale behind this approach centers on two main concepts: degrading of load required during successive cycles to a given displacement and defining a stabilized hysteretic system. The stabilized hysteretic response, as defined in footnote 1, provides information for defining more conservative estimates of performance and design, and is a more realistic expectation of the response of connections subjected to multiple loading cycles than that provided by monotonic loading.

Moisture Content and Specific Gravity Tests

Small specimens were cut from each connection in the vicinity of the nail or bolt immediately after the SPD test was complete. Moisture content and specific gravity were then determined for the wood components of the connection following ASTM D-143, standard methods of testing small clear specimens of timber (using oven dry weight and volume) (ASTM, 1993).

Property Definitions

All cyclic properties determined in this study were based on stabilized connection response. In other words, the hysteresis for the last cycle of each phase was extracted from the load-displacement time-history and used for analysis. Three cyclic properties were determined directly from the load-displacement time history. These properties are **hysteretic damping**, **cyclic stiffness**, and **equivalent viscous damping**.

Cyclic test properties obtained in this study are illustrated in Figure 4. This figure shows a typical hysteresis response for a nailed connection subjected to reversal cyclic load along with information required to calculate three properties. Figure 5 shows a typical hysteresis for a bolted connection with similar information required for calculating cyclic properties.

In Figure 4, the area enclosed by the actual load-deflection curve during one cycle represents **hysteretic damping**. This is a measure of actual energy dissipated by a connection. Values for this property are determined by integrating the area inside the hysteresis loop using a Simpson's rule algorithm.

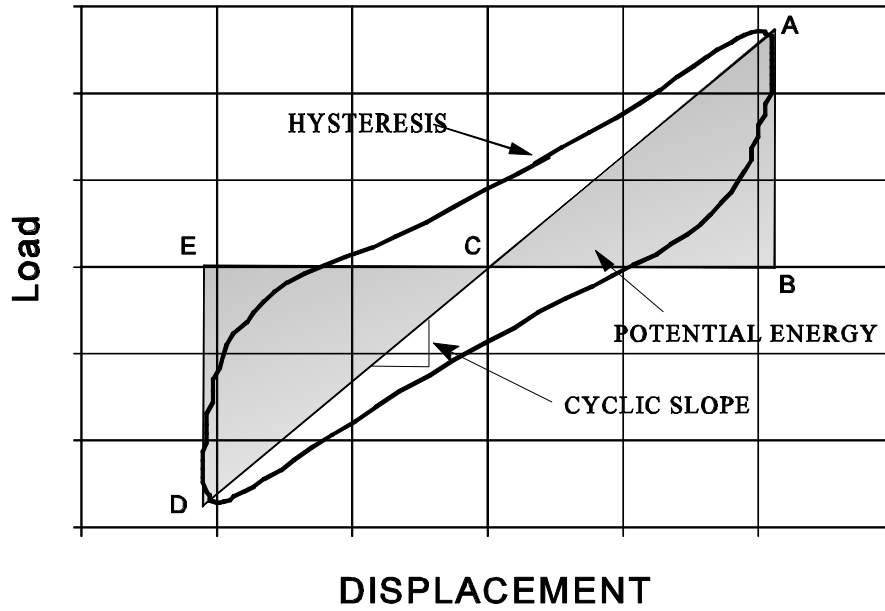


Figure 4. Typical hysteresis for a nailed connection with properties defined.

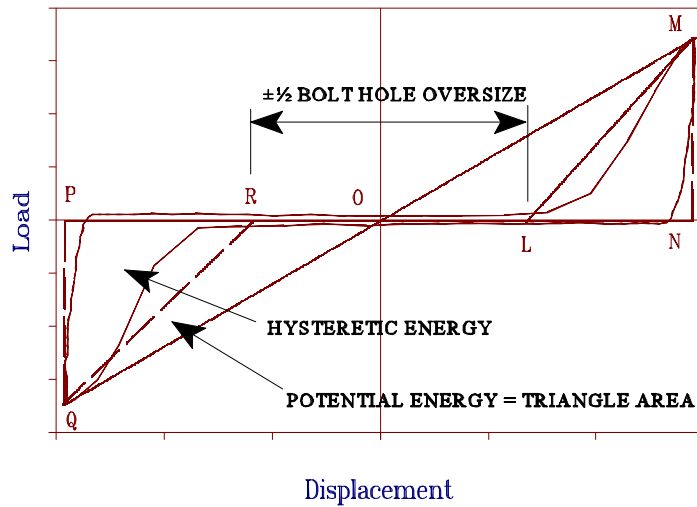


Figure 5. Typical hysteresis for bolted connection with properties defined.

Connection potential energy is defined as the area enclosed by triangles **OMN** and **OQP** and is used to calculate the equivalent viscous damping for connections with the equation,

$$\xi = \frac{D}{2\pi P} \times 100 \quad (1)$$

where:

ξ = the equivalent viscous damping ratio in percent

D = the hysteretic damping (dissipated energy during one cycle, in-lb)

P = the potential energy for the same cycle (in-lb)

The **equivalent viscous damping** is an indicator of how much energy an equivalent single degree-of-freedom, mass-dashpot system would dissipate, and is a useful property for numerical modeling structural systems or for making comparisons between connections manufactured of different materials.

Finally, **cyclic stiffness** for nailed connections is defined as the slope of the line connecting points **D** and **A** shown in Figure 4. This property indicates how the connection "softens" or degrades during loading.

Definitions of viscous damping and cyclic stiffness are different for bolted connections due to slackness in the connection associated with holes being 1/16-inch larger than the bolts. For bolted connections, two potential energies were defined. The first includes the effect of oversized holes (areas **MNO** and **OQP** shown in Figure 5), and the second excludes the effect of oversized holes (areas **LMN** and **RQP** shown in Figure 5). This change results in two calculated values of equivalent viscous damping for bolted connections. Cyclic stiffness was also defined for two cases, i.e. including the effect of oversized holes (slope of line **QM** shown in Figure 5) and excluding the effect of oversized holes (the average of the slopes of lines **LM** and **RQ** shown in Figure 5). The definition of hysteretic damping was not changed from that used for nailed connections and is equal to the area enclosed by the load-deflection curve for one complete cycle.

Changes in the definition for equivalent viscous damping and cyclic stiffness were made to provide information on the bounds of expected cyclic response of connections used in real structures. In section 8.1.2.1, the 1991 NDS provides for bolt holes to be a minimum of 1/32-inch and a maximum of 1/16-inch oversize. Therefore, the two values calculated for each property provide information on the bounds of possible performance of connections manufactured within the allowance of the 1991 NDS provisions. While total exclusion of the effects of oversized bolt holes may not be a realistic assumption since the minimum size for the holes is 1/32-inch oversize, it is an acceptable assumption for determining bounds of performance. Excluding the effect of oversized holes results in overestimated values for cyclic stiffness.

An equivalent energy elastic-plastic load-displacement curve was determined for each connection tested with the SPD procedure. Figure 6 illustrates the method of determining the elastic-plastic curve as well as the properties determined. First, a stabilized (as defined in footnote 1) load-displacement envelope was constructed by connecting the averages of maximum and absolute value

of minimum load and associated displacements of the hystereses (shown as the curvilinear line in Figure 6). The elastic stiffness line was then fit to the curve as a line passing through the origin and a point at $0.4 F_{MAX}$, where F_{MAX} is the stabilized capacity. The plastic response line of the idealized response was then fit such that two criteria were met, 1) yield load could not be lower than $0.8 F_{MAX}$, and 2) areas A_1 and A_2 equal. In this study, the maximum displacement, Δ_{max} , is defined as the displacement where a sudden significant drop in load resistance occurs or a displacement of 1.0 inches is reached. All displacements greater than Δ_{max} are ignored in the analysis due to the assumption of failure occurring at Δ_{max} . The concept of equivalent energy (represented by the area) under each of the two curves is obtained by requiring the areas under the two curves be equal.

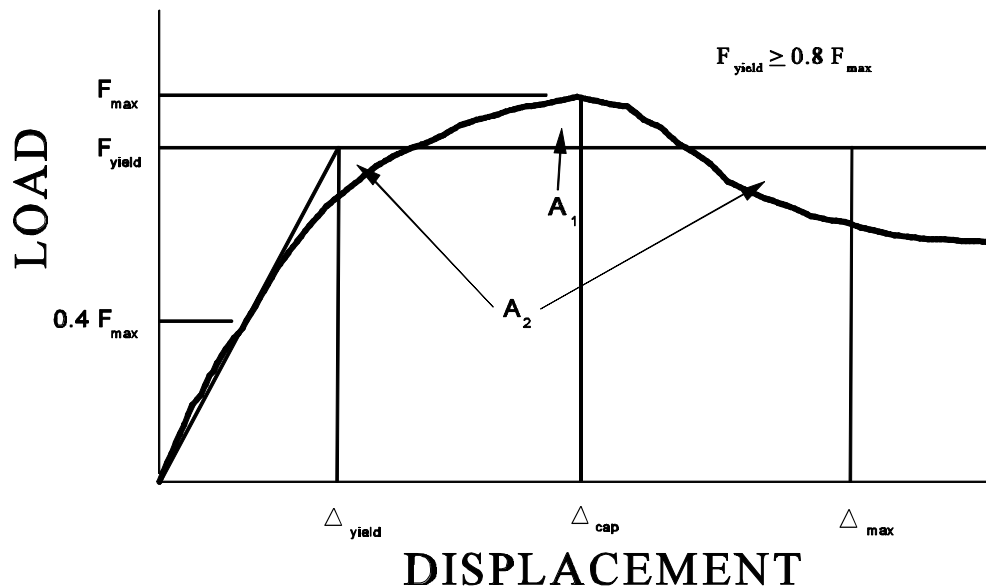


Figure 6. Equivalent energy elastic-perfectly plastic system.

An additional five properties were determined based on an equivalent energy, elastic-plastic load-displacement curve. The equivalent energy, elastic-plastic curve was based on the envelope curve containing the hysteresis curves for stabilized connection response, and has the same area below the curve as the envelope curve. These five properties are **elastic stiffness**, **yield load**, **yield displacement**, **stabilized capacity**, and **ductility**.

From information shown in Figure 6, five properties, **elastic stiffness**, **yield load**, **yield displacement**, **stabilized capacity**, **displacement at capacity** (Δ_{cap}), and **ductility** were determined. **Elastic Stiffness** was defined as the slope of the line passing through the origin and a point on the load-displacement curve where the load equals $0.4 F_{MAX}$. This stiffness represents a good estimate

of average stiffness that connections will exhibit after being loaded a number of times to low or moderate magnitudes ($\leq 0.6 F_{MAX}$).

Yield load is defined by the horizontal line, drawn such that the energy under the idealized elastic-plastic curve equals the energy under the actual curve. Yield load was also defined to be greater than or equal to $0.8F_{MAX}$.

Yield displacement is defined as the displacement coordinate where the elastic stiffness and yield lines intersect. This value is used to determine ductility of the equivalent energy system.

Stabilized capacity is the maximum load of the stabilized load-displacement envelope curve, and represents a conservative estimate of the maximum load expected in connections subjected to multiple cycles at a given displacement.

Displacement at capacity, Δ_{max} , is the connection displacement when the capacity or stabilized capacity is reached.

Ductility in these tests was defined as the ratio of maximum displacement to yield displacement of the equivalent energy, elastic-plastic system, and will always have a value greater than 1.0. Ductility of a connection is a measure of how much displacement the connection can sustain after yielding and not fail. This property is one indicator of how a structure will perform during an earthquake. Structures with higher ductility can sustain higher deflections imposed during a seismic event. Ductility of an equivalent energy, elastic-plastic system will always be lower than values quoted for monotonic tests due to differences in definitions for yield displacement. The result of different definitions of yield displacement is that monotonic yield values are significantly lower than yield displacements used in equivalent energy systems, and therefore monotonic ductility ratios are higher.

RESULTS AND DISCUSSION

Nailed Connection Results

Figure 7 shows a typical load-displacement response for a SPD test of a nailed connection. If the connection did not fail by the end of the initial test of ten phases, an additional test of nine phases was used, beginning at the maximum displacement of the initial test. Figure 8 illustrates the response of a nailed connection to the second test of nine phases. All nailed connections failed before the end of the second test of nine phases. Stabilized response was then determined by extracting the final hysteresis curve from each phase, and combining the average of maximum and absolute value of minimum load, and associated displacements at each cycle to construct the stabilized response envelope curve. Cyclic properties were also calculated for each stabilized hysteresis, and are presented in the appendix.

Average values and coefficients of variation for moisture content and specific gravity of nailed connections tested with the SPD procedure are presented in Table 3. Moisture content and specific gravity specimens were taken from the vicinity of the nail for every specimen. Average moisture content ranged from 13.9 to 15.2 for lumber used in the connections, and specific gravity ranged from 0.55 to 0.60.

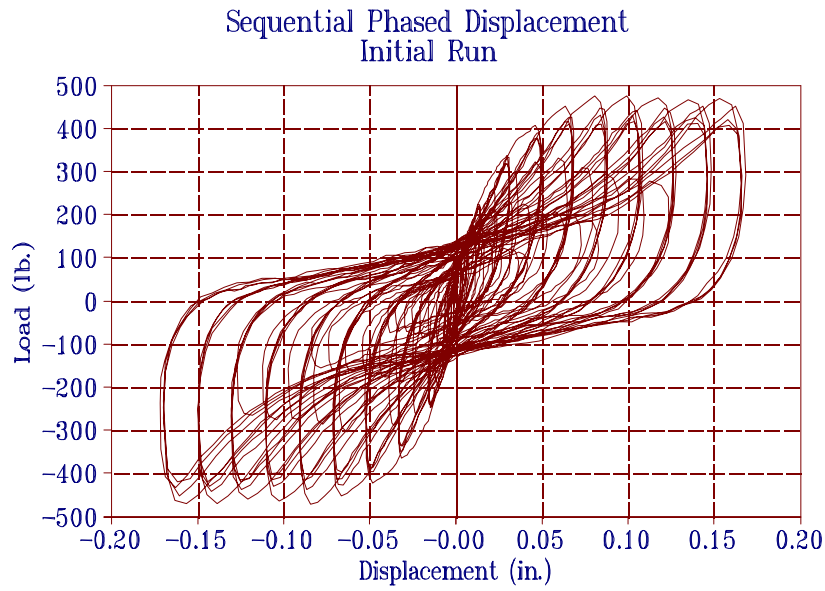


Figure 7: Typical response of a nail connection subjected to the SPD test (first 10 phases).

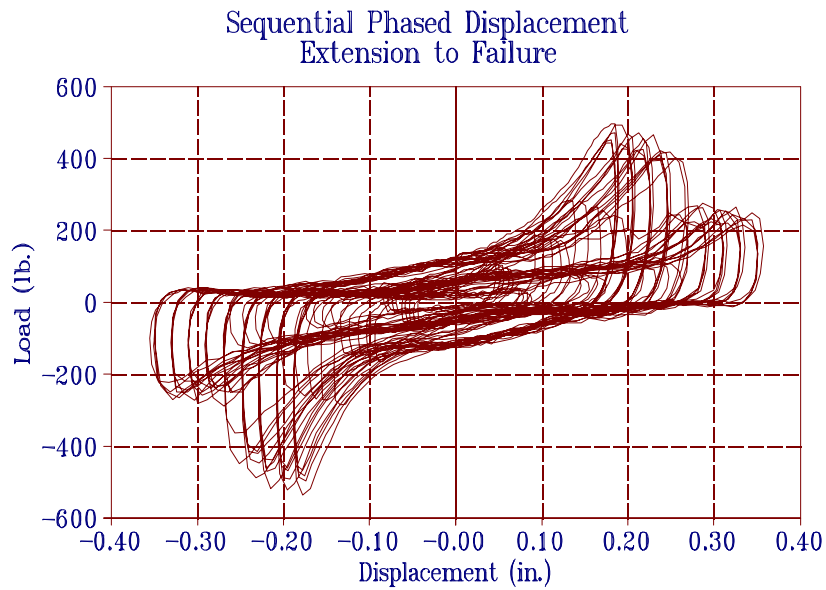


Figure 8: Typical response of a nailed connection subjected to the SPD test (second 9 phases).

Table 3: Averages and coefficients of variation (%) for moisture content and specific gravity (oven dry basis) of nailed connections subjected to sequential phased displacement tests.

2x4/2x4 16d nail	Parallel-to-grain			Perpendicular-to-grain		
	Sequential Phased Displacement			Sequential Phased Displacement		
	Stationary Member	Moving Member	Combined	Stationary Member	Moving Member	Combined
MC	14.8 (6.3)	15.2 (3.1)	15.0 (5.0)	14.2 (4.5)	15.1 (1.4)	14.7 (4.3)
SG	0.55 (9.3)	0.60 (8.5)	0.57 (9.5)	0.58 (13.2)	0.54 (10.6)	0.56 (12.4)
15/32" Plywood 10d nail	Parallel-to-grain			Perpendicular-to-grain		
	Sequential Phased Displacement			Sequential Phased Displacement		
	Stationary Member	Moving Member	Combined	Stationary Member	Moving Member	Combined
MC	14.9 (4.6)			14.9 (2.1)		
SG	0.56 (9.7)			0.56 (15.7)		
18 gage 10d nail	Parallel-to-grain			Perpendicular-to-grain		
	Sequential Phased Displacement			Sequential Phased Displacement		
	Stationary Member	Moving Member	Combined	Stationary Member	Moving Member	Combined
MC	13.9 (3.0)			14.5 (2.6)		
SG	0.60 (5.0)			0.59 (7.1)		

Table 4 presents average values and coefficients of variation for properties determined for an equivalent energy elastic-plastic system, as shown in Figure 6, for both parallel- and perpendicular-to-grain orientations. Points used to construct the curve were minimum and maximum loads and corresponding displacements for the stabilized hysteresis at each phase. Curves for the negative or compression side of the hysteresis were constructed, and absolute values of the parameters for tension and compression were averaged for each specimen.

The values shown in Table 4 are similar to those found in load-controlled cyclic testing (Dolan et al., 1994a). Yield load for steel plate-to-2x4 connections was the largest of the nail connections, followed by 2x4-to-2x4 and plywood-to-2x4 connections in that order. Initial stiffness, called elastic stiffness in this report, and capacity also followed this ranking, as they did in monotonic and load-controlled cyclic tests. However, the reader is reminded that property definitions for this test are different from those used for monotonic and load-controlled cyclic tests. Complete definitions of

Table 4: Average property values and coefficients of variation for the equivalent energy elastic-

plastic system determined in the sequential phased displacement testing.

	2x4/2x4 16d Common Nail		15/32" Plywood/2x4 10d Common Nail		18 Gage Steel/2x4 10d Common Nail	
	Mean	COV	Mean	COV	Mean	COV
Parallel-to-grain						
Yield Load (lbs.)	339	12.4	274	11.3	492	10.1
Yield Displacement (in.)	0.017	29.2	0.024	29.2	0.020	28.3
Elastic Stiffness (lbs./in.)	21785	27.0	13066	48.9	25578	25.1
Max. Displacement (in.)	0.255	9.3	0.220	10.4	0.155	6.6
Load at Max. Displacement (lbs.)	318	16.6	278	12.6	481	11.7
Stabilized Capacity (lbs.)	377	13.9	313	12.6	544	9.8
Displacement at stabilized Cap.	0.149	30.7	0.156	15.5	0.096	11.7
Yield Load/Stabilized Capacity	0.90	3.2	0.88	3.1	0.91	1.8
Absolute Capacity (lbs.)	473	15.0	389	10.3	661	7.3
Ductility Ratio	16.3	23.3	10.2	40.4	8.1	27.0
Perpendicular-to-grain						
Yield Load (lbs.)	350	13.1	281	11.2	500	20.5
Yield Displacement (in.)	0.022	25.5	0.023	24.2	0.019	25.4
Elastic Stiffness (lbs./in.)	17733	23.6	12669	24.3	27248	30.2
Max. Displacement (in.)	0.252	12.5	0.178	11.5	0.128	8.9
Load at Max. Displacement (lbs.)	364	16.8	285	15.3	500	21.5
Stabilized Capacity (lbs.)	402	14.0	309	11.5	544	20.3
Displacement at Capacity (in.)	0.153	36.8	0.132	25.3	0.088	25.1
Yield Load/Stabilized Capacity	0.91	3.0	0.91	1.9	0.92	2.4
Absolute Capacity (lbs.)	475	14.3	393	10.0	688	16.7
Ductility Ratio	12.3	24.0	8.1	27.2	7.0	23.1

properties for monotonic and load-controlled cyclic response can be found in Dolan et. al.. (1994a).

Yield loads determined by the SPD procedure were higher than those obtained by the five-percent of dowel diameter offset method used for monotonic tests. Yield displacements were correspondingly higher as well. Yield loads obtained for the three nailed connection types were typically about 90% of the maximum load for the stabilized envelope curve. Note that yield load was defined by the SPD procedure as having to be greater than 80% of maximum load for the stabilized system.

Average maximum displacement values shown in Table 4 are derived from curves developed according to the SPD procedure. Maximum displacement is defined as the point where a sudden significant drop in load-carrying capacity between two successive stabilized hysteresees was observed. Corresponding average load at this displacement is also shown in Table 4 for information purposes only.

Average stabilized capacities shown in Table 4 were determined directly from the highest load experienced by the stabilized hysteresses, and correspond to the point labeled F_{MAX} in Figure 6. Table 5 shows a comparison between the stabilized capacities and absolute capacities from the SPD tests with the monotonic capacities for the match samples reported by Dolan et. al. (1994A). With the exception of steel plate-to-2x4 connections in the parallel-to-grain orientation, stabilized capacities were lower than capacities determined in monotonic tests (Dolan et al., 1994a). Lower stabilized capacities determined from the SPD procedure can be attributed to damage associated with cyclic loading at a given displacement. For all nailed connections, the ratio of stabilized capacity to yield load remains fairly constant at about 0.90.

Table 5: Comparison of Absolute Capacity and Stabilized Capacity from SPD tests with Monotonic Capacity Obtained from Matched Samples of Nailed Connections.

	2x4/2x4 16d Common Nail		15/32" Plywood/2x4 10d Common Nail		18 Gage Steel/2x4 10d Common Nail	
	Parallel-to-grain	Perpendicular-to-grain	Parallel-to-grain	Perpendicular-to-grain	Parallel-to-grain	Perpendicular-to-grain
Monotonic Capacity	410 lbs.	455 lbs.	369 lbs	391 lbs.	527 lbs.	614 lbs.
Absolute SPD Capacity	473 lbs.	475 lbs.	389 lbs.	393 lbs.	661 lbs.	688 lbs.
Stabilized SPD Capacity	377 lbs	402 lbs.	313 lbs.	309 lbs.	544 lbs.	500 lbs.
Absolute / Monotonic Cap.	1.15	1.04	1.05	1.01	1.25	1.12
Stabilized / Monotonic Cap.	.92	.88	.85	.79	1.03	.81
Stabilized / Absolute Cap.	.80	.85	.80	.79	.82	.73

The absolute capacities shown in Table 4 represent the average maximum load measured during the tests of the connections. As shown in Table 5, the absolute SPD capacity is always higher than the monotonic capacity. This is due to the load rate effects. Because the SPD test cycles the connection at a rate of 1 Hz and the monotonic tests were run at a 5-10 minute to failure rate, the SPD tests displaced the connection at a significantly higher rate. Wood is known to have a higher strength when subjected to higher rate loading. Therefore, the absolute capacity for the SPD tests being higher than the monotonic capacity is not surprising.

As noted earlier, the stabilized capacity is lower than the monotonic capacity, with the exception of the light-gage steel plate-to-2x4 connection in the parallel-to-grain orientation. The reduction from monotonic capacity to stabilized capacity ranged from 8 to 21 percent, with the steel-to-2x4 parallel-to-grain connection being 3 percent stronger. These are the conversion factors that may be used to convert historic monotonic test results to an estimate of stabilized cyclic response for nail

connections.

Finally, Table 5 shows the ratio of stabilized capacity to absolute capacity for the SPD tests results. The reduction in resistance during the SPD test ranged from 15 to 28 percent.

Table 6 shows a comparison of the yield load and displacement, maximum displacement, and ductilities for the SPD and monotonic tests. Not only were the values effected by the difference in yield definition, but apparent ductilities determined in the SPD tests were affected by fatigue of fasteners. These differences, shown in Table 6, are a direct result of the difference in the 5 percent fastener diameter offset definition of yield used for monotonic tests and the equivalent energy definition used for the SPD tests. Yield loads determined by the SPD procedure were slightly higher than those determined in monotonic tests. Maximum displacements determined in the SPD procedure were significantly lower than displacements at capacity for monotonic tests. Differences in yield displacement are due to differences in definition, while differences in maximum displacement are due to fastener fatigue. By the time fasteners failed in fatigue, the connections had been subjected to a minimum of 70 complete cycles, far more than expected during multiple seismic or high wind events.

Table 6: Comparison of Stabilized and Monotonic Response for Yield Load, Yield Displacement, and Maximum Displacement for Nailed Connections.

	2x4/2x4 16d Common Nail		15/32" Plywood/2x4 10d Common Nail		18 Gage Steel/2x4 10d Common Nail	
	Monotonic	SPD	Monotonic	SPD	Monotonic	SPD
Parallel-to-Grain						
Yield Load (lbs)	241	339	160	274	305	492
Yield Displ. (in)	0.021	0.017	0.019	0.024	0.015	0.020
Max. Displ. (in)	0.617	0.255	0.698	0.220	0.206	0.155
Ductility	30.1	16.3	38.2	10.2	14.3	8.1
Perpendicular-to-Grain						
Yield Load (lbs)	213	350	161	281	309	500
Yield Displ. (in)	0.020	0.022	0.020	0.023	0.014	0.019
Max. Displ. (in)	0.415	0.252	0.428	0.178	0.231	0.128
Ductility	21.4	12.3	22.1	8.1	16.4	7.0

Although statistical differences were found between the two grain orientations for some of the

parameters, practical differences are negligible. Therefore, nailed connections can be considered to be independent of grain orientation.

Table 7 presents apparent and true factors-of-safety for nailed connections. The two factors shown were determined by dividing either the absolute or stabilized SPD capacity by the 1991 NDS seismic and wind design values. True factors-of-safety, shown in Table 7, which are based on the absolute highest load recorded during each connection test, are higher than the values reported by Dolan, et. al.. (1994A) for monotonic tests of matched samples. This is due to the higher loading rate used for the SPD tests.

Table 7: Apparent factors-of-safety resulting from stabilized capacities for nailed connections when compared to seismic and wind design values.

	2x4/2x4 16d Common Nail NDS Design: 154 lbs. NDS Yield: 339 lbs. Yield Mode: IV	15/32" Plywood/2x4 10d Common Nail NDS Design: 101 lbs. NDS Yield: 222 lbs. Yield Mode: III _s	18 Gage Steel/2x4 10d Common Nail NDS Design: 121 lbs. NDS Yield: 266 lbs. Yield Mode: III _s
Parallel-to-grain			
Average Capacity	377 lbs.	313 lbs.	544 lbs.
Absolute Capacity	473 lbs.	389 lbs.	661 lbs.
Wind/Seismic Design Value	246 lbs.	162 lbs.	194 lbs.
Apparent Factor-of-Safety (Based on Stabilized Capacity)	1.5	1.9	2.8
True Factor-of-Safety (Based on Absolute Capacity)	1.9	2.4	3.4
Perpendicular-to-grain			
Average Capacity	402 lbs.	309 lbs.	544 lbs.
1991 NDS Design Value	154 lbs.	101 lbs.	121 lbs.
Wind/Seismic Design Value	246 lbs.	162 lbs.	194 lbs.
Apparent Factor-of-Safety (Based on Stabilized Capacity)	1.6	1.9	2.8
True Factor-of-Safety (Based on Absolute Capacity)	1.9	2.4	3.5

Apparent factors-of-safety shown in Table 7 are based on the stabilized response, and are slightly lower than those determined from monotonic and load-controlled cyclic tests of matched samples

(Dolan et al, 1994a). Stabilized capacities tend to be lower than those determined from monotonic tests due to the reduction in load required to reach a given displacement with increased number of cycles. However, the definition of a stabilized system required that the reduction in load resistance be no more than 5% between successive cycles at a given displacement. Therefore, the apparent factors-of-safety for stabilized response, shown in Table 7, provide conservative estimates of performance of connections subjected to repeated seismic or wind loading. Apparent factors-of-safety for two different grain orientations were not statistically different, which reinforces the conclusion that nailed connection properties are independent of grain orientation.

Bolted Connection Results

The response of wood connections with larger than 0.25 inch diameter dowels is sensitive to grain orientation. Consequently, test results for bolted connections are divided into parallel- and perpendicular-to-grain classifications for presentation purposes. Table 8 presents average values and coefficients of variation for moisture content and specific gravity of matched samples of bolted connections tested according to the SPD procedure. Specimens for these tests were cut in the vicinity of the bolt immediately after the connections were tested. With the exception of 2x4-to-2x4 bolted connections, specific gravities were slightly lower than the 0.55 used for southern pine in the 1991 NDS.

The test procedure for bolts differed from that used for nailed connections, in that the displacement of the first phase was not defined as the average displacement at nominal design load as determined from monotonic tests. If the initial phase displacement had been defined in this manner, too few phases would have been used in the test, and cyclic connection properties would not have been determined accurately. Therefore, the initial phase displacement was determined by the maximum displacement that connections could be subjected to in fourteen phases. This resulted in an initial phase displacement of approximately ± 0.045 inches. The incremental increase in displacement between successive phases was approximately ± 0.09 inches (2 times the initial phase displacement.)

Since bolted connections had a 0.063 inch oversized bolt hole in each member, a total movement of approximately 0.125 inch was required before significant loading would occur. Therefore, the load at the initial phase displacement was essentially zero and is indicated by shaded regions for phase 1 in Tables A4 - A9, presenting cyclic properties. Unlike with nailed connections, all bolted connections were subjected to a common displacement pattern and magnitudes. Therefore, direct comparison of results at each phase, or displacement level, is possible.

Discussion of cyclic properties of bolted connections is included in the Appendix, following the cyclic properties for nailed connections. Tables A4 - A6 present the hysteretic damping, cyclic stiffness, and equivalent viscous damping for bolted connections loaded parallel-to-grain, while Tables A7 - A9 present similar information for bolted connections loaded perpendicular-to-grain.

Table 8: Averages and coefficients of variation (%) for moisture content and specific gravity of bolted connections tested using sequential phased displacement procedures.

2x4/2x4 3/4" bolt	Parallel-to-grain			Perpendicular-to-grain		
	Sequential Phased Displacement			Sequential Phased Displacement		
	Stationary Member	Moving Member	Combined	Stationary Member	Moving Member	Combined
MC	13.6 (7.3)	13.2 (9.5)	13.4 (8.5)	12.5 (7.2)	14.3 (3.3)	13.4 (8.6)
SG	0.55 (14.0)	0.61 (10.0)	0.58 (12.6)	0.50 (2.7)	0.59 (14.8)	0.54 (14.4)
1/4" steel/4x4 1/2" bolt	Parallel-to-grain			Perpendicular-to-grain		
	Sequential Phased Displacement			Sequential Phased Displacement		
	Stationary Member	Moving Member	Combined	Stationary Member	Moving Member	Combined
MC	13.3 (3.7)			15.1 (3.9)		
SG	0.53 (17.9)			0.49 (5.1)		
4x4/4x4 3/4" bolt	Parallel-to-grain			Perpendicular-to-grain		
	Sequential Phased Displacement			Sequential Phased Displacement		
	Stationary Member	Moving Member	Combined	Stationary Member	Moving Member	Combined
MC	15.9 (3.0)	15.4 (4.0)	15.6 (3.8)	16.1 (2.2)	16.4 (2.5)	16.3 (2.5)
SG	0.49 (8.8)	0.51 (12.1)	0.50 (10.9)	0.46 (6.0)	0.50 (6.1)	0.48 (7.4)

Equivalent Energy Elastic-Plastic Properties - Bolted Connections

Table 9 presents average values and coefficients of variation for properties of bolted connections loaded parallel-to-grain. These values were determined from equivalent energy, elastic-plastic load-deflection curves, as shown in Figure 6, along with the absolute capacity for the connection. Table 10 presents the same information, only for bolted connections loaded perpendicular-to-grain. Just as for nailed connections, envelope load-displacement curves were derived from stabilized hystereses obtained from the SPD test. Values for each connection type represent average values from absolute values of properties for tension and compression. Effects of oversized bolt holes were removed from displacement calculations by shifting the origin an amount equal to the oversize so that the origin was at the beginning of loading on the load-displacement curve.

Direct comparisons of these results with those derived from monotonic tests are not completely valid due to the differences in property definitions. However, useful observations can be made. Table 11 shows a comparison of the absolute and stabilized SPD capacities with the monotonic capacities

Table 9: Averages and coefficients of variation for properties, and apparent and true factors-of-safety developed from stabilized hysteresses in the sequential phased displacement tests for parallel-to-grain orientation.

Parallel-to-grain	2x4/2x4 (2x8) 3/4" Bolt		1/4" Steel/4x4 (4x6) 1/2" Bolt		4x4/4x4 (4x8) 3/4" Bolt	
	Mean	COV	Mean	COV	Mean	COV
Yield Load	3742	10.8	3685	16.6	4939	12.1
Yield Displacement (in.)	0.203	29.1	0.134	17.8	0.200	17.0
Elastic Stiffness (lbs./in.)	19553	24.1	28451	27.4	25223	16.6
Max. Displacement (in.)	0.463	22.2	0.405	28.9	0.756	26.7
Load at Max. displacement. (lbs.)	3823	14.1	3804	15.0	4961	16.1
Stabilized Capacity (lbs.)	4063	11.3	3979	16.4	5577	12.5
Displacement. at Stabilized Capacity (in.)	0.401	22.3	0.330	26.9	0.556	23.9
Yield Load/Max. Load	0.92	2.4	0.93	1.9	0.89	4.7
Ductility Ratio	2.4	21.4	3.1	30.5	3.8	27.8
Absolute Capacity (lbs.)	5389	10.6	5406	7.0	6892	10.9
Yield Mode	II		III _s		IV	
1991 NDS Yield Load	2880 lbs.		2496 lbs.		5408 lbs.	
1991 NDS Nominal Design Value	800 lbs.		780 lbs.		1690 lbs.	
Wind/Seismic Design Value	1280 lbs.		1248 lbs.		2704 lbs.	
Apparent Factor-of-Safety (Based on Stabilized Capacity)	3.2		3.2		2.1	
True Factor-of-Safety (Based on Absolute Capacity)	4.2		4.3		2.5	

reported by Dolan, et. al. (1994A), while Table 12 shows comparisons between the yield load and associated displacement, maximum displacement, and ductility for the same two load conditions.

Average stabilized capacity for bolted connections was lower than monotonic capacity found for similar connections (Dolan, et. al. 1994A). As shown in Table 11, the stabilized capacity is between 3 and 26 percent lower than the monotonic capacity. These reduction factors may be used to convert historical monotonic test results to estimates of stabilized cyclic response. This reduced resistance to load is expected since the stabilized load-displacement curve would be lower than the initial cycle loading curve. In parallel-to-grain orientations, 4x4-to-4x4 connections had the highest average stabilized capacity, as was observed in monotonic tests. In perpendicular-to-grain orientations, steel plate-to-4x6 connections had the highest average stabilized capacity. Again, this is a similar result to that found in monotonic tests. Several steel plate-to-4x6 connections had fatigue failures of the 1/2" bolt when loaded in the perpendicular-to-grain direction.

Table 10: Averages and coefficients of variation for properties, and apparent factors-of-safety developed from stabilized hysteresees in the sequential phased displacement tests for perpendicular-to-grain orientation.

	2x4/2x4 (2x8) 3/4" Bolt		1/4" Steel/4x4 (4x6) 1/2" Bolt		4x4/4x4 (4x8) 3/4" Bolt	
	Mean	COV	Mean	COV	Mean	COV
Perpendicular-to-grain						
Yield Load	3613	11.7	4662	9.0	4299	10.8
Yield Displacement (in.)	0.262	23.5	0.262	15.3	0.242	20.4
Elastic Stiffness (lbs./in.)	14259	17.4	18222	18.1	18394	20.8
Max. Displacement (in.)	0.825	17.5	0.934	7.9	0.910	16.7
Load at Max. Displacement. (lbs.)	4269	11.9	4346	10.5	4310	17.7
Stabilized Capacity (lbs.)	4341	10.8	5168	10.5	4846	11.0
Displacement. at Capacity (in.)	0.790	20.3	0.658	9.6	0.643	27.5
Yield Load/Max. Load	0.83	5.6	0.90	2.7	0.89	4.5
Ductility Ratio	3.3	24.8	3.7	18.6	3.8	18.7
Absolute Capacity (lbs.)	5328	8.6	5168	15.8	5948	8.3
Yield Mode	II		III _S		III _M	
1991 NDS Yield Load	1656 lbs.		1600 lbs.		3072 lbs	
1991 NDS Nominal Design Value	460 lbs.		500 lbs.		960 lbs.	
Wind/Seismic Design Value	736 lbs.		800 lbs.		1536 lbs.	
Apparent Factor-of-Safety (Based on Stabilized Capacity)	5.9		6.5		3.2	
True Factor-of-Safety (Based on Absolute Capacity)	7.2		6.5		3.9	

Average absolute SPD capacity was generally higher than the monotonic capacity. The absolute SPD capacity was from 1 to 19 percent higher than the monotonic values with the exception of the steel plate-to-4x6 connections loaded in the perpendicular-to-grain direction. The steel-to-4x6 connection's 21 percent lower absolute capacity for the SPD tests may be due to the general variation of wood as a material. There were no other obvious reason for the low values.

The reduction in resistance associated with cyclic loading is apparent when the stabilized and absolute capacities are compared. The reduction in load required to displace the connections to a given displacement multiple times, until a stabilized response is achieved, ranges from 6 to 26 percent.

Average connection yield loads and corresponding displacements, shown in Table 12 were higher for the equivalent elastic-plastic system than for monotonic tests. Just as for nailed connections, Table 9 shows that the yield load to stabilized capacity ratios for bolted connections were very consistent, and averaged approximately 0.90. Ductility ratios for bolted connections were lower than for nailed connections due to different displacement levels for cycling and to the larger yield

Table 11: Comparison of Absolute Capacity and Stabilized Capacity from SPD tests with Monotonic Capacity Obtained from Matched Samples of Bolted Connections Loaded Parallel-to-Grain.

	2x4/2x4 (2x8)		1/4" Steel/4x4 (4x6)		4x4/4x4 (4x8)	
	3/4" Bolt		1/2" Bolt		3/4" Bolt	
	Parallel-to-grain	Perpendicular-to-grain	Parallel-to-grain	Perpendicular-to-grain	Parallel-to-grain	Perpendicular-to-grain
Monotonic Capacity	5220 lbs.	5140 lbs.	5360 lbs	6510 lbs.	6280 lbs.	5000 lbs.
Absolute SPD Capacity	5389 lbs.	5328 lbs.	5406 lbs.	5168 lbs.	6892 lbs.	5948 lbs.
Stabilized SPD Capacity	4063 lbs	4341 lbs.	3979 lbs.	4876 lbs.	5577 lbs.	4846 lbs.
Absolute / Monotonic Cap.	1.03	1.03	1.01	0.79	1.10	1.19
Stabilized / Monotonic Cap.	0.78	0.84	0.74	0.74	0.89	0.97
Stabilized / Absolute Cap.	0.75	0.81	0.74	0.94	0.81	0.81

displacements associated with bolted connections.

Apparent and true factors-of-safety were determined for each connection, for both orientations. Apparent factors-of-safety were determined by dividing stabilized capacity by the 1991 NDS seismic and wind design values. As shown in Table 9, apparent factors-of-safety for loads oriented parallel-to-grain, ranged from 2.1, for a 4x4-to-4x4 connections with a 3/4" bolts, to 3.2 for the other two configurations. These values are lower than reported for monotonic and load-controlled cyclic tests conducted on matched samples. Again, the reason for this is that SPD values are calculated from the stabilized connection response rather than the virgin load-displacement curve. However, the minimum value of 2.1 is still an acceptable factor-of-safety when compared to other materials.

True factors-of-safety were determined by dividing the absolute capacity for the connection by the 1991 NDS seismic and wind design values. True factors-of-safety for bolted connections in the parallel-to-grain direction were about equal to the monotonic values. The perpendicular-to-grain true factors-of-safety for SPD testing were slightly higher than the monotonic values for the two wood-to-wood connections. The steel-to-wood bolted connection had a significantly lower value for the factor-of-safety for SPD loading perpendicular-to-grain than for the monotonic tests. This is due to fatigue of the bolt near the wood side of the steel plate.

Table 12 shows a comparison of the yield and ductility values for monotonic and SPD tests. In all cases, the yield load and displacement were higher for the SPD test than for the monotonic test. This is a direct result of the difference in definition used for yield in the two test protocols. Table 12: Comparison of Stabilized and Monotonic Response for Yield Load, Yield Displacement, and

Maximum Displacement for bolted connections.

	2x4/2x4 (2x8)		1/4" Steel/4x4 (4x6)		4x4/4x4 (4x8)	
	3/4" Bolt		1/2" Bolt		3/4" Bolt	
	Monotonic	SPD	Monotonic	SPD	Monotonic	SPD
Parallel-to-Grain						
Yield Load (lbs)	2810	3742	2930	3685	3470	4939
Yield Displ. (in)	0.112	0.203	0.102	0.134	0.144	0.200
Max. Displ. (in)	0.735	0.463	0.726	0.405	0.893	0.756
Ductility	6.5	2.4	7.5	3.1	6.3	3.8
Perpendicular-to-Grain						
Yield Load (lbs)	2550	3613	2400	4662	2510	4299
Yield Displ. (in)	0.168	0.262	0.146	0.262	0.172	0.242
Max. Displ. (in)	0.910	0.825	.0921	0.934	.0885	0.910
Ductility	5.5	3.3	6.5	3.7	5.4	3.8

Different yield definitions also affected the value for ductility shown in Table 12. Since the yield displacement is significantly higher in the SPD test, the ductility becomes smaller in this test. This is due to the yield displacement being in the denominator of the ratio used to define ductility.

CONCLUSIONS

Results of displacement-controlled cyclic tests of nailed and bolted connections have been presented. The tests were conducted according to a new ASTM standard test procedure that is currently being developed by ASTM Subcommittee E06.13. The standard is based on the Sequential Phased Displacement (SPD) procedure used by the Joint Technical Coordinating Committee on Masonry Research (TCCMAR) for the United States-Japan Coordinated Earthquake Research Program. This procedure is used by TCCMAR to serve as a uniform basis for comparing components not subjected to real-time earthquake loading during testing.

Results from SPD tests, when considered with results from monotonic and load-controlled cyclic tests, show that levels of safety in connections to resist seismic and wind loads when the load duration factor of 1.6 is used in design are at least as high, or higher, than safety levels associated with connections in other materials. If stabilized capacity is a criterion, then nailed connections resulted in factors-of-safety sufficient to ensure acceptable performance for connections subjected to very high

numbers of cycles. Capacities were based on stabilized response, and were therefore lower than the actual maximum load resisted during the complete test. Yet, the connections retained a significant level of reserve capacity and continued to dissipate significant amounts of energy after yielding. True factors-of-safety for nail connections were higher for the SPD tests than they were for monotonic tests.

Bolted 2x4-to-2x4 connection SPD factors-of-safety were approximately equal to those observed for monotonic tests. Bolted 4x4-to-4x4 connection SPD factors-of-safety were 10 to 19 percent higher than the monotonic values. The steel-to-wood bolted connection had an approximately equal factor-of-safety for loading in the parallel-to-grain direction, while it had a 21 percent lower value in the perpendicular-to-grain direction.

While ductilities determined with the new ASTM procedure are lower than those determined in monotonic and load-controlled cyclic tests, they remained at respectable levels of 7.0 - 16.3 for nailed connections and 2.4 - 3.8 for bolted connections. These ductilities were retained by the connections after more than 50 load cycles to relatively large displacement levels.

Fatigue affected all nailed connections and the steel plate-to-4x6 bolted connection, resulting in failures of the fasteners. All other bolted connections failed due to splitting or crushing of the wood. However, even connections that failed due to fatigue resisted over 50 load cycles to large displacements, which is far more cycles than would be expected in an earthquake or hurricane. Up to fatigue failure, connections continued to dissipate significant amounts of energy, which improves the associated structural response.

A few of the positive indicators of nailed and bolted connection performance are:

- 1) Test connections were subjected to more than 50 cycles of extreme loading before failure occurred. This is a significantly higher number of loading cycles at large displacements than would be experienced in an earthquake.
- 2) Test connections continued to dissipate large amounts of energy at high cycle numbers before failure occurred.
- 3) High ductility observed in monotonic and load-controlled cyclic tests (2.3 - 4.6 for parallel-to-grain orientation, and 3.3 - 8.1 for the perpendicular-to-grain orientation) indicates that bolted connections can sustain significant displacements and continue to resist the applied loads.

Additional connection properties are presented in the appendix to completely describe the SPD cyclic response of nailed and bolted connections. Results presented quantify several cyclic properties that were determined from the stabilized hysteretic response of connections. These properties include hysteretic damping, cyclic stiffness, and equivalent viscous damping. Values of these properties illustrate the ability of wood connections to dissipate significant quantities of energy during cyclic or dynamic loadings like as those expected during natural hazard events such as earthquakes and hurricanes.

Results provided by SPD tests are an improvement when compared to monotonic tests. The equivalent energy, elastic-plastic system can be used to make comparisons of cyclic performance of connections manufactured from different materials on a more equivalent basis than previously available. SPD test results also provide a conservative estimate of strength and stiffness for connections subjected to multiple cyclic loads such as seismic events. Monotonic tests, on the other hand, provide an optimistic estimate of connection performance in such conditions.

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APPENDIX

Cyclic Response Parameters for Nailed Connections

Tables A1 - A3 present cyclic properties of 2x4-to-2x4, 15/32-plywood-to-2x4, and 18 gage steel plate-to-2x4 connections, respectively. The same data are illustrated in Figures A1-A9. (Figures A1-A9 illustrate the magnitude of a particular cyclic property with respect to phase number. However, phase number is directly related to the magnitude of displacement. Therefore, the figures can effectively be viewed as relations between the cyclic property and displacement.) Each table is divided between the parallel- and perpendicular-to-grain orientations, and show average values and coefficients of variation determined for each property at the end of each phase of the SPD test. Minimum and maximum values of each parameter are highlighted by brackets. The right hand column of each load orientation in the tables provides the number of specimens that were included in the calculations; in other words, the number of specimens that had not failed prior to reaching the end of the noted test phase. All specimens, with the exception of one steel plate-to-2x4 specimen in parallel-to-grain orientation and one 2x4-to-2x4 specimen in perpendicular-to-grain orientation, failed before the end of the second test of nine phases (18 phases total).

As shown in each table and Figures A1, A4, and A7, hysteretic damping increased with the increase in displacement associated with each successive phase. The trends in hysteretic damping are intuitive since as displacements and load increase, the area enclosed by the hysteresis increased.

An additional influence on the magnitude of hysteretic damping may have been yield mode. The predicted yield mode for 2x4-to-2x4 connections is Mode IV, which involves two plastic hinges in the fastener. Plywood-to-2x4 and steel plate-to-2x4 connections both were expected to yield in Mode III_s, which involves one plastic hinge. The presence of two plastic hinges in the nail for 2x4-to-2x4 connections contributed to an observed higher energy dissipation than with connections yielding in Mode III_s. In fact, 2x4-to-2x4 connections had the highest hysteretic damping for the three connection types tested.

All nailed connections tested in this study experienced fatigue failure of the fastener during the SPD tests. Examination of the specimens after failure indicated that yield modes were the same as the predicted yield mode for all connections tested. That is, 2x4-to-2x4 connections yielded at two points along the nail as a Mode IV yield connection should, whereas the other two connection geometries were predicted to be Mode III_s yield and they did yield at a single plastic hinge point. All nailed connections failed due to fatigue of the metal fastener.

Cyclic stiffness, as illustrated in Figures A2, A5, and A8, decreased with increases in displacement for all nailed connections. As noted with companion tests using monotonic and load-controlled cyclic conditions (Dolan et al., 1994a), cyclic stiffness was highest for steel plate-to-2x4 connections, followed by 2x4-to-2x4 and plywood-to-2x4 connections. However, displacements at each phase number are not directly comparable between connection types since nominal design displacements (FME) are different for the three connection types.

Figures A3, A6, and A9 illustrate the magnitude of equivalent viscous damping with respect to Phase Number. Trends observed for equivalent viscous damping were inconsistent, and not intuitive. As Equation 1 indicates that, equivalent viscous damping can remain constant only if both hysteretic damping and potential energy increase. Therefore, in Figure 4, the areas enclosed by the triangles

must increase as the area enclosed in the hysteresis loop increases. This is logical since both displacement and load are increasing. Equivalent viscous damping values from SPD testing were somewhat lower than those reported for load-controlled cyclic testing (Dolan et al., 1994a). This can be explained by the effect of pinching of the hysteresis with larger displacements and repeated cycles to the same displacement level. With load-controlled testing, the hysteresis was observed to not pinch as much and resulted in higher calculated damping ratios. This phenomena is due to the load resistance decay effects under displacement control where the hysteresis becomes narrower near the maximum displacement regions. Under load control, the loops remain fairly broad, but the displacement increases between successive cycles to compensate.

Table A1: Cyclic parameters for the stabilized hysteresis at each test phase for 2x4-to-2x4 lumber connections with 16d common nails subjected to sequential phased displacement testing.

Phase No.	Parallel-to-Grain							Perpendicular-to-Grain						
	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>
	Mean	COV	Mean	COV	Mean	COV		Mean	COV	Mean	COV	Mean	COV	
1	[1.01]	30.0	[21139]	20.3	15.8	14.8	15	[1.14]	42.8	[18374]	14.2	16.4	23.2	15
2	2.94	25.3	14951	19.0	[14.5]	12.6	15	3.34	35.6	13341	12.9	15.3	20.4	15
3	9.07	18.3	9120	14.6	14.9	12.7	15	9.76	28.7	8831	11.9	[15.3]	15.9	15
4	18.2	15.4	6409	12.8	17.0	12.8	15	19.1	24.5	6502	11.4	16.9	13.7	15
5	28.7	13.6	4882	12.7	18.8	11.8	15	30.2	21.2	5109	11.8	18.4	12.4	15
6	39.9	12.4	3932	12.8	19.9	10.1	15	41.5	18.0	4165	12.2	19.2	9.9	15
7	50.2	11.5	3254	13.9	20.6	10.2	15	52.0	16.4	3464	12.7	19.7	9.7	15
8	59.6	11.4	2733	14.7	20.8	8.7	15	62.1	14.4	2940	12.8	20.0	9.3	15
9	68.6	11.0	2339	15.5	21.2	9.2	15	71.9	13.5	2519	13.1	20.3	8.5	15
10	76.8	10.5	2026	15.5	21.1	9.4	15	80.8	13.5	2206	13.1	20.1	8.1	15
11	90.9	14.8	1919	16.3	21.4	9.3	15	94.8	12.9	2063	14.3	20.6	8.6	15
12	97.8	13.8	1661	18.1	[21.9]	9.8	15	102.4	13.0	1810	15.8	20.8	9.2	15
13	103.7	13.5	1478	17.8	21.7	9.3	15	110.0	12.9	1621	14.9	20.8	9.3	14
14	111.3	9.2	1376	14.9	21.3	9.3	12	113.6	11.9	1420	14.1	[20.8]	9.1	12
15	115.0	9.6	1239	17.0	21.1	10.0	10	114.8	8.2	1268	14.9	20.3	11.6	7
16	117.3	12.0	[1146]	19.2	20.6	11.0	5	120.6	6.0	1275	12.9	18.0	10.5	3
17	[120.9]	17.8	1249	6.5	18.5	0.8	2	130.9	1.7	1202	14.9	18.3	15.5	2
18							0	131.8		1220		16.0		1
19							0	[134.2]		[1104]		15.7		1

Note: *n* = number of test specimens that had not yet failed during a particular phase; bracketed values are minimums and maximums.

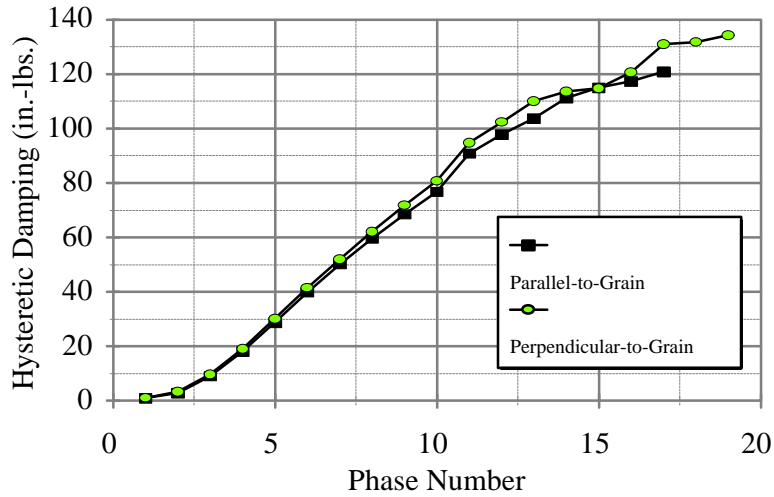


Figure A1: Hysteretic damping versus phase number for SPD stabilized response of 2x4-to-2x4 lumber connections with 16d common nails.

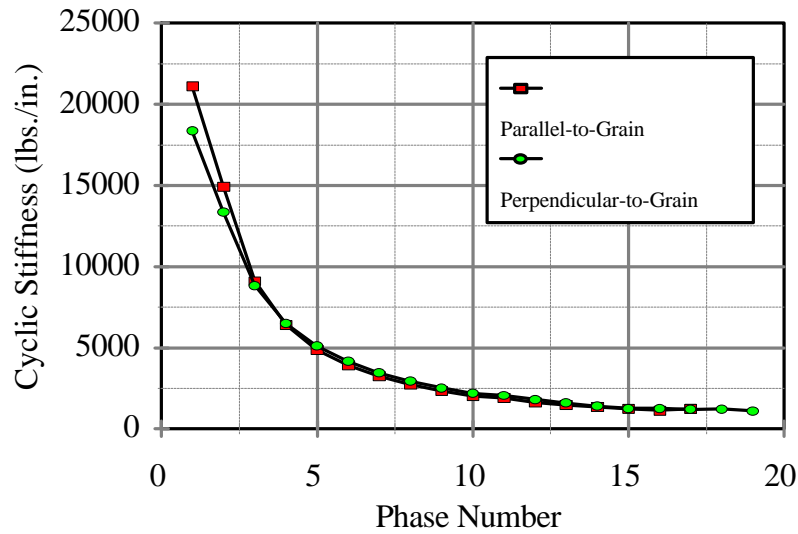


Figure A2: Cyclic stiffness versus phase number for SPD stabilized response of 2x4-to-2x4 lumber connections with 16d common nails.

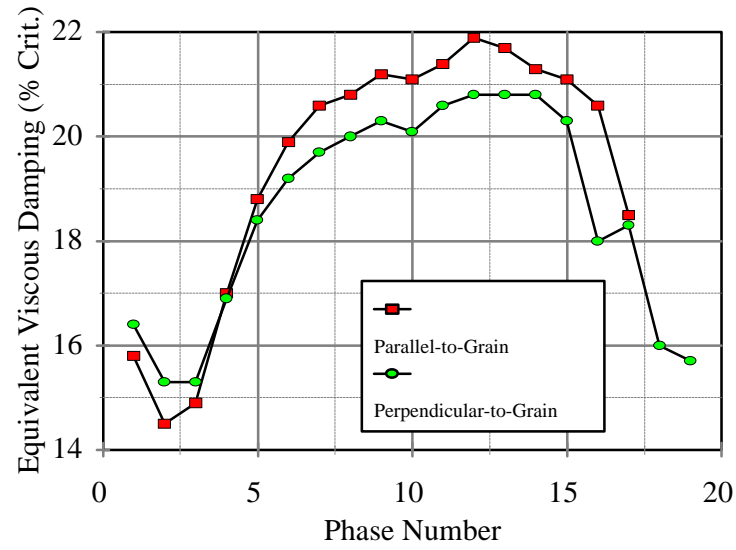


Figure A3: Equivalent viscous damping versus phase number for SPD stabilized response of 2x4-to-2x4 lumber connections with 16d common nails.

Table A2: Cyclic parameters for the stabilized hysteresis at each test phase for 15/32" plywood-to-2x4 lumber connections with 10d common nails subjected to sequential phased displacement testing.

Phase No.	Parallel-to-Grain							Perpendicular-to-Grain						
	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>
	Mean	COV	Mean	COV	Mean	COV		Mean	COV	Mean	COV	Mean	COV	
1	[0.68]	46.0	[14867]	29.3	17.6	30.2	15	[0.91]	24.8	[13593]	14.5	16.3	16.5	15
2	1.94	45.5	10729	23.3	16.6	27.8	15	2.49	22.0	10359	12.6	15.5	15.6	15
3	5.37	40.4	7127	18.1	15.7	25.3	15	6.65	18.1	7120	10.5	[14.9]	11.4	15
4	9.91	35.3	5314	15.3	16.4	21.9	15	12.1	16.1	5413	9.8	15.7	9.2	15
5	15.2	31.0	4216	13.7	17.1	19.2	15	18.4	14.5	4324	8.8	16.6	8.9	15
6	21.0	27.9	3478	12.9	17.8	17.6	15	24.4	14.4	3575	8.4	17.0	8.9	15
7	27.1	25.2	2973	13.4	18.2	16.4	15	30.4	14.0	3046	8.9	17.2	8.5	15
8	33.0	23.4	2603	13.4	[18.3]	15.3	15	36.2	12.4	2634	8.4	17.3	7.5	15
9	38.6	22.6	2310	13.4	18.1	15.0	15	41.4	11.1	2311	8.3	[17.3]	7.0	15
10	43.8	21.2	2071	12.8	17.7	14.6	15	45.6	9.5	2015	8.3	16.9	6.8	15
11	51.8	20.4	2017	13.0	17.5	14.5	15	51.0	9.5	1887	9.6	16.6	4.6	14
12	55.7	19.3	1811	12.5	17.2	14.2	15	53.5	4.8	1631	6.9	16.6	5.2	10
13	59.4	20.2	1652	10.5	16.7	15.0	14	56.2	5.2	1412	8.5	17.0	6.5	9
14	62.1	19.3	1484	10.4	16.4	14.9	14	[57.3]	6.6	[1231]	9.2	16.8	10.2	4
15	65.2	20.9	1319	11.5	16.5	16.2	12							0
16	66.9	23.2	1198	11.9	16.1	20.2	10							0
17	[74.7]	35.7	[1129]	15.2	16.9	30.3	4							0
18	66.4		1158		[13.2]		1							0
19							0							0

Note: *n* = number of test specimens that had not yet failed during a particular phase; bracketed values are minimums and maximums.



Figure A4: Hysteretic damping versus phase number for SPD stabilized response of 15/32" plywood-to-2x4 lumber connections with 10d common nails.

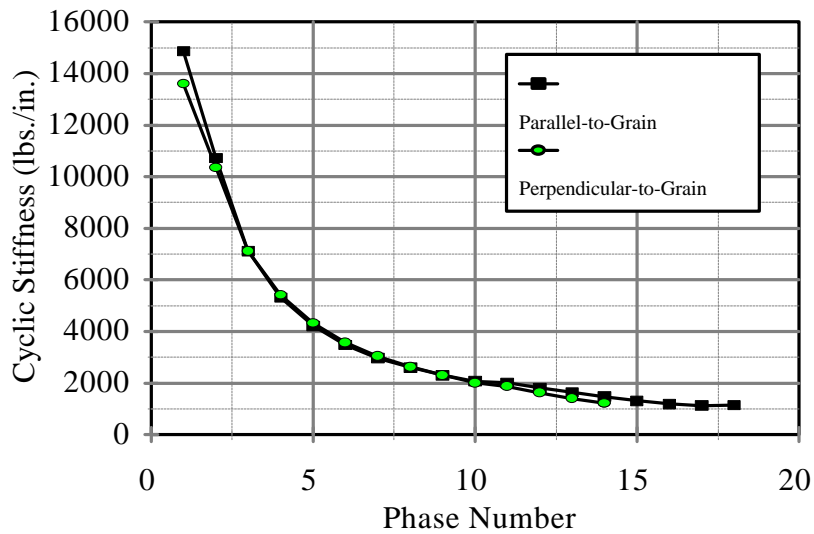


Figure A5: Cyclic stiffness versus phase number for SPD stabilized response of 15/32" plywood-to-2x4 lumber connections with 10d common nails.

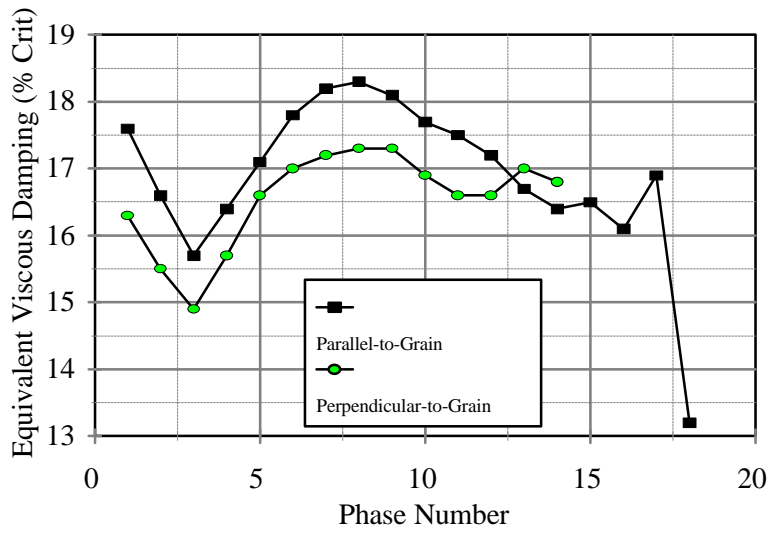


Figure A6: Equivalent viscous damping versus phase number for SPD stabilized response of 15/32" plywood-to-2x4 lumber connections with 10d common nails.

Table A3: Cyclic parameters for the stabilized hysteresis at each test phase for 18 gage steel plate-to-2x4 lumber connections with 10d common nails subjected to sequential phased displacement testing.

Phase No.	Parallel-to-Grain							Perpendicular-to-Grain						
	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>
	Mean	COV	Mean	COV	Mean	COV		Mean	COV	Mean	COV	Mean	COV	
1	[0.72]	28.0	[33206]	20.3	[19.1]	22.5	15	[0.61]	28.9	[34338]	24.4	[17.3]	20.6	15
2	1.88	22.8	24718	14.0	16.0	16.0	15	1.65	27.0	27151	23.1	15.0	16.7	15
3	5.20	20.4	17316	13.5	14.9	13.1	15	4.57	27.4	19531	20.7	13.3	15.9	15
4	9.68	20.2	13761	11.4	14.9	11.7	15	8.46	25.0	15535	19.5	[13.2]	15.2	15
5	14.9	20.4	11472	10.3	15.1	11.5	15	13.2	23.7	12914	18.1	13.5	13.7	15
6	20.5	19.3	9834	10.2	15.2	11.0	15	18.6	22.3	10893	18.4	13.8	12.9	15
7	26.4	17.7	8529	9.5	15.3	9.9	15	23.8	20.7	9307	18.1	14.0	11.1	15
8	32.1	16.9	7579	9.2	15.2	9.6	15	29.1	18.8	8126	18.0	14.0	9.1	15
9	37.3	16.0	6727	8.3	14.9	9.1	15	34.2	18.1	7122	18.2	14.0	8.4	15
10	42.0	15.4	6027	8.0	14.4	8.5	15	38.6	17.1	6272	18.2	13.7	7.7	15
11	47.3	14.1	5601	7.8	14.3	8.0	15	44.0	16.0	5621	17.3	14.0	8.0	15
12	51.2	13.7	4999	7.5	14.1	8.1	15	48.4	15.3	5029	16.9	14.0	8.2	15
13	54.7	13.1	4515	7.5	13.9	8.4	15	53.2	15.8	4830	32.8	14.9	18.6	15
14	58.0	12.9	4088	7.1	13.7	8.4	15	56.1	18.3	3999	19.2	14.2	9.6	12
15	60.8	12.9	3694	7.4	13.6	8.8	15	61.0	18.2	3621	20.1	14.6	9.0	8
16	62.1	13.0	3322	7.4	13.4	9.6	14	[66.5]	22.8	[3568]	22.5	13.9	4.1	4
17	64.6	9.9	3026	9.1	13.4	7.1	10							0
18	64.7	9.8	2742	10.7	[13.2]	9.2	4							0
19	[76.6]		[2691]		14.3		1							0

Note: *n* = number of test specimens that had not yet failed during a particular phase; bracketed values are minimums and maximums.

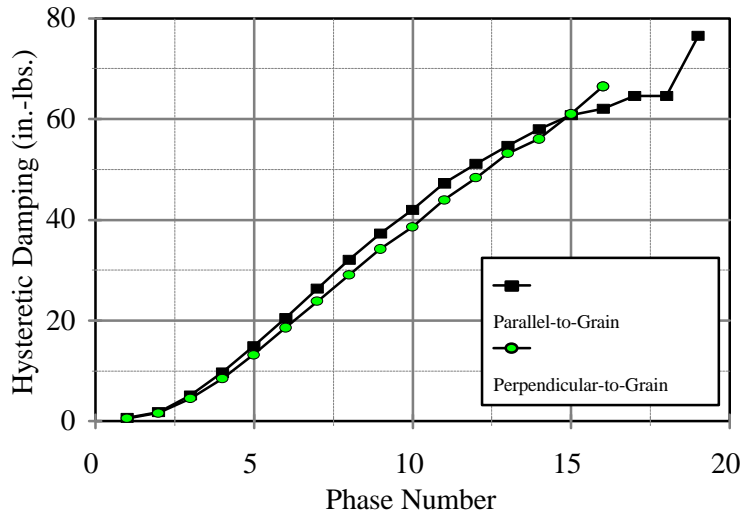


Figure A7: Hysteretic damping versus phase number SPD stabilized response of 18 gage steel plate-to-2x4 lumber connections with 10d common nails.

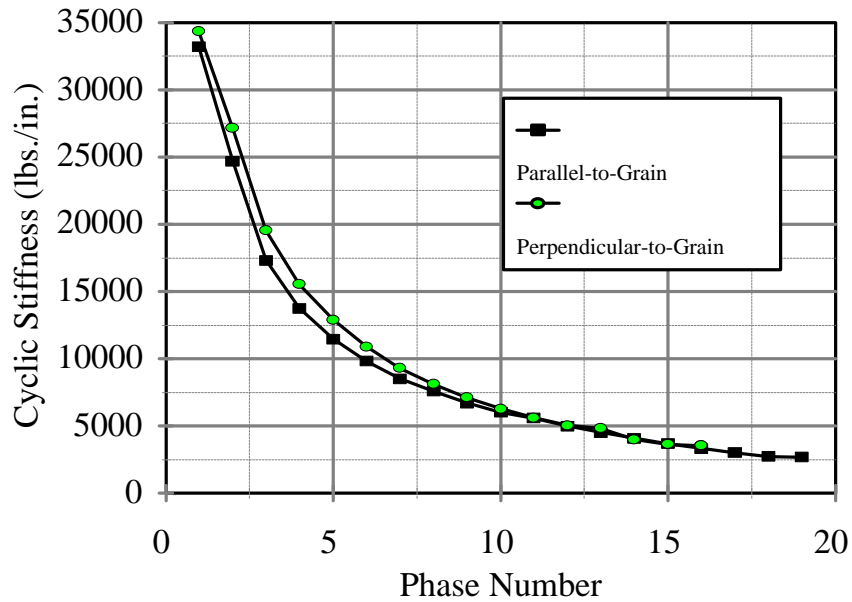


Figure A8: Cyclic stiffness versus phase number SPD stabilized response of 18 gage steel plate-to-2x4 lumber connections with 10d common nails.

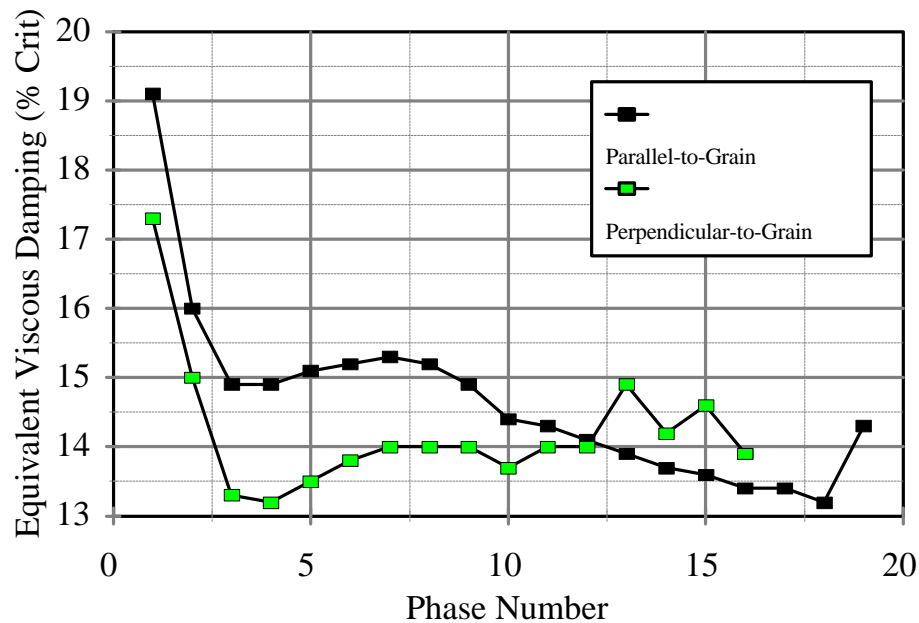


Figure A9: Equivalent viscous damping versus phase number SPD stabilized response of 18 gage steel plate-to-2x4 lumber connections with 10d common nails.

Cyclic Properties - Bolted connections Tested Parallel-to-Grain

Tables A4 - A6 and Figures A10 - A18 present cyclic properties for connections loaded parallel-to-grain. As discussed in the variable definition section of this report, cyclic stiffness and equivalent viscous damping were calculated for two conditions, inclusion and exclusion of the oversized bolt hole effects. These two cases provide estimates of the range of property values for connections constructed according to tolerances provided in the 1991 NDS. While complete exclusion of oversized hole effects is more stringent than allowed by the 1991 NDS (minimum specified is 1/32" oversize), total exclusion was used to provide an extreme possibility that maybe found in field construction. Note that hysteretic damping values were independent of any consideration of the holes. This is because the amount of energy dissipated within the range of displacements defining the bolt hole oversize is insignificant. However, cyclic stiffness and equivalent viscous damping are effected by hole oversize. Therefore, the range of cyclic stiffness and equivalent viscous damping provide an indication of the range of expected performance for connections fabricated within the code specifications. Minimum and maximum values for properties are highlighted in brackets.

As shown in Tables A4 - A6 and Figures A10, A13, and A16, hysteretic damping increased with increasing displacement for bolted connections. Hysteretic damping at a given displacement was greatest for steel plate-to-4x4 connections, followed by 4x4-to-4x4 and 2x4-to-2x4 connections, respectively. Tables A4 - A6 also show that 4x4-to-4x4 connections were more resilient than the other two types, in that a higher number of phases were required to fail 4x4-to-4x4 connections. Failure for most bolted connections occurred in the form of wood splitting. Exceptions were found in several steel plate-to-4x4 connections where bolt fatigue was a factor.

Figures A11, A14, and A17 illustrate the trends of cyclic stiffness for the three bolted connection configurations. Cyclic stiffness of bolted connections increased for the first few phases. This is due to the hole oversize used in bolted connections. A minimum connection slip is required before full bearing between the wood and bolt occurs. This agrees with results of load-controlled cyclic tests of matched specimens. Maximum cyclic stiffness values also compared well with those determined in load-controlled tests (Dolan et al., 1994a).

Figures A12, A15, and A18 illustrate the trends of equivalent viscous damping for the three bolted connection configurations. Equivalent viscous damping ratios were similar to those determined from load-controlled tests of matched samples (Dolan et al., 1994a). If the initial three to four phases are disregarded to account for the initial oversize in the bolt holes, the equivalent viscous damping for the bolted connections ranged from 5 - 10 percent of critical for all configurations. This property remains fairly constant for all displacements larger than the initial oversize of the holes.

Table A4: Cyclic properties for the stabilized hysteresis at each phase for 2x4-2x4 connections with 3/4" bolts and loaded parallel-to-grain.

Phase No.	Inclusion of the hole oversize							Exclusion of the hole oversize							
	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	
	Mean	COV	Mean	COV	Mean	COV		Mean	COV	Mean	COV	Mean	COV		
1															
2	[8.5]	30.0	[3705]	27.3	[5.4]	21.4	10	[8.5]	30	15174	29.8	[22.5]	24.5	10	
3	86	26.7	11038	26.0	4.9	14.4	10	86	26.7	[18255]	27.8	8.2	13.3	10	
4	214	14.9	[12340]	11.5	4.9	10.8	10	214	14.9	16779	12.2	6.7	10.4	10	
5	351	11.4	11022	8.7	5.0	6.8	10	351	11.4	13723	9.0	6.2	6.9	10	
6	466	9.1	9324	8.1	[4.9]	4.9	9	466	9.1	11029	8.2	5.8	4.8	9	
7	620	10.9	8214	12.7	5.0	13.1	8	620	10.9	9414	12.9	5.8	12.7	8	
8	723	14.0	6720	15.4	5.1	8.2	6	723	14	7534	15.5	5.7	7.9	6	
9	[851]	8.2	6326	14.6	5.0	7.6	2	[851]	8.2	[6994]	14.6	[5.6]	7.7	2	
10							0							0	
11							0							0	
12							0							0	
13							0							0	
14							0							0	

Note: *n* = number of test specimens that had not yet failed during a particular phase; bracketed values are minimums and maximums.

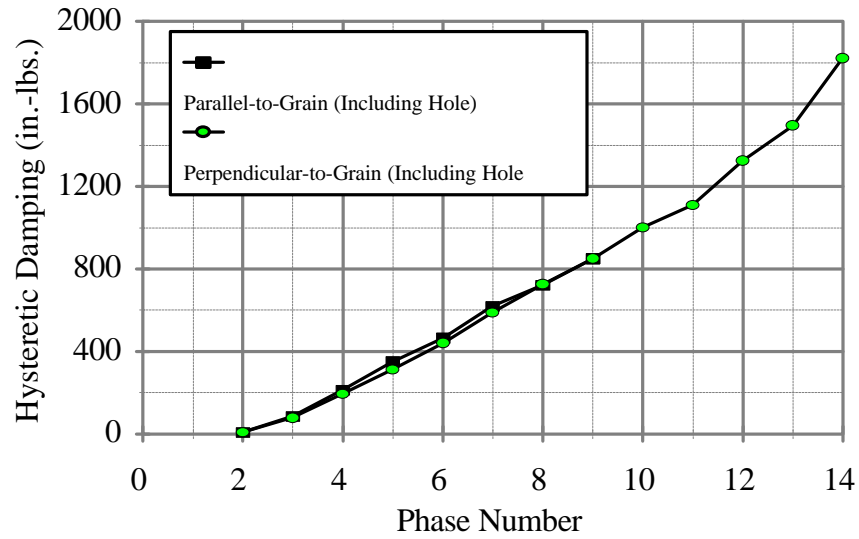


Figure A10: Hysteretic damping versus phase number SPD stabilized response of 2x4-to-2x4 lumber connections with 3/4" Bolts.

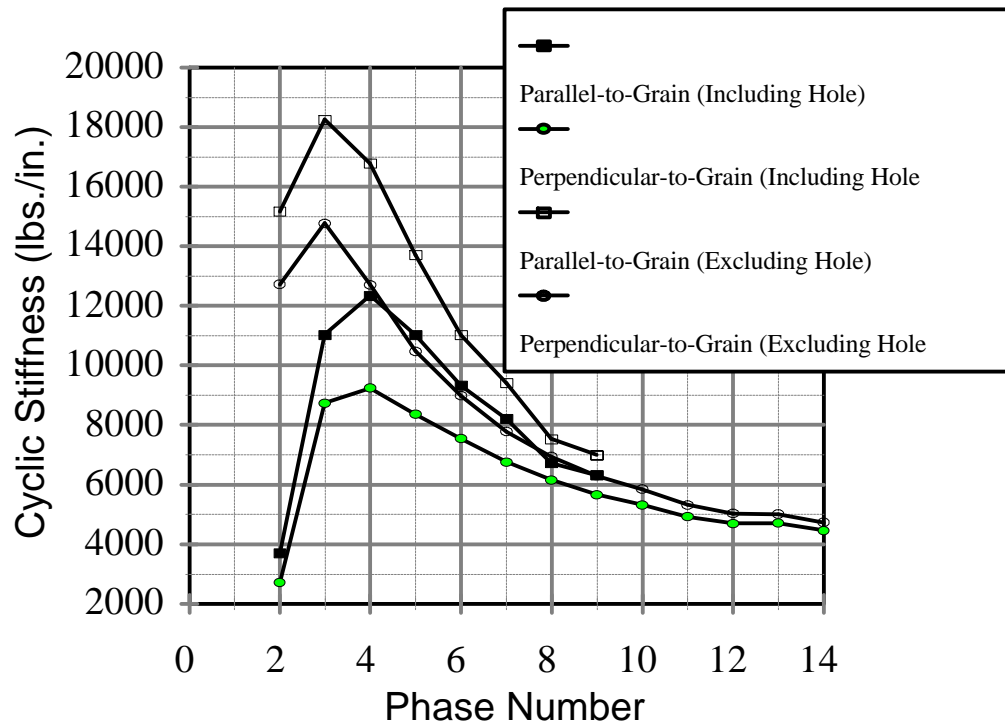


Figure A11: Cyclic stiffness versus phase number SPD stabilized response of 2x4-to-2x4 lumber connections with 3/4" Bolts.

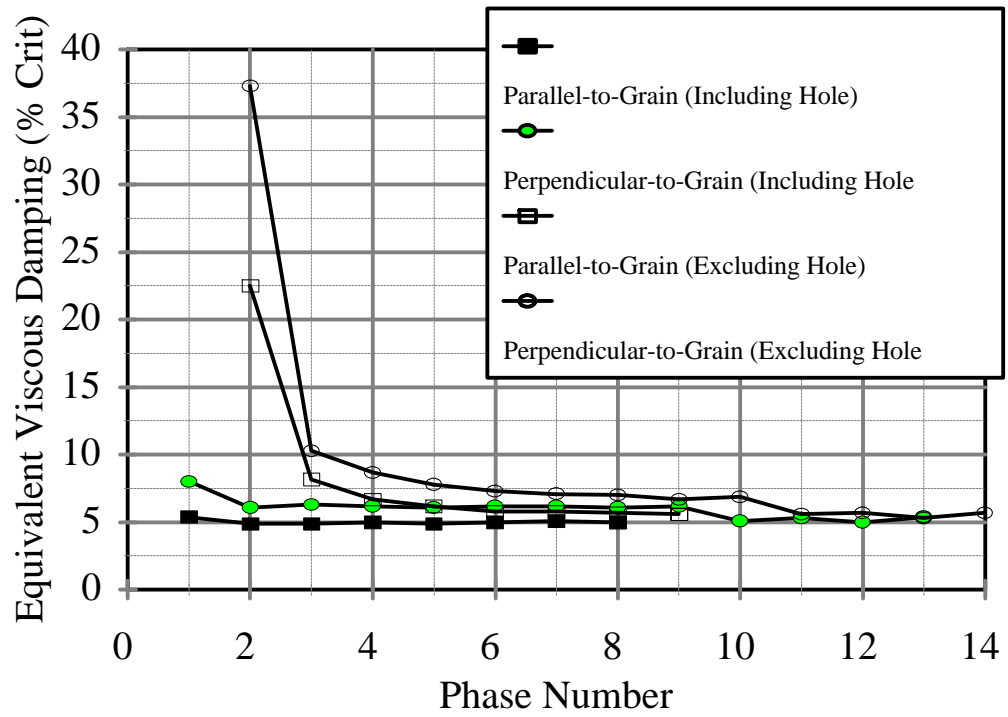


Figure A12: Equivalent viscous damping versus phase number SPD stabilized response of 2x4-to-2x4 lumber connections with 3/4" Bolts.

Table A5: Cyclic properties for the stabilized hysteresis at each phase for 1/4" steel-to-4x4 connections with 1/2" bolts and loaded parallel-to-grain.

Phase No.	Inclusion of the hole oversize							Exclusion of the hole oversize							
	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	
	Mean	COV	Mean	COV	Mean	COV		Mean	COV	Mean	COV	Mean	COV		
1															
2	[10.6]	41.6	[4493]	40.4	7.1	66.3	10	[10.6]	41.6	22051	42.3	[35.7]	69.8	10	
3	91	24.7	[16438]	18.3	[4.2]	17.7	10	91	24.7	[29001]	20.5	[7.3]	18.0	10	
4	287	28.5	14864	18.3	6.1	17.0	10	287	28.5	20681	19.5	8.4	17.5	10	
5	515	27.6	12258	19.0	7.1	15.7	10	515	27.6	15432	19.7	8.9	16.2	10	
6	762	24.9	10574	16.7	7.6	13.9	8	762	24.9	12624	17.2	9.1	14.2	8	
7	936	23.9	8700	15.4	7.7	14.7	7	936	23.9	10042	15.8	8.9	14.9	7	
8	1203	23.2	7822	14.8	[8.3]	13.0	3	1203	23.2	8846	15.0	9.4	13.2	3	
9	[1205]	28.4	6393	15.2	7.9	19.6	2	[1205]	28.4	[7118]	15.6	8.8	20.0	2	
10							0							0	
11							0							0	
12							0							0	
13							0							0	
14							0							0	

Note: *n* = number of test specimens that had not yet failed during a particular phase; bracketed values are minimums and maximums.

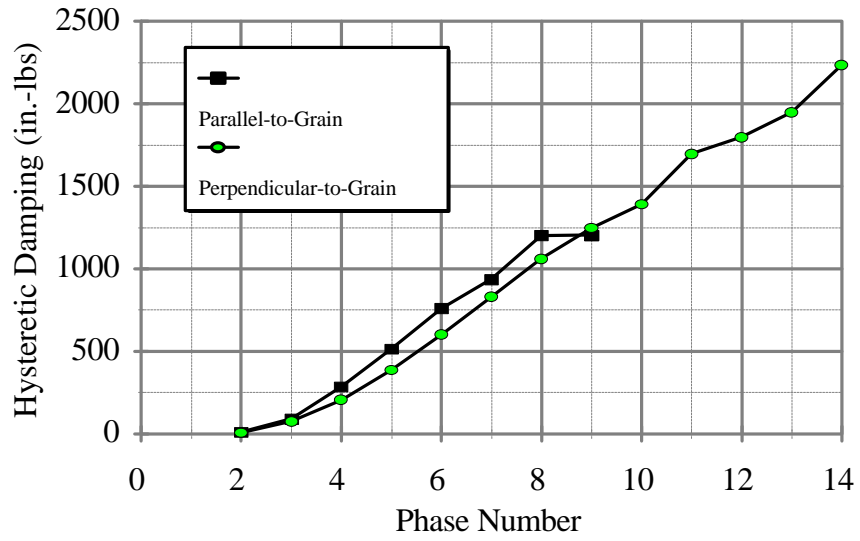


Figure A13: Hysteretic damping versus phase number SPD stabilized response of 1/4" steel plate-to-4x4 lumber connections with 1/2" Bolts.

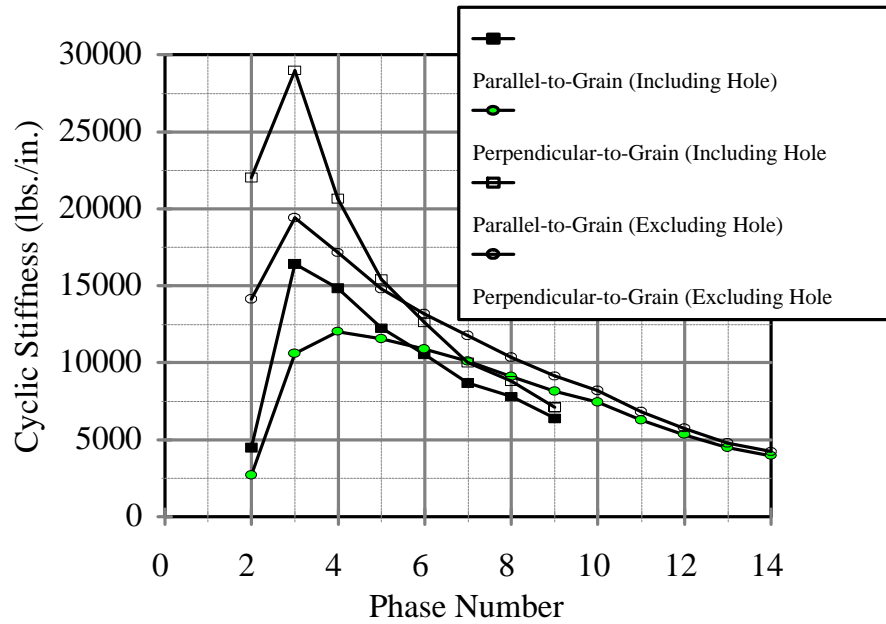


Figure A14: Cyclic stiffness versus phase number SPD stabilized response of 1/4" steel plate-to-4x4 lumber connections with 1/2" Bolts.

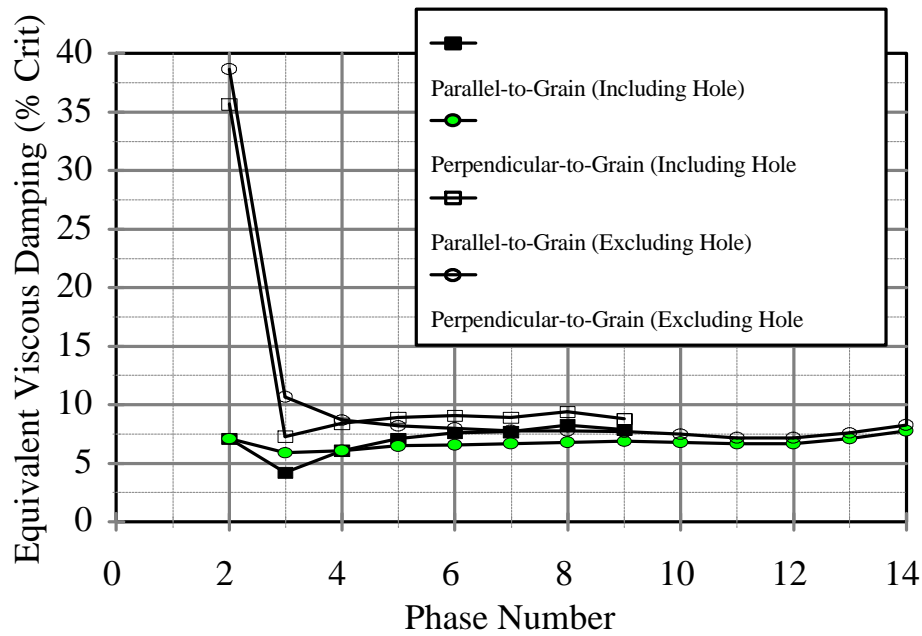


Figure A15: Equivalent viscous damping versus phase number SPD stabilized response of 1/4" steel plate-to-4x4 lumber connections with 1/2" Bolts.

Table A6: Cyclic properties for the stabilized hysteresis at each phase for 4x4-to-4x4 connections with 3/4" bolts and loaded parallel-to-grain.

Phase No.	Inclusion of the hole oversize							Exclusion of the hole oversize							
	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	
	Mean	COV	Mean	COV	Mean	COV		Mean	COV	Mean	COV	Mean	COV		
1															
2	[6.9]	14.6	[2444]	34.5	7.7	28.4	10	[6.9]	14.6	11535	44.0	[37.2]	23.9	10	
3	109	20.4	14486	12.7	[5.7]	16.4	10	109	20.4	[25437]	13.3	9.9	16.3	10	
4	261	23.7	[15376]	12.0	5.7	15.2	10	261	23.7	21603	12.4	8.0	15.4	10	
5	455	25.9	14323	14.1	6.0	16.0	10	455	25.9	18304	15.2	7.7	16.1	10	
6	670	25.1	12650	13.4	6.1	15.4	10	670	25.1	15237	13.8	7.4	15.7	10	
7	880	21.9	11220	12.4	6.2	12.8	10	880	21.9	13049	12.6	7.2	13.0	10	
8	1075	22.0	9819	11.9	6.3	13.1	10	1075	22	11147	12.1	7.1	13.3	10	
9	1240	23.8	8611	12.4	6.3	13.8	9	1240	23.8	9613	12.6	7.0	13.9	9	
10	1476	20.8	8000	12.7	6.7	13.3	7	1476	20.8	8832	12.8	7.4	13.3	7	
11	1646	31.4	6771	17.6	5.9	19.8	6	1646	31.4	7341	17.7	[6.4]	19.9	6	
12	1996	36.8	5926	20.3	6.7	31.4	5	1996	36.8	6372	20.4	7.2	31.4	5	
13	[2182]	35.5	5121	24.8	7.1	37.0	4	[2182]	35.5	5468	25.0	7.5	36.9	4	
14	2155	52.3	3628	7.1	[7.9]	42.7	2	2155	52.3	[3850]	7.0	8.3	42.6	2	

Note: *n* = number of test specimens that had not yet failed during a particular phase; bracketed values are minimums and maximums.

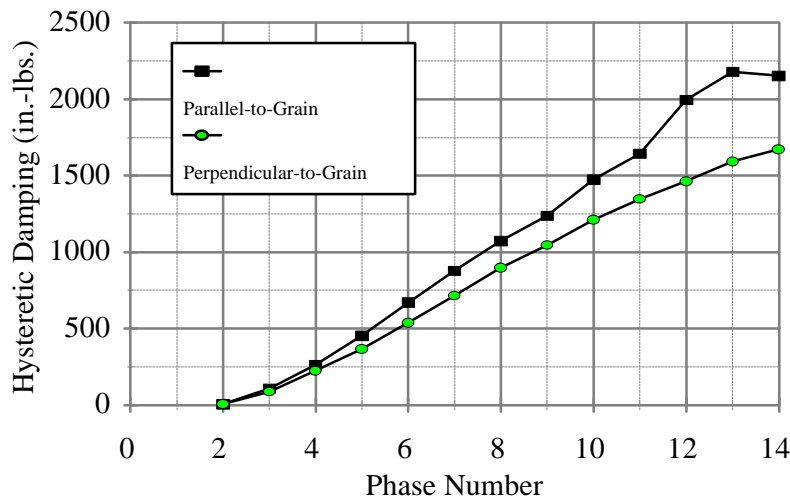


Figure A16: Hysteretic damping versus phase number SPD stabilized response of 4x4-to-4x4 lumber connections with 3/4" Bolts.

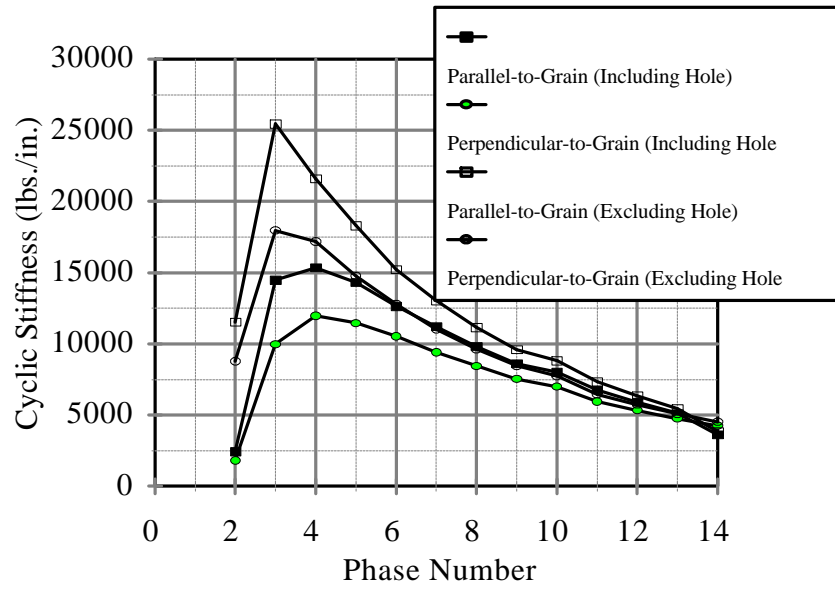


Figure A17: Cyclic stiffness versus phase number SPD stabilized response of 4x4-to-4x lumber connections with 3/4" Bolts.

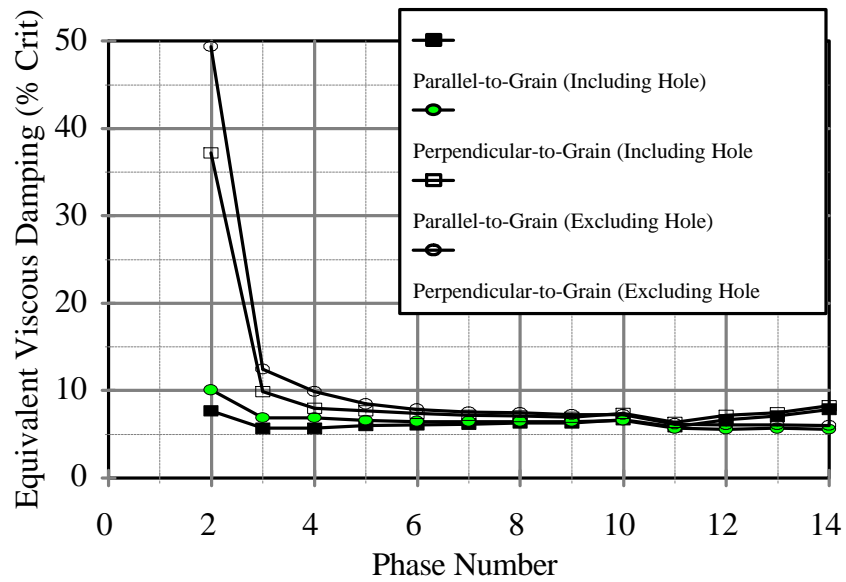


Figure A18: Equivalent viscous damping versus phase number SPD stabilized response of 4x4-to-4x lumber connections with 3/4" Bolts.

Cyclic Properties - Bolted Connections Tested Perpendicular-to-Grain

Average values and coefficients of variation for cyclic properties of bolted connections tested in the perpendicular-to-grain orientation are presented in Tables A7 - A9. As for parallel-to-grain results, two sets of values are presented in each table; one for inclusion and one for exclusion of the effects of oversized bolt holes. Comparisons with values in Tables A4 - A6 are illustrated in Figures A10 - A18, and show that perpendicular-to-grain orientations tended to fail at greater displacements than did parallel-to-grain orientations. This was due to some difference in failure modes; parallel-to-grain orientations failed in splitting of the wood, while the perpendicular-to-grain orientations tended to fail by wood crushing if failure occurred in the main member. If failure occurred in the active member, the failure mode was splitting of the wood.

A necessary consequence to achieving higher displacement levels is that hysteretic damping increased. The 2x4-to-2x8 and steel plate-to-4x6 connections achieved higher displacements, while 4x4-to-4x8 connections failed at lower displacements than their counterparts in parallel-to-grain tests. Lower displacements associated with 4x4-to-4x8 connections are probably a direct result of the lower average specific gravity for the 4x8 members than the 4x4 members used for the parallel-to-grain connections.

Table A7: Cyclic properties for the stabilized hysteresis at each phase for 2x4-to-2x8 connections with 3/4" bolts and loaded perpendicular-to-grain.

Phase No.	Inclusion of the hole oversize							Exclusion of the hole oversize							
	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	
	Mean	COV	Mean	COV	Mean	COV		Mean	COV	Mean	COV	Mean	COV		
1															
2	[8.2]	18.1	[2707]	21.8	[8.0]	25.9	10	[8.2]	18.1	12722	20.0	[37.3]	30.0	10	
3	79	22.1	8737	18.0	6.1	10.0	10	79	22.1	[14783]	18.6	10.3	10.8	10	
4	194	16.5	[9251]	11.7	6.3	9.4	10	194	16.5	12718	12.0	8.7	9.6	10	
5	313	10.9	8363	8.5	6.2	9.8	10	313	10.9	10475	8.6	7.8	9.8	10	
6	442	8.2	7552	9.1	6.1	9.8	10	442	8.2	8986	9.2	7.3	9.8	10	
7	588	6.1	6760	10.1	6.2	8.9	10	588	6.1	7785	10.1	7.1	8.9	10	
8	727	6.5	6161	10.9	6.2	9.1	10	727	6.5	6947	10.9	7.0	9.1	10	
9	851	6.7	5667	10.0	6.1	8.5	10	851	6.7	6291	10.0	6.7	8.5	10	
10	1001	7.7	5323	9.2	6.2	8.8	9	1001	7.7	5850	9.2	6.9	8.8	9	
11	1111	8.4	4928	10.2	5.1	5.1	8	1111	8.4	5327	10.3	5.6	5.0	8	
12	1326	10.6	4704	9.5	5.3	8.2	7	1326	10.6	5045	9.5	5.7	8.2	7	
13	1497	9.7	4706	6.8	[5.0]	6.5	3	1497	9.7	5019	6.8	[5.3]	6.5	3	
14	[1821]	6.2	4462	7.3	5.4	2.7	2	[1821]	6.2	[4733]	7.5	5.7	2.9	2	

Note: *n* = number of test specimens that had not yet failed during a particular phase; bracketed values are minimums and maximums.

Lower load-carrying capacity of perpendicular-to-grain connections when compared to the parallel-to-grain orientation was illustrated by the lower maximum cyclic stiffness. For equal displacements for tests with both grain orientations, a lower cyclic stiffness in perpendicular-to-grain connections indicated a lower load-carrying capacity of wood directly adjacent to the bolt. An interesting point is that maximum cyclic stiffness for all connections occurred at approximately the same displacements in both grain orientations. Excluding the effects of bolt hole oversize increased the cyclic stiffness, as would be expected.

Equivalent viscous damping magnitudes were essentially independent of grain orientations and averaged between 5 and 10 percent for most displacement levels. The effect of oversized bolt holes had the least effect on viscous damping, and changed the magnitude approximately 1% - 2% on average. As illustrated in Figures A10 - A18, hysteretic damping and cyclic stiffness were always higher for the perpendicular-to-grain orientation, regardless of whether the oversize hole effects are included or excluded. Equivalent viscous damping is always higher for the perpendicular-to-grain orientation.

Table A8: Cyclic properties for the stabilized hysteresis at each phase for 1/4" steel plate-to-4x6 connections with 1/2" bolts and loaded perpendicular-to-grain.

Phase No.	Inclusion of the hole oversize							Exclusion of the hole oversize							
	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	
	Mean	COV	Mean	COV	Mean	COV		Mean	COV	Mean	COV	Mean	COV		
1															
2	[7.1]	12.2	[2722]	15.9	7.1	17.5	10	[7.1]	12.2	14138	16.4	[38.7]	25.9	10	
3	76	19.0	10599	10.4	[5.9]	13.5	10	76	19	[19421]	10.8	10.7	13.3	10	
4	206	14.2	[12051]	11.2	6.1	5.4	10	206	14.2	17165	11.4	8.7	4.8	10	
5	387	15.6	11558	11.0	6.5	5.1	10	387	15.6	14799	11.1	8.2	4.8	10	
6	602	12.1	10922	8.1	6.6	5.4	10	602	12.1	13197	8.3	8.0	5.4	10	
7	830	10.4	10108	7.4	6.7	4.9	10	830	10.4	11779	7.5	7.8	4.9	10	
8	1061	11.0	9119	6.6	6.8	7.3	10	1061	11	10369	6.7	7.8	7.4	10	
9	1249	11.3	8173	6.6	6.9	7.2	10	1249	11.3	9136	6.7	7.7	7.4	10	
10	1391	9.1	7437	5.7	6.8	5.4	10	1391	9.1	8219	5.8	7.5	5.5	10	
11	1697	10.2	6295	5.0	6.7	6.9	10	1697	10.2	6827	5.1	[7.2]	7.0	10	
12	1797	12.0	5360	6.3	6.7	9.1	10	1797	12	5765	6.4	7.2	9.1	10	
13	1949	18.1	4505	7.9	7.1	15.1	8	1949	18.1	4812	8.0	7.6	15.1	8	
14	[2236]	8.5	3989	7.6	[7.8]	9.2	4	[2236]	8.5	[4237]	7.7	8.3	9.2	4	

Note: *n* = number of test specimens that had not yet failed during a particular phase; bracketed values are minimums and maximums.

Table A9: Cyclic properties for the stabilized hysteresis at each phase for 4x4-to-4x8 connections with 3/4" bolts and loaded perpendicular-to-grain.

Phase No.	Inclusion of the hole oversize							Exclusion of the hole oversize						
	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>	Hysteretic Damping (in. lbs.)		Cyclic Stiffness (lbs./in.)		Equivalent Viscous Damping (%)		<i>n</i>
	Mean	COV	Mean	COV	Mean	COV		Mean	COV	Mean	COV	Mean	COV	
1														
2	[6.8]	27.0	[1801]	27.8	[10.1]	27.1	10	[6.8]	27	8788	30.2	[49.4]	26.1	10
3	87	28.7	9982	17.2	6.9	24.7	10	87	28.7	[17959]	19.3	12.5	25.6	10
4	224	22.3	[11985]	12.8	6.9	19.5	10	224	22.3	17177	13.7	9.9	19.1	10
5	368	18.8	11457	12.9	6.6	15.7	10	368	18.8	14771	13.5	8.5	15.5	10
6	538	16.6	10536	10.7	6.5	13.6	10	538	16.6	12801	11.0	7.9	13.5	10
7	717	14.5	9415	8.2	6.5	11.2	10	717	14.5	11016	8.3	7.6	11.0	10
8	897	14.1	8447	8.1	6.5	10.4	10	897	14.1	9634	8.2	7.5	10.3	10
9	1048	13.4	7542	6.4	6.5	9.9	10	1048	13.4	8449	6.4	7.3	9.8	10
10	1213	12.5	6994	6.4	6.6	8.7	10	1213	12.5	7742	6.4	7.3	8.6	10
11	1349	15.3	5948	10.3	5.7	10.9	8	1349	15.3	6457	10.4	6.2	10.8	8
12	1462	12.6	5350	11.3	[5.6]	7.2	7	1462	12.6	5760	11.4	6.1	7.2	7
13	1593	11.8	4752	12.0	5.7	6.2	7	1593	11.8	5081	12.1	6.1	6.2	7
14	[1674]	17.6	4261	16.4	5.6	6.6	6	[1674]	17.6	[4530]	16.5	[6.0]	6.6	6

Note: *n* = number of test specimens that had not yet failed during a particular phase; bracketed values are minimums and maximums.