LABORATORY TESTING OF AS BUILT TIMBER DIAPHRAGM TO SHEAR WALL CONNECTIONS

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ABSTRACT

Laboratory tests were performed to establish a capacity for two conditions that commonly occur in residential wood frame construction. Both conditions are connections from unblocked plywood diaphragms to shear walls below. The first condition occurs at a roof eave. It is the connection of a sloping plywood roof diaphragm to an exterior wall. This condition is shown in Figure 1. The second condition occurs at the connection of a horizontal floor diaphragm to a shear wall below. This condition is shown in Figure 2.

![Diagram of Roof Diaphragm to Shear Wall Assembly]

FIGURE 1. Roof Diaphragm to Shear Wall Assembly

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FIGURE 2. Floor Diaphragm to Shear Wall Assembly

INTRODUCTION

Both of the tested assemblies differ from typical engineered connections in the following ways: 1) the roof or floor plywood is not boundary nailed into the blocking above the wall, 2) the blocking between the joists is not directly nailed to the top plate of the wall below and 3) the roof or floor diaphragm is nailed with 8d box nails (0.113" dia. x 2 1/2") rather than common nails. The shear transfer mechanism is from the plywood to the joist, from the joist to the slant nails, and from the slant nails into the top plate of the wall below.

Historically observed failures have not occurred in these connections, although their "repair" is often specified as part of a seismic strengthening project. This testing was undertaken to better understand why this assembly has performed so well in the field, and establish an allowable design value for this existing condition.

The capacity of this assembly is calculated based on the allowable diaphragm shear value and the allowable lateral shear value of the slant nails from the joist to the top plate of the wall. The lack of boundary nailing to the blocking does not affect the calculated capacity of the diaphragm since the diaphragm is unblocked and contains numerous edges of plywood that are not nailed. The allowable diaphragm capacity for the tested system is listed in the ICBO Evaluation Report NER-230 dated 5/1/91. For 1/2 or 5/8 inch plywood with 8d box nails the allowable value is listed at 165 pounds per foot. The yield strength of the nail in this ICBO Report appears to be assumed at 100 ksi. Nails of this diameter commonly encountered in the field and used in this test are 135 to 145 ksi.[1] Therefore the allowable load for the diaphragm would be higher than 165 pounds per foot. Due to the small size of the sample the diaphragm capacity may also be considerably stronger than a larger unblocked diaphragm. Since this testing is used to determine the capacity of the subassembly below the diaphragm this does not affect the results obtained.

The lateral design value of the slant nails in the joists is based on the yield mode equations that have been developed, verified in research, and used in the 1991 National Design Specification for Wood Construction.[2] [3] [4] The geometry of the slant nail from the joist to the top plate is shown in Figure 3. The thickness of the main member and
the depth of penetration are taken from the recommendations listed in the Commentary to the 1991 National Design Specifications. [5]

![Diagram of slant nails and nailing](image)

**SECTION**

**TOP VIEW OF SAMPLE NAILING**

**FIGURE 3.** Geometry and Location of Slant Nails in Tested Samples

Due to the angle that the nail is driven this application is commonly referred to as a toe nail. The \( \frac{5}{6} \) reduction in the lateral load capacity associated with toe nails is to account for a nail being driven parallel to grain. [5] The nails from the joist to the top plate are not parallel to grain and would therefore not require a \( \frac{5}{6} \) reduction. For clarity these nails are referred to in this text as slant nails.

The slant nails used in this test are commonly available 16d vinyl coated sinker nails (0.148 inch diameter x 3 1/4 inch length).[6] The yield strength of these nails is approximately 130 ksi.[1] The dowel bearing strength of the joist and top plate was taken as 4450 psi for Douglas Fir - Larch North.[2] The following equations are the governing yield mode equations (IIIa).[2]

\[
\begin{align*}
  k_2 &= -1 + \sqrt{\frac{2}{R_e} \left( 2 + R_e \right) D^2 + \frac{2 F_{pe} (2 + R_e)}{3 F_{em} t^2}} \quad (1)
  
  Z &= \frac{k_2 D t F_{em}}{K_D (2 + R_e)} = 125.0 \text{ pounds} \quad \text{Mode IIIa} \quad (2)
\end{align*}
\]

The calculated allowable seismic shear per sample for the 6 nails at 125 pounds per nail with a 1.33 load duration factor is 1000 pounds.

**TESTING SAMPLES**

Four testing assemblies with two samples each, one per side, were tested. The sample names and descriptions are shown in Figure 4.

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<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>Plywood Thickness</th>
<th>Slant Nails</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Roof Sample #1</td>
<td>½</td>
<td>6 - 16d Sinker per side</td>
</tr>
<tr>
<td>R2</td>
<td>Roof Sample #2</td>
<td>½</td>
<td>6 - 16d Sinker per side</td>
</tr>
<tr>
<td>F1</td>
<td>Floor Sample #1</td>
<td>5/8</td>
<td>6 - 16d Sinker per side</td>
</tr>
<tr>
<td>F2</td>
<td>Floor Sample #2</td>
<td>5/8</td>
<td>6 - 16d Sinker per side</td>
</tr>
</tbody>
</table>

**FIGURE 4. Sample Matrix**

Figures 5 and 6 show the top view of the two sample types. R1 and R2 are identical samples. F1 and F2 are identical samples. The details of the connection assemblies are shown in Figures 7 and 8. The testing apparatus is shown in Figures 9 and 10. Figure 11 shows the nailing pattern of the blocking to the joists.

![Diagram of sample matrix and nailing pattern](image)

**FIGURE 5.** Roof Samples (R1 and R2)  
Top View

All Plywd. and 1x6 Nails = 0.113" φ x 2 ½"  
Spacing as shown
FIGURE 6. Floor Samples (F1 and F2)
Top View

FIGURE 7. Detail of Roof Sample
Connection Assembly - Section
FIGURE 8. Detail of Floor Sample Connection Assembly - Section

FIGURE 9. Side View of Testing Apparatus (Floor Sample)
MATERIALS

The roof rafters, floor joists and blocking used are Douglas Fir No. 2, except inadvertently one of the 16 joists tested was Select Structural. The plywood used is 1/2" (3 ply) and 5/8" (5 ply) CDX. The top plates are Douglas Fir Standard and Better Grade. All lumber is S Green. The roof joists are birds mouthed to a 1 inch depth.

All nails used were obtained at local suppliers. The roof and floor plywood nails are 8d box nails (0.113" dia. x 2 1/2"). [6] The slant nails from the joists to the top plates...
are 16d vinyl coated sinker nails (0.148" dia. x 3 1/4"). [6] The nails from the blocking to
the rafters or joists are also 16d vinyl coated sinker nails.

TESTING

A cyclic test is performed for the 4 foot by 10 foot test panels. The load is applied
perpendicular to the joists at the center of the sample and is resisted by two test locations
(one on each side of the test sample). The load is applied directly to the plywood
diaphragm from a steel channel with 18 #12 sheet metal screws from the channel into the
plywood. The steel channel is bolted to the hydraulic ram. Load is measured by a 10,000
pound load cell at the loading ram. The deflection relative to the top plates of the sample is
measured at the plywood over the blocking, at the top of the joist, and at the bottom of the
joist on both sides of the sample. The sampling rate at the load cell and at each of the 6
displacement monitoring locations is 50 samples per second.

An uplift restraint was utilized to prevent the sample from overturning. The
restraint is provided by a steel S section that is bolted to the reaction floor at each end and
has 2 sets of slip pads between the bottom of the section and the top of the sample. This is
shown in Figure 9. No vertical preload was applied to the sample from the uplift restraint.

The loading sequence is shown in Figure 12. This displacement based sequence is
used to simulate seismic loading. The sequence is a modified version of the cyclic test
sequence now under consideration by the Structural Engineers Association of Southern
California Ad hoc Committee on Testing Standards. The proposed sequence from the
Testing Committee has a four cycle ring down series plus three additional cycles at each
increment of displacement, whereas the modified sequence has only the four cycle ring
down series at each increment of displacement. Each four cycle ring down series consists
of an initial maximum induced displacement for that increment followed by a ring-down to
75%, to 50% and to 25% of the initial displacement. The modified sequence reduced the
total number of cycles from 114 to 63 cycles. This was done to more closely resemble
actual seismic loading. The larger number of cycles in the sequence under consideration by
the Testing Committee can cause fracture of nails due to fatigue. Fatigued or fractured nails
have not been reported in timber structures damaged by seismic events.
FIGURE 12. Loading Sequence Used to Test all Samples

RESULTS

The results of the tests are summarized in Figure 13. The load versus displacement hysteresis loops are plotted for each of the samples in Figures 14, 15, 16, 17, 18, 19, 20 and 21. The displacement used for the figures is the plywood diaphragm deflection above the blocking relative to the top plate of the sample. Due to the geometry of the testing samples, the maximum load is governed by the weaker of the two end assemblies. This produces a downward biased recorded maximum load.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum Load Forward</th>
<th>Maximum Load Reverse</th>
<th>Joist to Top Plate Slip @ 1000 lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Left</td>
<td>2750 lbs.</td>
<td>3000 lbs.</td>
<td>0.006 inch</td>
</tr>
<tr>
<td>R1 Right</td>
<td>2750 lbs.</td>
<td>3000 lbs.</td>
<td>0.007 inch</td>
</tr>
<tr>
<td>R2 Left</td>
<td>2500 lbs.</td>
<td>2350 lbs.</td>
<td>0.007 inch</td>
</tr>
<tr>
<td>R2 Right</td>
<td>2500 lbs.</td>
<td>2350 lbs.</td>
<td>0.009 inch</td>
</tr>
<tr>
<td>F1 Left</td>
<td>2750 lbs.</td>
<td>2800 lbs.</td>
<td>0.009 inch</td>
</tr>
<tr>
<td>F1 Right</td>
<td>2750 lbs.</td>
<td>2800 lbs.</td>
<td>0.009 inch</td>
</tr>
<tr>
<td>F2 Left</td>
<td>3000 lbs.</td>
<td>2950 lbs.</td>
<td>0.010 inch</td>
</tr>
<tr>
<td>F2 Right</td>
<td>3000 lbs.</td>
<td>2950 lbs.</td>
<td>0.009 inch</td>
</tr>
</tbody>
</table>

**FIGURE 13.** Matrix of Test Results

**FIGURE 14.** Sample R1 Left
FIGURE 15. Sample R1 Right

FIGURE 16. Sample R2 Left
FIGURE 17. Sample R2 Right

FIGURE 18. Sample F1 Left
FIGURE 19. Sample F1 Right

FIGURE 20. Sample F2 Left
FIGURE 21. Sample F2 Right

The majority of the assembly displacements at the design load occurred as a result of the rotation of the blocking between the joists. The slip of the joist relative to the top plate is less than 0.010 inches at the design load. Slip between the joist and top plate becomes more dominate as the load level increases toward the ultimate capacity.

The failure mode of the samples was bending of the slant nails in a III<sub>n</sub> yield mode. This is consistent with the calculated controlling yield mode. Approximately 50% of the joists experienced some cracking at the nailed connection after severe bending of the nail occurred. This cracking was the start of the degradation of the samples visible in some hysteresis loops. The deflection within the short plywood diaphragm itself was not measured but was visually observed to be significant.

CONCLUSION

A comparison of the data obtained from the tested samples to the calculated values yields the following results. Figure 22 lists an equivalent factor of safety for the tested samples. This factor of safety is obtained by dividing the ultimate test load by the calculated capacity including the 1.33 load duration factor. It is important to realize that the testing procedure limits the maximum sample load to the weakest of the two simultaneously tested specimens. This produces a downward biased recorded maximum load. The testing covered 63 cycles of load. This may result in a lower recorded maximum capacity than if the tests were performed monotonically. All the 8 tested specimens yielded a factor of safety greater than 2.5. One of the test specimens produced a factor of safety of 2.36 in one direction after obtaining a factor of safety of 2.51 in the opposite direction. These tests appear to validate the calculated allowable lateral design value of the slant nails at approximately 125 pounds per nail plus a 1.33 load duration factor if the loading is of similar duration as the performed tests.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum Load per Side</th>
<th>Maximum Load per Slant Nail</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Forward</td>
<td>2750 lbs.</td>
<td>458 lbs</td>
<td>2.93</td>
</tr>
<tr>
<td>R1 Reverse</td>
<td>3000 lbs.</td>
<td>500 lbs.</td>
<td>3.01</td>
</tr>
<tr>
<td>R2 Forward</td>
<td>2500 lbs.</td>
<td>417 lbs.</td>
<td>2.51</td>
</tr>
<tr>
<td>R2 Reverse</td>
<td>2350 lbs.</td>
<td>392 lbs.</td>
<td>2.36</td>
</tr>
<tr>
<td>F1 Forward</td>
<td>2750 lbs.</td>
<td>458 lbs</td>
<td>2.93</td>
</tr>
<tr>
<td>F1 Reverse</td>
<td>2800 lbs.</td>
<td>467 lbs.</td>
<td>2.81</td>
</tr>
<tr>
<td>F2 Forward</td>
<td>3000 lbs.</td>
<td>500 lbs.</td>
<td>3.01</td>
</tr>
<tr>
<td>F2 Reverse</td>
<td>2950 lbs.</td>
<td>492 lbs.</td>
<td>2.96</td>
</tr>
</tbody>
</table>

**FIGURE 22.** Comparison of Tested to Calculated Capacity

**REFERENCES**


