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Lateral Resistance of Walls and Anchorage in Log Structures

By Robert Leichti, Randy Scott, Thomas Miller, P.E., and Jeff Sharpe, P.E.

Log structures are part of American history and the contemporary building inventory. The early structures were low, squat buildings with few wall perforations for windows and doors. However, newer log structures often are large, have many and/or large wall perforations for windows and doors, and include high aspect ratio wall segments, especially at the corners. Just as in older log structures, new log buildings incorporate interlocked corner connections, and the wall height changes dimension during the life of the structure as the logs lose and absorb moisture. The interlocked corners contribute integrity to the building system, but the joints at the window and door openings typically permit slip to accommodate moisture response dimensional change.

Log shear walls typically are also bearing walls and resist lateral loading through a different mechanism than light-frame walls. In light-frame walls, the lateral loads are transferred from the top plate to the foundation through the nailed sheathing. Nail bending, nail withdrawal, and nail pull-through are important energy dissipation mechanisms in light-frame shear walls. According to Haney (Log Building News, 2000), lateral loads in log shear walls (*Figure 1*) are transferred from top plate to foundation through log-to-log friction, inter-log hardware, and inter-wall corner connections. Log-log slip is a critical energy dissipater in log shear walls

In a recent research project, Scott (MS Thesis, Oregon State University, 2003) examined foundation anchorage and base shear capacity for log buildings and the effect of construction details on lateral force resistance in walls made with manufactured logs. The manufactured logs investigated were surfaced top and bottom so that flat or mated surfaces are in contact. These are distinguished from round and scribe-fit logs, which typically have a linear contact with the neighbor logs.

Inter-Log Connection

The engineering purpose of inter-log hardware is to provide a positive load path for the lateral force from roof to foundation and to increase the stability of the wall segments. The small and simple log structures of yore could stand without inter-log connection, because logs ran from corner to corner and wall perforations were small. The inter-log connectivity for contemporary log structures can be designed using yield mode equations in Chapter 11 of the *National Design Specification*® (NDS®) *for Wood Construction* (AF&PA 2005).

A plethora of fasteners for log buildings has emerged in the last decade. Spikes, lag screws, through-bolts, threaded log-home screws, drift pins, and wood dowels, are all recognized (Log Homes Council, 2003). Through-rods can be tightened by automatic take-up springs as the building shrinks or by manually tightening the nuts at the top plate, but lag screws and spikes are not accessible and are not tightened later. The choice of inter-log fastener is affected by many factors including log alignment, log profile, management of settlement, length of logs, corner details, and unit shear requirements of the building system (Log Homes Council, 2003). Each of these fasteners has installation requirements, and building system performance can be affected by small changes in installation and construction details (Scott et al, Forest Products Journal, 2005b).

Foundation and Base Shear Capacity

Foundation anchorage is an important component of seismic performance in log buildings. Mahaney and Kehoe (The CUREE CalTech Wood Frame Project, 2001) provided a literature review on the subject of foundation anchorage for light-frame buildings. Log structures are typically placed on foundations of similar design to those used for light-frame wood and masonry construction. Shear forces that develop at the base of the wall are transferred from the sill log (bottom log in the wall) to the foundation by anchor bolts. Common anchor bolt spacing is 48 inches, and anchor bolt holes are oversized to facilitate construction. Anchor bolts lose tightness as the log shrinks due to drying (Scott et al., Forest Products Society Annual Meeting, 2002), and anchor bolt nuts may be inaccessible so they cannot be tightened later in the life of the structure. In addition, the building mass is often significantly greater than a light-frame building and connection geometry is different because the log diameter is larger than the thickness of a typical 2-by sill plate.

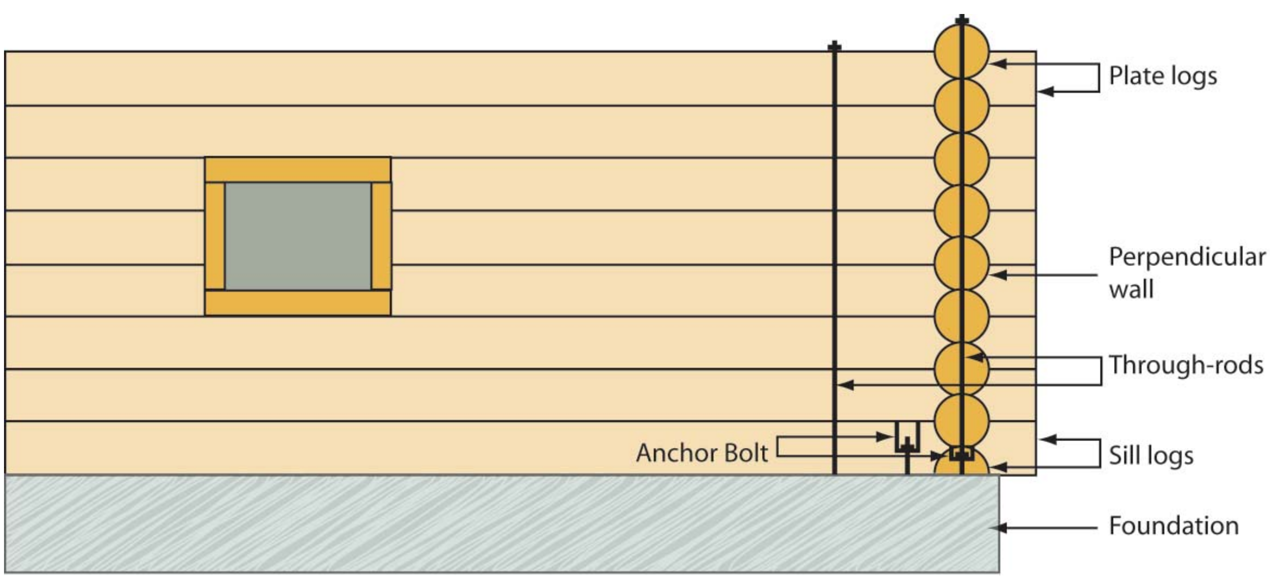

Figure 1: Log wall including a window opening and an inter-wall connection on a rigid foundation (from Scott et al. 2005a)

Two foundation/anchorage details common to log structures were explored (*Figure 2*). The first has the log wall sitting on the floor diaphragm. In this case, the anchor bolt must be long enough (or coupled) to extend from the top of the foundation wall through the floor cavity and the sill log. In the second design, the sill log is in contact with the foundation wall or sits on a treated wood plate. In this second instance, the anchor bolts pass from the foundation directly into the sill log.

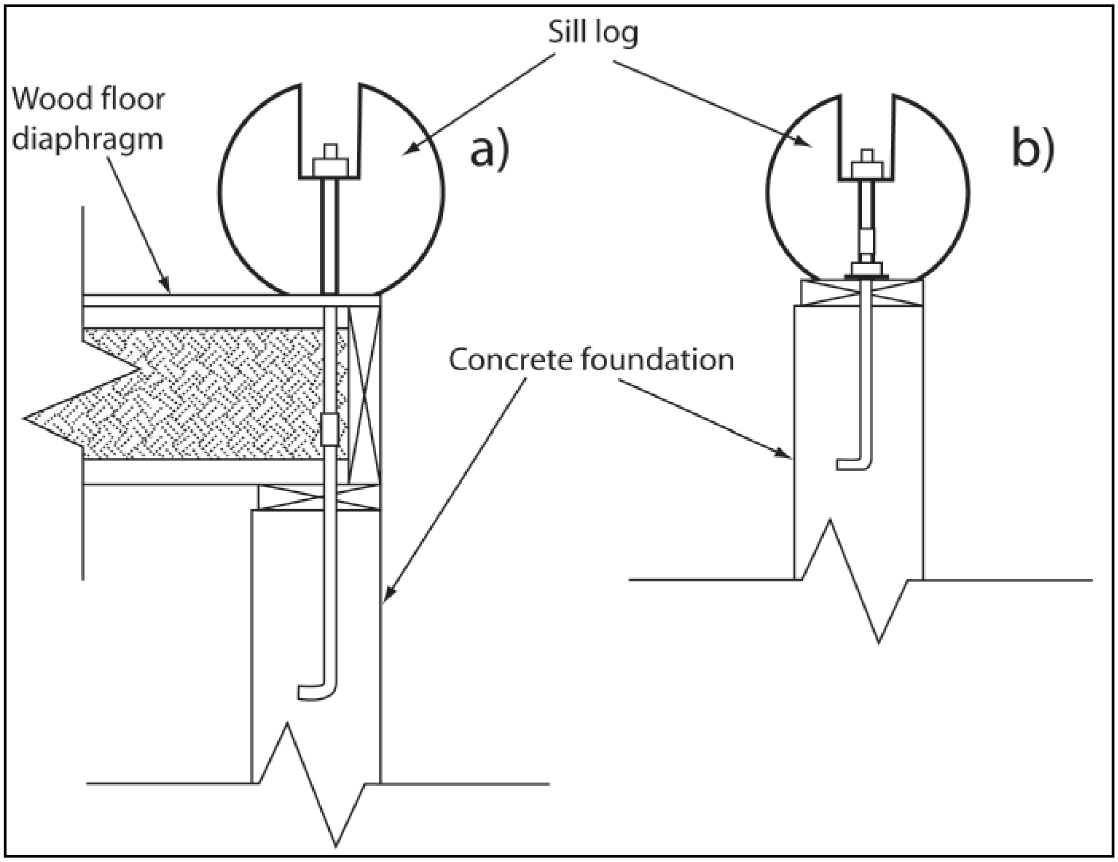

Figure 2: Typical foundation details for log buildings; (a) sill log on floor diaphragm, (b) sill log on concrete foundation wall (from Scott et al. 2005a)

A series of tests was conducted to evaluate the effectiveness of the two foundation/anchorage designs. The tests were of assembled systems that included all the components of each foundation, sill log, and anchorage hardware. Static tests of each were performed and these were followed by a set of quasi-static tests based on the CUREE test protocol (Krawinkler et al., CUREE/CalTech Wood Frame Project Report, 2000). The test configuration included a vertical load to mimic dead and live loads in the designed wall system as well as the lateral loading mechanism. Details of the testing apparatus and protocol are given by Scott (2003).

Test results (*Figure 3*) for each of the foundation/anchorage details showed that friction between the sill log and the sill plate is an important part of system behavior. The open boxy shapes of the hysteresis diagrams are typical of friction damping behaviors. These tests were terminated when the lateral force reached 10 kips, which was before the system failure. For the sill log on the floor diaphragm, the system was still accepting load at 10 kips, but it appeared that the ultimate yield mode would include the rim board to sill plate toenail connection. In the system with the sill log on the foundation wall, the sill plate sustained damage, but the system capacity was limited by anchor bolt bending.

For seismic design, the *Uniform Building Code* (UBC) (ICBO 1997) requires design for an earthquake load (E),

$$E = \rho E_h + E_v \qquad Eq.\ (1)$$

The redundancy factor ρ has an upper bound of 1.5, which is used here. E_h is the load due to horizontal ground motion (base shear), while E_v is the load effect attributed to vertical ground motion and is zero for allowable stress design.

The *UBC* base shear formula is,

$$V = \frac{C_v I}{RT} W \qquad Eq.\ (2)$$

The *UBC* also defines the upper bound for base shear as,

$$V = \frac{2.5 C_a I}{R} W \qquad Eq.\ (3)$$

C_v = 0.64 and C_a = 0.44 are the seismic (response spectrum) coefficients (*UBC* Tables 16-R and 16-Q) for type S_D soil profile and seismic zone 4, I = 1 is the importance factor (*UBC* Table 16-K), T = 0.11 seconds is the fundamental period that is calculated from *UBC* equation 30-8 for height = 10 feet, and the response modification factor R depends on the structural system. A specific value for R has not yet been assigned to log structures. However, R could range from 2.8 (light steel frame and some gravity-force braced frames) to 5.5 (light-frame walls with shear panels less than three stories). The most conservative estimate for V is used assuming R = 2.8. A less conservative value for V is obtained using the R-value for masonry walls (Scott et al., Forest Products Journal, 2005a). Calculations show that the upper bound for V controls for this log structure. Seismic dead load W=4880 pounds includes the weight of the wall and the roof. When the upper bound is divided by 1.4 to convert from strength level to allowable stress design, E = 2050 pounds for a representative wall that is 8 feet long.

The tested foundation/anchorage assemblies resisted lateral forces of at least 9890 pounds. Thus, the ratio of capacity to design is at least 4.8, which is consistent with the factor of safety for mechanical connections.

Uang (Journal of Structural Engineering, 1989) provides a method to establish design coefficients and factors (response modification, system over-strength, and deflection amplification) for building seismic provisions. The basic formulas derived by Uang can be used for a rational analysis of these factors so they can be consistent with the *International Building Code* (IBC) (2003). As for masonry structures, several different sets of design coefficients may be needed depending on the log profiles and type of inter-log fasteners. The Wood Materials Engineering Lab at Washington State University and the Department of Wood Science and Engineering at Oregon State University are developing a collaboration to establish the underlying support for the design coefficients.

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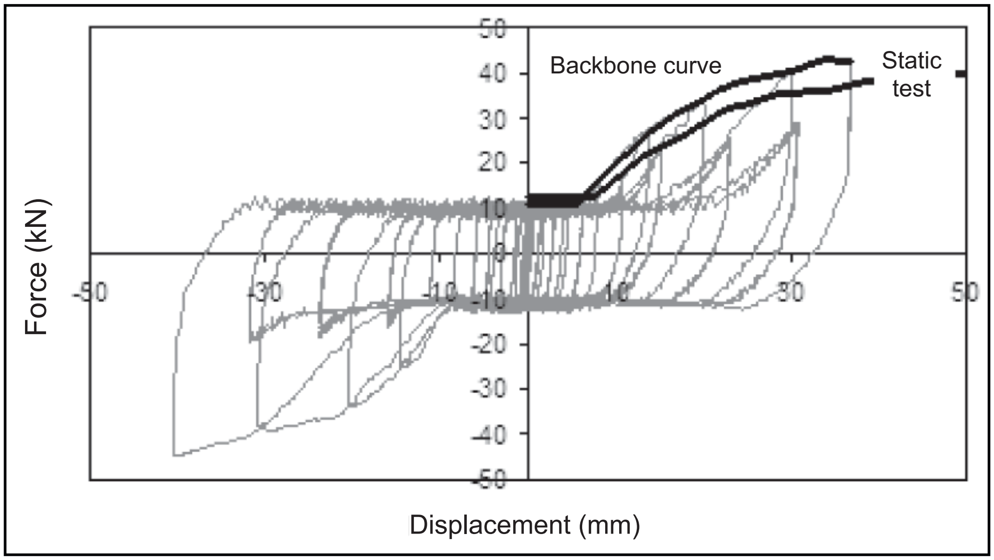

Figure 3: Hysteresis diagram from a fully-reversed quasi-static test of a sill log on a floor diaphragm (from Scott et al. 2005a)

Modeling the Effect of Construction Details

A common construction detail is to place through-rods within 8 to 12 inches of the wall ends and each window and door opening, as well as 6 feet on center along the wall. When through-rods are used, they are installed through oversized holes and are continuous from the top plate log to the sill log or foundation. A common approach is to post-tension through-rods to 1000 pounds using continuous take-up springs at the top of the wall.

Gorman and Shrestha (Forest Products Society, 2002) tested two log walls using the sequential phase displacement test method. The walls were made with manufactured logs and were 11.3-feet long and 8-feet tall and included through-rod hardware. Their tests showed that log shear walls with through-rods exhibit initial linear behavior followed by slip and additional capacity, which is observed as an ascending load-displacement response before failure. This is the same behavior that was seen by Scott (2003) while testing log building foundation/anchorage assemblies.

Finite-Element Models

Wall dimensions, rod placement, and boundary conditions of the models by Scott (2003) closely matched log walls tested by Gorman and Shrestha (2002). The finite-element models were 8 feet wide by 8 feet high and 6 inches thick. Two through-rods extended from top to bottom of the wall and are located 8 inches from each end. The models consisted of solid, beam, nonlinear spring, and elastic spring elements. The logs were modeled as rectangular bodies using 4-node, plane-stress elements and assigned elastic properties typical of Douglas-fir. The through-rods, represented by beam elements and assigned properties of plain carbon steel, were pretensioned at various levels as part of the parametric investigation. The models included log-log friction as represented by nonlinear spring elements and log weight. The details of the modeling process, force-displacement behaviors, boundary conditions, and loading are given in Scott et al. (2005b). A parallel basic model was developed for the two basic foundation/anchorage systems.

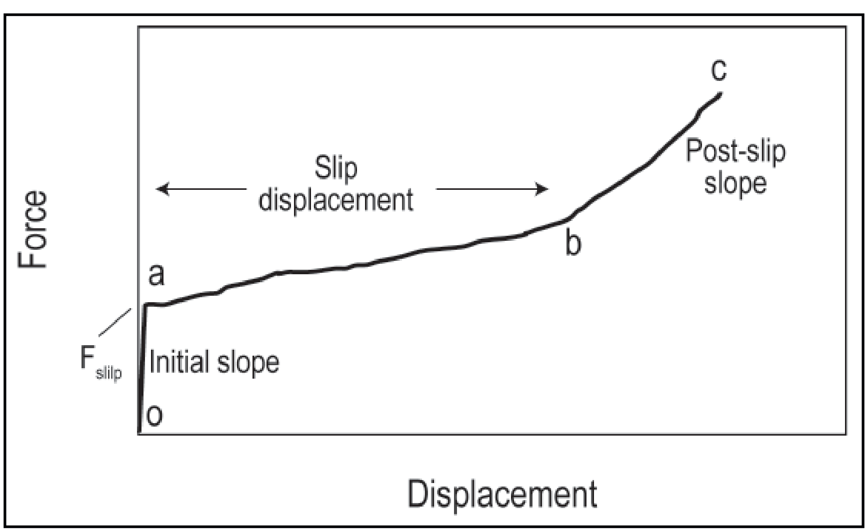

Figure 4: Basic force-displacement curve for a log shear wall with through-rods (Scott et al. 2005b)

Finite-Element Results

The log shear wall model shows three main behaviors in the load-displacement diagram (*Figure 4*), where displacement is the horizontal motion of the top plate log. The wall begins to slip at the top plate and then slips at consecutive interfaces between logs following a top down displacement process because the models have both weight and inter-log friction. The first section, ***0a***, represents the system stiffness before the friction is overcome (initial stiffness). At point ***a*** (slip force), friction is overcome so that path ***ab*** represents slip displacement, which is limited by thru-rod and anchor bolt oversized hole slack. The third section (post-slip stiffness), ***bc***, represents the system stiffness after the slack is taken up and the thru-rods and anchor bolts are engaged.

The wall model is compared to the backbone curve (*Figure 5*) from fully-reversed cyclic tests by Gorman and Shrestha (2002). The foundation model was compared to data generated in the Scott (2003) foundation/anchorage tests.

A series of parametric studies was undertaken to assess the effects of friction as generated by through-rod hardware, window and door openings, and wall aspect ratio. In all, 14 models were developed to evaluate the effect of construction variables on lateral force resistance and stiffness of log shear walls (Scott et al. 2005b). It was shown that:

- Wall performance is strongly influenced by the coefficient of friction and the normal forces developed by through-rods and dead loads. Thus, maintaining through-rod tension will enhance building system performance under seismic loads.
- Changing the wall aspect from 1:1 to 2:1 decreased the post-slip stiffness and increased overall wall displacement more than any other attribute. High aspect ratio walls may require additional stiffening.

- Additional through-rods are often included in construction details for doors and windows and are important in minimizing the effect of wall perforations and improving wall stability.
- Through-rod hole size affects overall wall displacement. Minimizing hole diameter minimizes slip displacement potential.
- The results are expected to be much different for other log-log interfaces and inter-log fasteners.

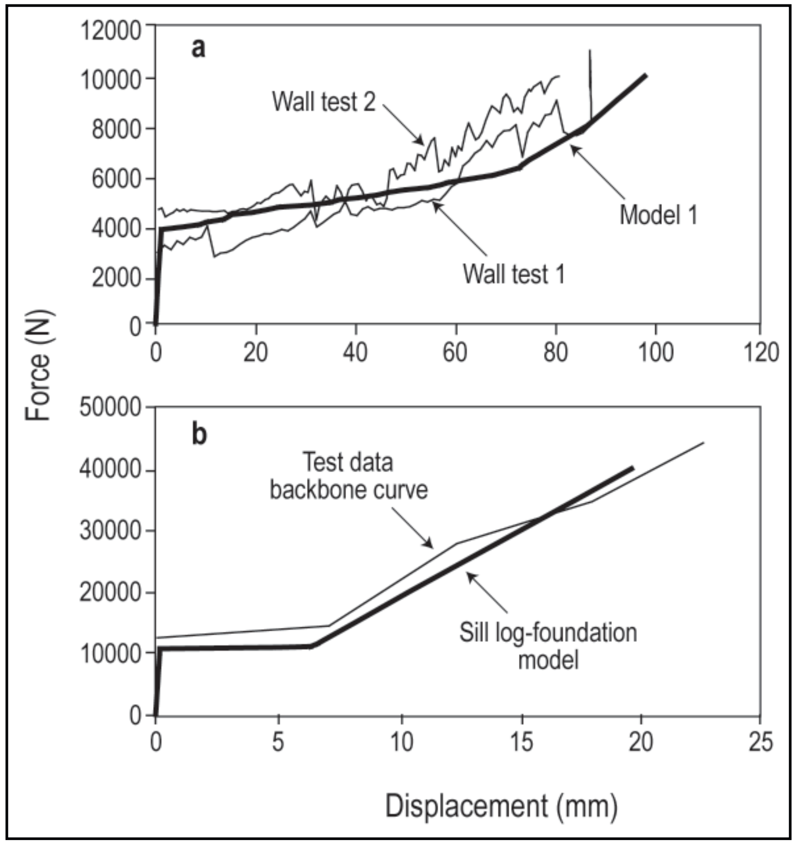

Figure 5: Comparison of (a) wall model load-displacement performance to the backbone curve from Gorman and Shrestha (2002) and (b) sill log tests and the model

Conclusions

The log structure foundation/anchorage systems explored appear to be adequate for lateral force resistance, and the anchor bolts can be designed using the yield mode models of the *NDS*. Seismic design coefficients have not been established for log buildings, and it is likely that they will depend on inter-log fasteners and log profiles. Safety levels using conservative R-values appear to parallel those for dowel-type connections used in wood construction.

Finite-element models have reproduced basic behavior of log wall systems and were extended to assess several common construction details including through-rod tension, wall perforations, and through-rod hole sizes. Further studies are planned to generate the data and determine rational R-values for various log-log interfaces and inter-log fasteners.▪

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References

American Forest & Paper Association (AF&PA). 2005. National Design Specification® for Wood Construction. AF&PA, Washington, DC. 173 pp.

Gorman, T., and D. Shrestha. 2002. Shear tests for log home walls. Session 5: Testing and analysis of large-scale wood structural systems. Forest Products Society, Madison, WI.

Haney, T. 2000. How log buildings resist lateral loads. Log Building News, 32:1-6.

International Codes Council (ICC). 2003. International Building Code. ICC, Falls Church, VA.

International Conference of Building Officials (ICBO). 1997. Uniform Building Code. ICBO, Whittier, CA.

Krawinkler, H., F. Parisi, L. Ibarra, A. Ayoub, and R. Medina. 2000. Development of a testing protocol for wood frame structures. CUREE/CalTech Wood Frame Project Report. Stanford University, Stanford, CA. 85 pp.

Log Homes Council. 2003. Fasteners for log homes, log tech note 02-02. Log Homes Council, National Association of Home Builders, Washington, DC. 1 p.

Mahaney, J.A., and B.E. Kehoe. 2001. Anchorage if woodframe buildings , Task No. 1.4.1.1 Woodframe Project Testing and Analysis Literature Reviews, The CUREE Caltech Wood Frame Project, University of California, San Diego, CA. pp. 75-88.

SAS IP, Inc. 2001. ANSYS®, version 6.0. SAS IP, Inc., Houston, PA.

Scott, R.J. 2003. Lateral force resisting pathways in log structures. MS thesis, Oregon State University, Corvallis, OR. 173 pp.

Scott, R.J., R.J. Leichti, and T.H. Miller. 2005a. An experimental investigation of foundation details and base shear capacity for log buildings. Forest Products Journal, 55(4):38-45.

Scott. R.J., R.J. Leichti, and T.H. Miller. 2005b. Finite-element modeling of log wall lateral force resistance. Forest Products Journal, 55(9):48-54.

Scott, R.J., R.J. Leichti, and T.H. Miller. 2002. Foundation anchorage in residential log structures. Biographies & Abstracts – Forest Products Society 56th Annual Meeting, Forest Products Society, Madison, WI. p. 48.

Uang, C.-M. 1989. Establishing R (or R_w) and C_d factors for building seismic provisions. Journal of Structural Engineering, 117(1):19-28.