Wood Construction Codes Issues in the United States

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1. Introduction

The current wood construction codes find their origin in the 1935. Wood Handbook: Wood as an Engineering Material published by the USDA Forest Service. Many of the current design recommendations can be traced back to statements from this book. Since this time a series of development both historical and recent has led to a multi–layered system for use of wood products in the United States. The following paper will first discuss the wood construction design criterion referenced by model codes used in the United States; second, touch on product standards; third, briefly discuss US model codes and their current status, and finally, discuss potential changes to the fastener design criteria.

2. Wood Construction Standards

The basic design criteria from which most wood structures are constructed, is specified in the three following documents; the National Design Specification for Wood Construction (NDS), Load and Resistance Factored Design for Engineered Wood Construction (LRFD), and the Wood Frame Construction Manual (WFCM).

2.1 National Design Specification for Wood Construction

Originally created in the late 1940's, the National Design Specification for Wood Construction (AF&PA 2005) is the most nationally recognized design guide for wood structures. The foundation of this design guide is Allowable

Stress Design (ASD), where stresses generated from design loads are compared to allowable material stresses. In general the NDS provides the requirements, design provisions and formulas for structural lumber, glued laminated timber, structural–use panels, shearwalls and diaphragms, poles and piles, I–joists, structural composite lumber, and structural connections (nails, bolts, screws, split ring and shear plate connectors, and timber rivets). In 2005, the NDS adopted a dual format approach which enables the designer to use either an allowable stress design approach or a load and resistance design approach.

2.2 Load and Resistance Factored Design for Engineering Wood Construction

The American Society of Civil Engineering (ASCE) 16-95 Standard for Load and Resistance Factor Design for Engineered Wood Construction (ASCE 1995) was approved in November 1995 as a consensus standard through the ASCE standards development process. In general the LRFD addressed the same concern as the NDS. The development of this standard was an outgrowth of a larger effort to develop code criteria based on a reliability approach. This approach compares the forces resulting from applied factored loads to the resistance of the specific member, connection, or assembly. Due to a code calibration process when the LFRD was developed, typically the NDS and LRFD result in the same member design.

In 2005, the NDS incorporated the reliability based design approach to give designers the option to choose either an ASD or LRFD approach for design.

2.3 Wood Frame Construction Manual

The Wood Frame Construction Manual (AF&PA 2001) for One– and Two–Family Dwellings, provides engineered and prescriptive requirements for wood frame construction based on dead, live, snow, seismic and wind loads derived from the 2000 International Building Code (IBC 2000). Developed over a six–year period concluding in 2001, the WFCM gives designers and code enforcement officials a design reference to provide solutions for residential wood construction, which is increasingly being regulated, especially in higher load regions. The WFCM includes design and construction provisions for connections, wall systems, floor systems, and roof systems. Structural elements covered include sawn lumber, structural glued laminated timber, wood structural sheathing, I–joists, and trusses. Also included are provisions approved by the 2000 IBC for perforated shearwalls, wall stud system factors, and increased capacities for shearwalls and diaphragms used in high wind applications.

3. Structural Wood Products

3.1 Product Standards

In the U.S., wood products used in structural applications must meet minimum required performance levels. Product performance is assured by specifying manufacturing requirements, quality control programs, and assignment of design values. Manufacturing standards assure that production facilities operate above minimum required tolerances, and that the structural wood products are made according to a required grade or layup. Quality control standards assure that these levels are met on a daily basis, typically by random testing of products and components. Third-party inspection agencies are a required component in this process, to certify that production facilities follow these required standards. Design standards provide design values for structural wood products, which meet the required manufacturing and quality control standards.

For established structural wood products such as glued-laminated timber (glulam), analysis methods exist that allow new species and/or new layups to be introduced. New structural wood products cannot be introduced into the marketplace until mechanical property information and design calculations are reviewed by a third-party inspection agency.

3.2 National Evaluation Reports

An alternative approach for introducing new products in the U.S. marketplace is based on testing. In this case, producers provide test data and any supporting documentation to an evaluation service, International Code Council Evaluation Service (ICC-ES), showing that the new product meets certain performance levels. After review of the performance data, and if justified, ICC-ES will issue a National Evaluation Report establishing the performance level of the product and approval for use in structural applications.

For more detailed information about the product standards and evaluation reports pertain to the structural wood products see Green and Hernandez (1998).

4. Model Codes

Construction in virtually every jurisdiction is regulated by building codes for the purpose of providing minimum standards of health and safety for the public. Private model building code organizations develop and maintain model building codes for use by state and local jurisdictions. A model building code is not enforceable until it is adopted by a state or local jurisdiction, with or without amendments, and it becomes law. Within the United States the key word with codes and standards is 'home rule'. Home rule is the ability of local governments to establish their own sets of codes and standards specific to their community. Typically these model codes empower the use of a given building material while at the same time creating the bounds for which the material can be used. For wood construction this is accomplished by referencing one of the three design specifications (NDS, LRFD, or WFCM) and wood product standards.

Prior to 2000 most of the United States adopted one of three model codes; National Building Code, Standard Building Code and Uniform Building Code. In 1994, the three competing code creating organizations agree to work toward developing single coordinated set of national model building codes. Their need lead to the development of the International Code Council (ICC) under which this activity would take place. Codes generated from the ICC are typical called the I-Codes. One interesting goal of the ICC was the development of a residential building code. Previously, the three model codes typically dealt with the non residential construction arena.

The first generation of the I-codes was published in 2000 and consists of the following documents:

- International Building Code- addresses design and installation of building systems with requirements that emphasize performance.
- International Residential Code- addresses one- and two-family dwellings and townhouses up to three stories and is coordinated with additional I-codes to address building, plumbing, mechanical, and electrical requirements.

Additional I-codes that complete the set include the fire code, plumbing code, mechanical code, fuel gas code, energy conservation code, private sewage code, performance code, electrical code, property maintenance code, zoning code, existing building code, and urban-wildland interface code.

During the formation of the first set of I–codes, the National Fire Protection Association (NFPA) withdrew from participation and started the development of a model code independent of the ICC process. In 2003, the association published the NFPA 5000 Building Construction and Safety Code. In 2004, NFPA announced a plan to develop an additional model code dealing with one– and two– family dwelling by 2008 to complete their model code package.

Neither model code, I–code or NFPA 5000, is enforceable until it is adopted by a state or local jurisdiction, with or without amendments, and it becomes law. Figure 1 shows the current adoption status of the I–codes and if the I–code is adopted statewide or at a local level in the United States. As evident from the figure, most jurisdictions have adopted I–codes.

- 47 dates plus Washington, D.C use the International Building Code
- 45 dates plus Washington, D.C use the International Residential Code
- 42 dates plus Washington, D.C use the International Fire Code

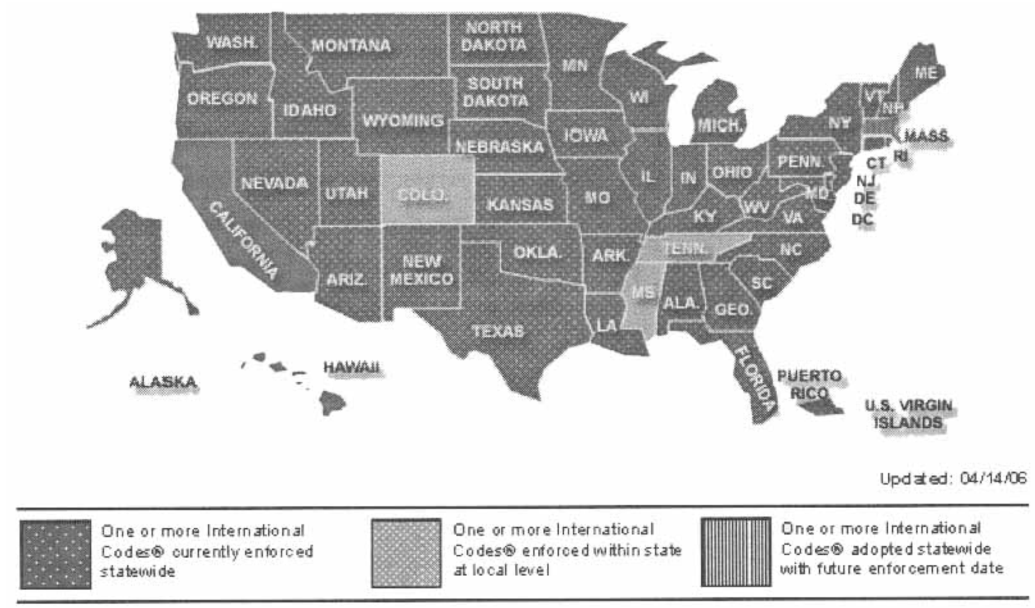

Figure 1 Current adoption status of the I-codes.

5. Fastener Design Criteria

Specifications for wood construction are constantly being modified and updated. One significant area under revision is the design criteria dealing with fasteners. A brief discussion of the current design approach for multiple fasteners is presented. Next, research highlighting the need to develop new fastener design criteria addressing wood failure mechanisms is discussed. Finally, proposed work items for the fastener sections of the next version of the NDS are presented.

5.1 Yield Theory and Prescriptive Spacing Requirements for Multiple Fasteners

Since 1991, the capacity of a multiple bolted connection loaded parallel to grain *(Z')* was determined using the single fastener yield connection value *(Z)*, duration of load factor *(C_D)*, wet service factor *(C_M)*, group action factor *(C_g)*, and number of bolts within the connection (n) in the following expression

$$Z' = nC_D C_M C_g Z$$

along with prescriptive spacing requirements. In general the design of the multiple bolted connection focuses on the single-fastener yield performance, group action or load distribution factor, and the prescriptive spacing requirement.

5.1.1 Single-fastener yield performance- The nominal single-fastener yield connection value is dependent on the joint geometry thickness of main and side members), bolt diameter, dowel bending-yield strength, dowel-bearing strength, and direction of load to the grain. Yield expressions relating these parameters were developed by Johansen (1949) using a static analysis that assumes the wood and the bolt are both perfectly plastic. The yield model theory selects the worst case of yield modes based on different possibilities of wood bearing and nail bending. Mode I is a wood-bearing failure in either the main or side member; mode II is a rotation of the fastener in the joint without bending; modes III and IV are a combination of wood-bearing failure and one or more plastic hinge yield formations in the fastener. Illustrations of these modes for a single shear and double shear connection is shown in Figure 2.

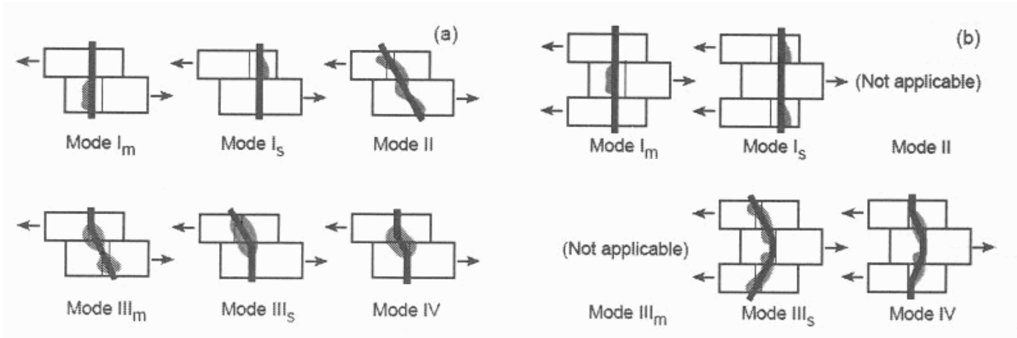

Figure 2. Possible yield modes for (a) Single and (b) double shear connections.

5.1.2 Load distribution factor–When fasteners are used in rows parallel to the direction of loading, total joint load is unequally distributed among fasteners in the row. Simplified methods of analysis have been developed to predict the load distribution among the fasteners in a row. These analyses indicate that the load distribution is a function of (a) the extensional stiffness of the joint members, (b) the fastener spacing, (c) the number of fasteners, and (d) the single–fastener load deformation characteristics.

Theoretically, the two end fasteners carry a majority of the load. For example, in a row of six bolts, the two end bolts will carry more than 50% of the total joint load. Adding bolts to a row tends to reduce the load on the less heavily loaded interior bolts. The most even distribution of bolt loads occurs in a joint where the extensional stiffness of the main member is equal to that of both splice plates. Increasing the fastener spacing tends to put more of the joint load on the end fasteners. Load distribution tends to be worse for stiffer fasteners.

The actual load distribution in field–fabricated joints is difficult to predict. Small misalignment of fasteners, variations in spacing between side and main members, and variations in single–fastener load deformation characteristics can cause the load distribution to be different than predicted by the theoretical analyses.

5.1.3 Prescriptive spacing requirements– The final procedure for the design of a multiple fastener connection is to assure that the fastener yield mode capacities are achieved prior to wood failure. Wood failure may occur by a loss of net tension capacity, row shear out capacity, or group tear out capacity. This historical has been achieved by prescriptive spacing requirements. Table 1 listed these prescriptive spacing requirements for multiple bolted connections as identified in the NDS. When the full prescriptive requirements are not achieved, the fastener capacity is reduce in proportion to the ratio of the actual spacing to the full design spacing.

Requirement for:		Minimum spacing for design value	
		Reduced	Full
End distance	Softwoods	3.5D	7D
	Hardwoods	2D	4D
Spacing in a row		3.0D	4D
Spacing between rows		–	1.5D

5.2 Failure Mechanisms

As a consequence of testing results that probed the lower limits of the prescriptive spacing requirements, the NDS developed language to require engineers to calculate the wood failure mechanisms of dowel fasteners and presented a procedure in a non–mandatory appendix to estimate the failure of dowel fasteners loaded parallel to grain. These non–mandatory expressions are as follows:

$$\textit{Net tension}: \quad Z_{NT}' = F_t' A_{net}$$

$$\textit{Row tear-out}: \quad Z_{RT_i}' = n_i \frac{F_v' A_{critical}}{2}$$

$$Z_{RT}' = \sum_{i=1}^{n_{row}} Z_{RT_i}'$$

$$\textit{Group tear-out}: \quad Z_{GT}' = \frac{Z_{RT-1}'}{2} + \frac{Z_{RT-n}'}{2} + F_t' A_{group-net}$$

where Z_{NI}' = allowable tension net section capacity, Z_{RI}'= allowable row tear out capacity of multiple rows, Z_{GT}'= allowable group tear–out capacity, F_t'= allowable tension parallel to grain design value, A_{net} = net section area, Z_{RI}' = allowable row tear out capacity of row i, n_i = number of fasteners in row i, F_V'= allowable shear parallel to grain design value, $A_{critical}$ = minimum shear area of any fastener in row i, Z_{RT-1}' = allowable row tear–capacity of row 1 of fasteners bounding the critical group area, Z_{RT-n}' = allowable row tear–capacity of row n of fasteners bounding the critical group area net section area, and $A_{group-net}$ = critical group net section area between row 1 and row n.

Allowable multiple bolt design values were calculated using to yield mode expressions and load distribution factors, along with wood failure capacities (Z_{NT}, Z_{RT}, and Z_{GT}) for comparison to experimental results (Table 2). Figure 3 shows four connections and the typical failure modes.

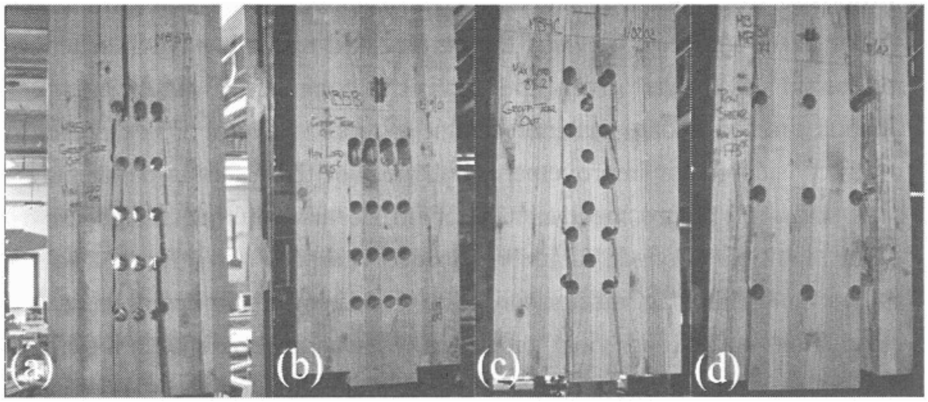

Figure 3. Representative failures for (a) configuration A, (b) configuration B, (c) configuration C, and (d) configuration D.

Calculated bolt design values using the single fastener yield capacity and group action factor for configurations A through C was approximately 60% the tested capacity for the lower limits of the spacing requirements. This indicates the current prescriptive spacing requirements are not effective at ensuring that fasteners achieve the predicted yield mode. Calculated wood failure capacity (Z_{NT}, Z_{RT}, and Z_{GT}) for the multiple bolted connection are also given in Table 2. For these cases, the group tear–out limit state governed the design for configurations A through C and was the observed experimental limit state. For configuration D, where the fasteners were placed as far apart as possible, the bolt design value was governed by Mode III behavior or bending of the bolt. Visual observations of the bolt indicated a Mode II behavior took place during the experiment prior to wood failure.

Table 2. Comparison of experimental results to NDS connection design values.

Joint	Avg. Max. load (kN)	Multiple bolt design values $Z_{//}$ (kN)	Allowable wood capacity			Limit state [a]	Max. load Limit state
			Net section Z_{NT} (kN)	Row shear Z_{RT} (kN)	Group tear-out, Z_{GT} (kN)		
A	381	594	690	525	226	GT	1.7
B	386	641	627	560	217	GT	1.8
C	376	559	689	490	226	GT	1.7
D	770	362	689	552	527	Y	2.1

[a] *Y*= yield model, NT = net section failure, RS = row shear failure, and GT = group tear–out

This research highlighted a need for improving the NDS connection criteria, especially for multiple fasteners, in the next cycle of code development.

5.3 Proposed work items for the 2010 NDS connection criteria

The five-year cycle between the current and upcoming NDS, scheduled for release in 2010, has given the technical committees of American Wood Council time to update fastener design criteria. Several topics are currently being considered for improvement, but most of the effort is developing wood limit states or failure mechanisms for single and multiple fasteners.

For multiple bolted fasteners loaded parallel to grain, two design approaches are being discussed. The first allows the designer to use the wood limit states and yield mode expressions in combination to design a connection. In this case, either a wood limit state or the yield mode state would govern the connection capacity. The second would specify a single fastener yield mode must be achieved prior to wood failure. In this case the wood limit states expression would only be used to set the minimum spacing requirements.

More research and fastener criteria are needed for two cases. One case is wood splitting failure mechanisms for bolted connections loaded in tension parallel to grain. The second case is wood limit mechanisms for connections loaded perpendicular to grain. Both cases depend on wood perpendicular to grain tensile strength.

Finally, additional items for consideration are; modification of yield mode material input, combined lateral and withdrawal load interaction expressions for nails and threaded fasteners, construction staples, and placement criteria for split ring and shear connectors.

6. Concluding Remarks

The US construction industry has a multi-layered system of design specifications, products standards, and model codes. Implementation and enforcement of this system is controlled at the state or local jurisdiction level, with or without amendments specific to their region. Design changes can be suggested at various points in the process. Understanding this system, and equivalent systems worldwide, is essential to promoting free exchange of wood products.

Recent studies have pointed to the need to update the fastener design criteria for the NDS. In the next cycle of development of this standard, issues related to the wood limit states criteria for connection loaded parallel and perpendicular to grain, material inputs, and load interaction expression will be discussed and/or developed.

References

[1] AF&PA 2005. ANSI/AF&PA NDS®–2005National Design Specification® (NDS®) for wood construction. Washington, DC. American Forest & Paper Association.

[2] ASCE 1995. Load and resistance factored design for engineered wood construction. Washington. DC. American Society of Civil Engineering.

[3] AF&PA 2001. Wood Frame Construction Manual for One– and Two–Family Dwellings. Washington. DC. American Forest & Paper Association.

[4] Green, D.W. and Hernandez, R. 1998. Codes and standards for structural wood products and their use in the United States. Proceedings of the Forest Products Study Group Workshop, Forest Products Society Annual Meeting, June 23, Mérida, Yucátan, Mexico.