REPORT ON LABORATORY TESTING OF ANCHOR BOLTS CONNECTING WOOD SILL PLATES TO CONCRETE WITH MINIMUM EDGE DISTANCE

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ABSTRACT

The 2006 International Building Code (IBC-06) is the "Model Code" for the 2007 California Building Code (CBC-07). IBC-06 references ACI 318-05 Appendix D for the determination of anchor bolt capacity (in single-shear) when attaching wood sill plates to concrete foundations. Many practicing engineers and building officials are currently mystified by the low anchor bolt capacities obtained from the application of Appendix D equations for wood framed construction in seismic design categories D, E and F.

In the absence of available test data, members of the 2008-2009 Structural Engineers Association of California (SEAOC) Seismology Committee concluded that the development and support of a study to characterize typical foundation anchor bolted to wood sill plate connections was necessary to establish a basis for evaluating design capacities while better understanding the behavior of this basic connection.

Results obtained through initial rudimentary experiments provided the authors and the SEAOC Seismology Committee with a basis for the development of the test set-up and protocol contained herein. The experimental tests contained herein were performed at the Tyrell Gilb Research Laboratory in Stockton California. All tests were single-bolt tests in wood sill plates connected to concrete with standard cast-in-place steel anchor L-bolts.

In addition, nondestructive testing was performed concurrently on concrete surfaces to detect any flaws and delaminations that may have formed during testing.

The test program yielded results indicating that the connection of wood sill plate to concrete using cast-in-place steel anchor bolts is ductile and that design capacities (both past and present) are conservative.

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INTRODUCTION

Seismic force resisting systems for wood framed buildings typically comprise wood structural panel shear walls with anchor bolts located at the edge of foundations. These connections often have an edge distance of 1-3/4” from the bolt center line to the face of the concrete slab or footing. Engineers have historically anticipated the controlling failure of this connection to occur between the anchor bolt and the wood sill plate. However, design capacities for break-out strength of the anchor bolt in shear, determined in accordance with ACI 318-05 Appendix D, are greatly reduced and typically less than the design capacity applicable to the wood to concrete connection with small edge distances. ACI 318-05 provides an increase to break-out design capacity where connections are ductile but application of “ductile” provisions to the wood to concrete connection is not clearly defined within ACI 318-05.

Lacking specific test data to substantiate the reduced design capacities for anchors in concrete in a typical wood to concrete connection loaded parallel to the edge (per ACI 318-05, Appendix D), the Structural Engineers Association of California (SEAOC) Seismology Committee supported the development of a study to characterize typical anchor bolted connections through a comprehensive experimental testing program.

The testing program has the following goals:

- Establish test data for the connection capacity when loaded parallel to the edge.
- Determine whether the connection exhibits “ductile” behavior.
- Propose rational design capacities for the connection based on test results.

All tests were single-bolt tests in wood sill plates connected to concrete with standard cast-in-place steel anchor bolts. A total of 28 tests were performed; 24 primary tests and four auxiliary tests. Additional nondestructive testing was performed concurrently on concrete surfaces to detect flaws and delaminations if formed during testing.

TEST SET-UP AND INSTRUMENTATION

All tests were conducted at the Tyrell Gilb Research Laboratory in Stockton, California. The laboratory is owned and operated by the Simpson Strong-Tie Company (SSTC) who generously agreed to donate material and testing services to this project. The majority of the testing occurred between November 12-14, 2008 (four tests were completed on November 19, 2008). Figure 1 is annotated to show the typical set-up for the single-anchor tests.

Monotonic tests were run as displacement controlled at a rate of 0.75”/minute. Cyclic tests were run as displacement controlled at a frequency of 0.2Hz (1 cycle every 5 seconds). Each anchor bolt was tested as a single element connecting a 7 foot long sill plate to the larger concrete “foundation” element. Four loading “grips” transferred the parallel force from the loading beam to the sill plate. The “grips” were attached to the sill plate with a group of 1-1/2” long SDS Series wood screws. A total of 64 screws, distributed amongst multiple load transfer assemblies (see Fig. 1) were used to transfer the applied load into each test specimen. No vertical load was introduced into the test specimen.

Displacement was measured horizontally at two locations; (1) at the loading ram and (2) at the sill plate adjacent to the anchor bolt. All loads and displacements were collected via a state-of-the-art digital data acquisition system. Data was collected at a rate of 8 readings per second for monotonic tests and 32 times per second for cyclic tests.

Specimen details were documented before and after each test. Real-time video was collected during each test from two camera angles: (1) side elevation to observe the face of concrete at the "near edge," and (2) from above to observe sill plate and anchor bolt behavior. The clear cover of each anchor location was determined through the use of a Profometer re-bar locator (pachometer).

During each test, impact-echo testing was used to "sound" for internal flaws. From earlier experiments, it was determined that concrete delamination can form before anything is visually apparent from the exterior face of the concrete.

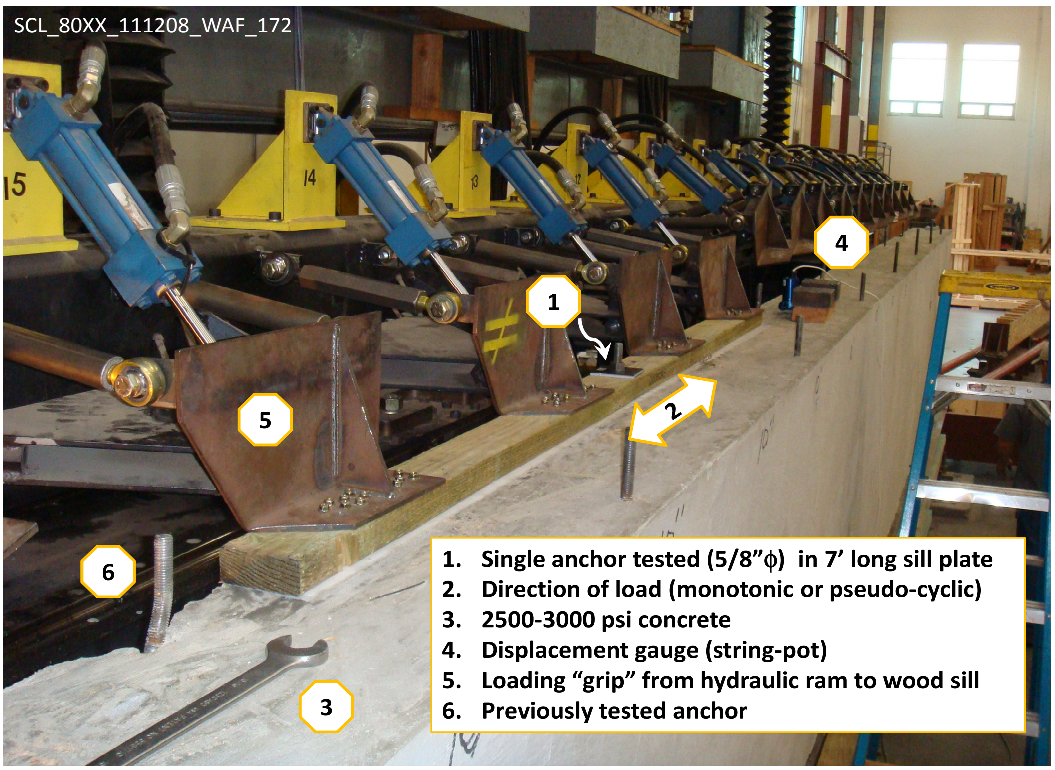


Fig. 1 – Annotated view of the typical testing set-up.

TEST PLAN DEVELOPMENT

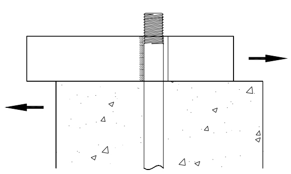
Prior testing of wood sill plates bolted to concrete (Reference 1) using ½" and ¾" diameter anchor bolts with 1-3/4" edge distance, located approximately 8" from the ends of the concrete specimen exhibited yielding of the bolt as predicted by the NDS yield limit equations associated with Mode IIIs and Mode IV behavior. Observations from the monotonic tests included yielding of the bolt "at the surface of the concrete" followed by rotation of the bolt such that the washer below the nut was pressed into the wood sill plate. Concrete degradation was observed in the vicinity of the bolt after yielding. The reported testing however, did not evaluate a wood sill plate bolted to concrete subjected to cyclic loading.

Comparative data on the capacities of ½” and ¾” diameter bolted connections (wood-to-wood) using various loading protocols (pseudo-cyclic, monotonic, and sequential phased displacement, Reference 3) indicated fastener fatigue was not a likely failure mode and that ultimate strength was not significantly influenced by various loading protocols.

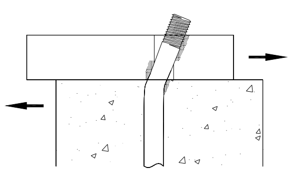
Preliminary experiments conducted during summer 2008 (performed at Scientific Construction Laboratories (SCL), Inc.) provided basic information on connection behavior and testing variables. Specimen configuration (e.g. single 5/8’ diameter anchors with 1-3/4” edge distance) was identical to that specified for the Stockton tests.

Observations from the preliminary tests indicated the following:

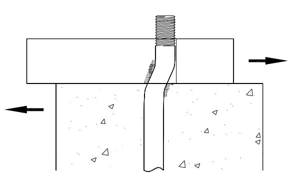
- NDS Yield Mode IIIs and IV were the governing yield mode for wood sill plate anchors loaded parallel to the concrete edge for 2x and 3x nominal thickness wood members, respectively
- Concrete side break-out occurs, but usually at relatively large loads and displacements when compared to calculated design capacities
- Initial nut tightness has an effect on connection performance as significant friction develops between the concrete and the wood during lateral translation with a bolted connection
- Early stages of concrete side break-out are not visually detectable during the test



<u>Mode I</u> - wood bearing
deformation in side member.



<u>Mode III$_s$</u> - wood bearing
deformation in side member &
dowel bending in concrete.



<u>Mode IV</u> - wood bearing
deformation in side member &
dowel bending in wood & concrete.

From the preliminary experiments, friction between the wood sill plate and concrete was considered to be significant. The amount of shear resisted by friction was not known and the amount of friction present in the test may not be present in real applications. The membrane tests were therefore recommended to simulate “pure shear” through the minimization of the effect of friction on connection behavior, and conservatively force the majority of lateral load into the anchor bolt.

Peak loads from monotonic tests were used to establish the reference force term, Q_0, which establishes a base value for the load steps in the pseudo-cyclic testing. Monotonic tests were run at a sufficiently slow rate such that any internal flaws forming within the concrete could be detected using impact-echo testing. The loading rate for the monotonic tests was deemed appropriate for establishing the reference force term (Q_0) and to allow for careful monitoring of the test specimen and mechanism formation.

The loading protocol adopted for the Stockton tests, identified as the SEAOC Modified Load Protocol, was developed by the SEAOC Seismology Committee and the SEAOC Light-Frame Construction Subcommittee. The SEAOC Modified Load Protocol is based on the CUREE loading protocol (See Reference 2) with cycles added at lower force levels. Additional loading protocols described in FEMA-461 (See Reference 7) were also considered as part of the loading protocol development effort.

RESULTS AND DATA ANALYSIS

Without re-printing all 50 pages of the testing report, it is not possible to adequately summarize the results and data analysis in this forum. The B&W printing would also serve to frustrate the reader. We therefore refer the reader to the full published testing report available for download from the SEAONC website. http://www.seaonc.org

FINDINGS AND CONCLUSIONS

This test program was designed to achieve the following primary goals:
Determine whether the wood controls the connection capacity when loaded parallel to the edge: It appears that wood "yield" represents the first material limit state. The "Peak" values derived from the average values extracted from average cyclic envelope curves correlate strongly with concrete degradation (when detected in this testing program).

The connection assembly appeared to exhibit the following behavior phases described qualitatively as:

- initial take-up and displacement (connection assembly gets "seated")
- elastic bolt bending combined with wood crushing (dowel bearing)
- plastic bolt bending combined with wood crushing and some bolt elongation (as the bolt deflects and goes into tension; a clamping force also develops)
- plastic bolt bending combined with wood crushing and shallow concrete delamination (clamping forces continue to develop at as the bolt resists increasing tension forces). See Figure 3.
- plastic bolt bending combined with wood crushing and shallow spalling of concrete adjacent to anchor bolt. Again, see Figure 3.
- sill plate splitting (if developed during testing; occurs during the last 2 phases described above).

Fig. 3 – Concrete side break-out development.

Determine whether the connection exhibits "ductile" behavior. The connection behavior is clearly ductile as shown in Chart 1 below. For additional discussion, refer to the SEAOC Seismology Committee's Blue Book article on anchor bolt and wood sill plate connections.

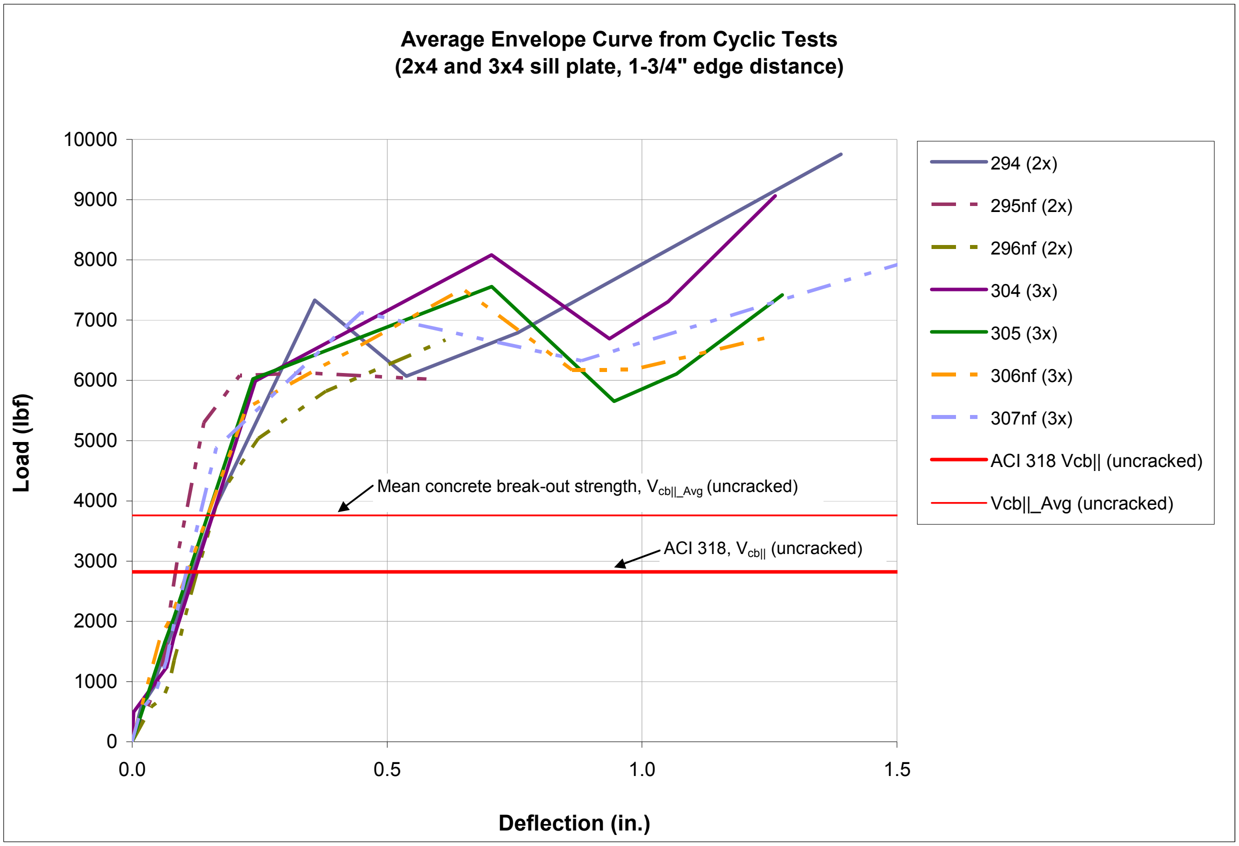


Chart 1 – Envelope curve (Chart 9 in full report)

Propose design capacities for the connection based on this testing. This program developed data that supports the development of design capacities for shear parallel to free edge in pounds (ASD). These design capacities are recommended for use in the design of similar connections intended to resist seismic loading in Seismic Design Categories C through F, (SDC C-F).

The test data for 2x4 and 3x4 plates indicate that the average peak strengths were:

- more than 6 times higher than ductile design strengths obtained from ACI 318-05 (and -08) Appendix D, and
- more than 4 times higher than the allowable capacity obtained from IBC-2006 (NDS-05)

The actual development of design capacities is deferred to the full SEAOC Seismology Committee. Their development and recommendation of appropriate design capacity for these connections is presented in a Blue Book article on this subject (available from http://www.SEAOC.org/bluebook). It should be noted that load values from these tests should be considered to be 10-minute values (including CD = 1.6).

In addition to primary goals, the test results indicate support of the following findings:

- Friction developed between the bottom of the wood sill plate in resistance to shear loading is real and substantial. The report did not attempt to quantify the effect. Future testing should consider incorporating a friction-reducing membrane into testing protocols to maintain a certain level of conservatism related to the capacity of such an assembly with a reduced level of friction. It is possible that the friction reducing membrane may replicate actual as-built assemblies such as a sill plate installed in conjunction with a sheet-metal termite shield.

- Concrete degradation (i.e. delaminations and/or the formations of flaws within the concrete) is often detectable during testing if the impact-echo nondestructive testing method is correctly applied. Since visually-apparent spalls often formed some time after initial flaw detection; impact-echo nondestructive testing is recommended for future testing programs.
- Damage following cyclic loading was not readily apparent when viewed from above, even with the nut and plate washer removed. The tested specimens exhibited limited plate splitting and bolt hole elongation at the upper surface of the sill plate. Wood crushing and subsequent concrete degradation are only visible when a section of sill plate is removed or when the affected face of concrete is exposed/testable.

In conclusion, the tests indicate that 5/8 inch diameter L anchor bolts in 2x4 and 3x4 wood sill plates attached at the edge of a concrete foundation exhibit ductile behavior and attain peak loads much higher than design strengths obtained using ACI 318-08 (and ACI 318-05), Appendix D and IBC 2006. The test data supports the design of this connection using NDS bolt shear capacity values.

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REFERENCES

Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary, American Concrete Institute (ACI), Farmington Hills, MI 48333.

Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary, American Concrete Institute (ACI), Farmington Hills, MI 48333.

California Building Code (CBC), 2007, California Building Standards Commission, Sacramento, CA.

Development of a testing protocol for wood-frame structures. CUREE Publication W-02.

Dolan, J.D.; Gutshall S.T.; and McLain T.E. 1996b. - Determination of short-term duration-of-load performance of nailed and bolted connections using sequential phased displacement tests. VPI Research Report No. TE-199 4-003 Virginia Polytechnic Institute and State University, Blacksburg, VA.

Fuchs, W., Eligehausen, R., and Breen, J. E., "Concrete Capacity Design (CCD) Approach for Fastening to Concrete," ACI Structural Journal, V. 92, No. 1, January-February 1995, pp. 73-94.

International Building Code (IBC), International Code Council (ICC), 2006. Falls Church, VA 22041

Krawinkler, Helmut; Parisi, Francisco; Ibarra, Luis; Ayoub, Ashraf; Medina, Ricardo, "Development of a Testing Protocol for Wood-Frame Structures". CUREE Publication W-02. Consortium of Universities for Research in Earthquake Engineering, Richmond, CA.

Mohammad, M.; Karacabeyli, E.; and Quenneville, J.H.P.,2003, Lateral resistance of bolted wood-to-concrete connections loaded parallel or perpendicular to grain. Canadian Journal of Civil Engineering, -

National Design Specification® (NDS®) for Wood Construction. 2005. American Forest & Paper Association (AF&PA). Washington, DC 20036.

Protocols for determining seismic performance characteristics of structural and nonstructural components through laboratory testing. FEMA 461 - May 2007.

Soltis, L.A.; Wilkinson, T.L., 1991, United States adaptation of European Yield Model to large diameter dowel fasteners specifications, International Timber Engineering Conference, London, UK

Standard Test Method for evaluating dowel-bearing strength of wood and wood-based products, 2007. ASTM Standard D 5764 - 97a, - ASTM International, West Conshohocken, PA.

Standard Test Methods for cyclic (reversed) load test for shear resistance of vertical elements of the lateral force resisting systems for buildings, 2008. ASTM Standard E 2126- ASTM International, West Conshohocken, PA.

Standard Test Methods for measuring the P-Wave speed and the thickness of concrete plates using the impact-echo method, 2004. ASTM Standard C 1383- ASTM International, West Conshohocken, PA.

Summary Presentation of SCL experiments as presented to the SEAOC Seismology & Structural Stands Committee. September 23, 2008. SEAOC Convention, Hawaii.

Testing Specifications and Loading Protocols for the Preliminary Phase of Anchor Bolt Testing. Approved by SEAOC Seismology & Structural Standards Committee. October 15, 2008.