Anchor Bolts in Light-Frame Construction at Small Edge Distances

Seismology Committee, Structural Engineers Association of California

To have a realistic understanding of anchor bolt behavior on exterior wood-framed walls, the engineer needs to know the behavior of the "L-bolt" that is commonly specified and constructed. In this connection, in-plane shear from wood-framed walls are typically transferred from wood sill plates through steel anchor bolts to a concrete foundation or deck. The testing reported here provides valuable insight for the behavior of this connection, and clarifies the assumptions required to provide an economical design using the most recent codes and standards. The testing indicates that the yield strength of the wood sill plate and steel anchor bolt subassembly of the connection, rather than the bolt-to-concrete portion of it, governs the connection strength, and that the connection performs in a ductile manner. SEAOC (Structural Engineers Association of California) Seismology Committee also provides design recommendations based on the testing.

Figure 1: Test set-up. Direction of loading is parallel to the concrete foundation. A bolt deformed in a previous test is shown in the foreground. The arrow points to a single anchor bolt with square washer in a 7-foot-long sill plate ready for testing.

Recent Changes in Codes and Standards

The change of model codes in California in January 2007 from the 1997 *Unified Building Code* (UBC) to the 2006 *International Building Code* (IBC) required a number of fundamental changes to accepted design practices of sill plate anchorage in light-frame structures. A significant change to design practice was required to apply the IBC provisions for the seismic design of anchor bolt connections occurring near a concrete edge. These changes have been a source of much discussion and frustration for code users in high seismic areas subject to the IBC and American Concrete Institute (ACI) codes.

In California, the design procedure and code-prescribed capacity of these anchor bolts in concrete had not changed since the values were first tabulated and introduced in the 1979 UBC. In the IBC jurisdictions outside California, new ACI strength-based provisions for the design of seismically loaded cast-in anchors have been a part of the IBC since the 2000 edition. Regarding the provisions of the 2006 IBC, which are currently applicable in many states, anchor bolt design is covered in IBC sections 1911 (*Allowable Stress Design*) and 1912 (*Strength Design*). IBC 1911 requires that, with any seismic loading, anchor bolt capacities must use a strength-based design procedure. Thus, per IBC 1912, the L-bolt is specifically required to be designed to the requirements of *ACI 318 Appendix D*, provided its application "is within the scope of the appendix." For the strength design of anchors that are not within the scope of Appendix D, the anchors shall be designed by an "approved procedure." Therefore the subject sill plate anchorage is required to use the strength-based Appendix D design for seismic loads, but for wind loads the anchor bolt capacities may be taken from IBC Table 1911.2, which still contain the historical values used prior to the IBC.

The scope and provisions of ACI 318 Appendix D resulted from many years of testing, and substantial effort directed at providing designers more transparency into the limit states associated with various classes of concrete anchorage. Wood sill plate anchorage forms a small subset of possible anchorage conditions covered by Appendix D. This connection is of greater regional importance than international importance, and there was a gap in the literature addressing this condition prior to the SEAOC testing. As a result, the present code provisions did not fully anticipate application to this narrow but important condition falling within the category of concrete anchorage, and the general provisions produced design results inconsistent with the needs of light-frame design.

Using Appendix D, light-frame designers have derived bolt values on the order of one-quarter to as little as one-fifth of the traditional value when assuming a non-ductile connection and cracked concrete. Such a result is very low and leads to a design solution that would be physically impossible for the wood sill attachment of many code-listed shear wall systems. For example, some designers have derived a capacity of approximately 300 pounds (ASD) for an anchor that traditionally carried approximately 1200 pounds (ASD). Accordingly, a fairly heavily loaded shear wall that would have traditionally required two anchors per stud bay would now require eight anchors per stud bay, which do not physically fit. Since issues with the old values were not apparent, the need for substantial change was puzzling, both with respect to significantly lower connection values and also the complexity of the required analysis, which utilizes over a dozen variables.

Code Issues Targeted by the Testing Project

Two assumptions that affect the ACI Appendix D calculation are the ductility parameter and the cracked concrete parameter. The ductility parameter of

IBC 1908.1.16 [D3.3.5] can be considered extremely sensitive, as it requires a 60 percent reduction to the connection capacity in concrete if the attachment to concrete is deemed to be not ductile at the concrete design strength. (ACI 318-08 has reduced the reduction to 50 percent in light-frame construction.) The resultant low concrete capacity values suggest that a failure of the connection is expected to occur in the concrete long before it occurs in the anchor bolt or the wood sill plate. However, the SEAOC Seismology Committee performed a literature search of anchor bolt testing for wood sill plates with small concrete edge distances and discovered very limited research was available. The SEAOC Seismology Committee then decided to embark on an anchor bolt testing program. Using the Tyrell Gilb facility of Simpson Strong-Tie Company in Stockton, California, a facility accredited to comply with ANSI/ISO/IEC Standard 17025:2005, members of the SEAOC Seismology Light-frame Subcommittee conducted the first test program of its kind, where the behavior of light-frame wood sill plate anchorage at small edge distances was targeted. The results of this testing program are published in the document *Report on Laboratory Testing of Anchor Bolts Connecting Wood Sill Plates to Concrete with Minimum Edge Distances*, dated March 29, 2009, available from the SEAONC (Structural Engineers Association of Northern California) website: **www.seaonc.org**.

Testing Procedures

The SEAOC tests included two unique features. First, the effect of friction was isolated on half of the tests by providing a lubricated polyethylene membrane at the wood-concrete interface. This allowed the contribution of friction to be better understood in analyzing the test data. Second, the impact-echo method was used to continuously monitor the status of any delamination that developed in the concrete during the testing that may not have been visible. For the test setup, (*Figure 1*) every effort was made to test materials representative of the most common shear wall connections. Anchor bolts were ⅝-inch nominal diameter A36 "L-bolts" with 7 inches embedment into approximately 2500 psi concrete. Sill plates of 2x4, 2x6, and 3x6 dimensions were tested, with anchor bolt edge distances of 1.75 or 2.75 inches depending upon the sill plate size.

A new displacement-based loading protocol was developed. Using data from an initial set of monotonic pull tests, cyclic tests were calibrated so that damage produced by the test would best represent and measure actual in-service failure modes. For the new protocol, the SEAOC Seismology Committee used a hybrid approach, essentially taking the CUREE Woodframe Project protocol with additional cycles added at low load levels. Independently, the SEAOSC (Structural Engineers Association of Southern California) sequential phased displacement (SPD) loading was used on several tests and results compared favorably.

Findings from the Testing

Based upon the test report, the L-bolts may be conservatively designed assuming a wood yield mode as predicted by the yield limit equations associated with Mode III$_s$ and Mode IV behavior in the *ANSI/AF&PA NDS-2005 National Design Specification® (NDS) for Wood Construction*. These values are subject to the same limitations as NDS Table 11E and do not apply to anchorage in light-weight concrete, post-installed anchors, or anchorage of cold-formed steel track.

For loads in the range of design values, which were well within the elastic range, there was little difference between the pseudo-cyclic, monotonic, and sequential phased displacement test results. Once the anchors were loaded to approximately 5000 pounds, the anchors slowly started to exhibit some plastic behavior as further displacement occurred. The frictionless membrane applied under the length of the sill plate had a minor effect at small displacements within the elastic range.

Fastener fatigue was not a limit state influenced by any of the various loading protocols. This is an important observation, since it limits the area of concern to the strength of wood and concrete elements tested.

The class of anchorage connections tested was ductile, and concrete side-breakout was not detected until the resistance force was significantly beyond the elastic range, specifically not until the peak value was achieved.

The predicted ACI Appendix D concrete break-out strength (taken from the estimated mean) appears overly conservative for the 2x4 and 3x4 wood sill plates. In the test, considering the case either with or without the friction-reducing membrane, the 2x4 and 3x4 cyclic tests averaged 1.9 times the predictive value associated with the ACI provisions. Similarly, the 2x6 and 3x6 cyclic tests achieved 1.4 times the ACI assumptions. If the ACI Appendix D mean values were to accurately reflect the test results, the comparison would be expected to be on the order of 1:1. (These ratios are not applicable to design loads.)

Finally, since the ultimate values corresponded to large displacements, it should be noted the data reduction used in the test report was conservatively modified from the ASTM E2126 standard. In particular, the first peak was used rather than the ultimate load specified by the standard. This peak value was defined by the SEAOC Seismology Committee as the highest load prior to any drop of 5 percent in capacity.

Assumptions Applicable to Anchor Bolt Design

Scope of ACI Appendix D

Generally speaking, sill plate anchorage is not a low redundancy application, and thus designers may be tempted to conclude that the typical cast-in L anchor bolt is not within the scope of ACI appendix D, because ACI-05 commentary indicates those provisions apply to non-redundant conditions. There are typically at least four connections present in the sill plate, even with a narrow shear wall application (two hold downs and two anchor bolts). Also, there

Table 1: Anchor Bolt Shear Values Based on the NDS 05 (CD=1.6)

Sill Plate	Bolt Diameter[1,2]		
	½-inch	⅝-inch	¾-inch
2x	1040	1488	2032
3x	1232	1888	2426

[1] ¾-inch anchor bolt limited to 6-inch nominal width sill plates
[2] Values are shown in lbs. (ASD basis)

are often other interior walls present and there is a likelihood of substantial friction at the sill plate connections. While a redundancy-based argument may have certain merits, the IBC states that if anchors are not to be regulated by Appendix D, another "approved method" is necessary. Such an approved method should incorporate a similar level of sophistication as Appendix D. However, IBC Table 1911.2 does not incorporate the various failure mechanisms that are addressed by Appendix D.

Supplementary Reinforcement

Supplementary reinforcement qualifies for a higher strength design factor as per ACI 318-05 section D4.4. However, on this point the SEAOC Seismology Committee cautions designers who may be tempted to categorize the typical continuous #4 or #5 reinforcement bar or post-tension tendon near the top and along the edge of the slab or curb as supplementary reinforcement. In the test, we found that the #4 bar placed near the top of the footing did not appear to directly influence concrete side-break-out. In practice, the bar location in the field is not sufficiently accurate to benefit the relatively shallow subject anchor bolt.

Cracked Concrete Assumption

The first UBC code reference regarding cracked concrete appeared in 1997 UBC section 1923.2, which referred to anchorage embedment in "tension zones." At the time, overhead anchorage of structural members and equipment were a primary concern, and these regulations applied to anchorage occurring below the neutral axis on bending members such as beams or elevated concrete decks. However, the uncracked assumption is generally justified in light-frame construction. This view is supported by the review of available test information recently published by Eligehausen, Mallée, and Silva in the publication *Anchorage in Concrete Construction* (2006), where it is concluded that no reduction was discovered when anchors were loaded perpendicular to the cracks. In light-frame construction, any cracks occurring in the concrete substrate would be expected to be more or less perpendicular to the concrete edge, and thus perpendicular to the applied load and not affecting the subject anchors.

It bears repeating that the code requires the determination of cracked versus uncracked to be made at service level loads, and that the crack reduction applies to a full-depth crack along the axis of the anchor. Given the inherent redundancy of anchors in light-frame construction, coupled with the low probability of coincidence between qualifying cracks and typical anchor placement, it is not reasonable to assume a cracked substrate unless specific conditions clearly indicate otherwise.

Based upon the test report, it is rational to use either the values obtained from ACI Appendix D assuming uncracked concrete and a ductile attachment, or the NDS-05 design values for this common light-frame connection, as is detailed in the SEAOC bluebook article. (*Table 1*)

Finally, the reader is cautioned that any damage occurring to this connection may not be readily apparent, because it may be obscured by the sill plate. The photos in the testing report provide some inspection guidance for those involved in post-event observations.▪

*Questions concerning this article may be directed to the Chair of the SEAOC Seismology Committee, Mehran Pourzanjani (**mehran@sbise.com**). The complete Blue Book article on this subject may be accessed at **www.seaoc.org/bluebook**.*

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