A Grading Protocol for Structural Lumber and Timber in Historic Structures

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Lumber and timbers in historic structures can be graded visually in situ to determine appropriate design values, thus reducing the need to replace historic fabric and avoiding costly, and often unnecessary, repair and replacement decisions.

Fig. 1. Structural timbers without grade stamps, Denver, Colorado. Images by the author, unless otherwise noted.

Introduction

Every day structural engineers make decisions about lumber and structural timber (wood members) in historic structures. They do so often without the tools necessary to properly assess the capability of historic fabric to provide reliable, long-term, safe performance. Due to uncertainties about the allowable design values (i.e., working stresses for loads in bending, shear parallel to grain, compression perpendicular to grain, compression parallel to grain, tension parallel to grain, and modulus of elasticity) that can be assigned to the wood members, engineers often make very conservative decisions to replace or reinforce these elements even though they are "working," i.e., they have and will continue to safely carry the loads imposed upon them. Too many of these decisions result in the replacement of historic fabric that, in fact, could have remained in service without compromising structural integrity. The goal of this grading protocol, when combined with a wood-condition assessment, is to change typical decision-making processes by giving engineers and architects the means to grade wood members while facilitating an understanding of the relevance of the grade in relation to building-code requirements.

Background

Lumber and structural timbers used in new construction are intended to comply with the relevant building codes for that jurisdiction. For wood construction, structural engineers rely on design values referenced in the building codes to determine an acceptable species, size, and grade for a particular load condition. The design values given in the building codes for solid wood products are established by the American Forest & Paper Association and published as the *National Design Specification for Wood Construction*.[1] The published values are based on various test data and procedures published by the American Society for Testing and Materials (ASTM) that demonstrate the engineering performance of the material.[2]

These design values are given for wood members of a particular species (or species group) and structural grade. Milled wood products are graded and stamped in accordance with procedures promulgated by one of several forest-products industry associations, such as the Western Wood Products Association, the Southern Pine Inspection Bureau, the West Coast Lumber Inspection Bureau, or the Northeastern Lumber Manufacturers Association, each of which defines grades for a specific species or a limited group of species.

Assessing Historic Structures

For historic structures engineers often rely on current standards and design values to determine the adequacy of wood members to remain in service; however, current standards are based on wood of lower quality than was typically used in historic buildings. Since many historic buildings were built before building codes or design values for wood products were established (and thus there are no grade stamps on individual members), these structures present a quandary when trying to determine appropriate design values (Fig. 1). Frequently a species and grade are assumed based on contemporary, commonly used species and grades. The subsequent calculations using these assumptions then show that the wood members are structurally deficient, despite the fact that the structure has stood for decades or centuries without

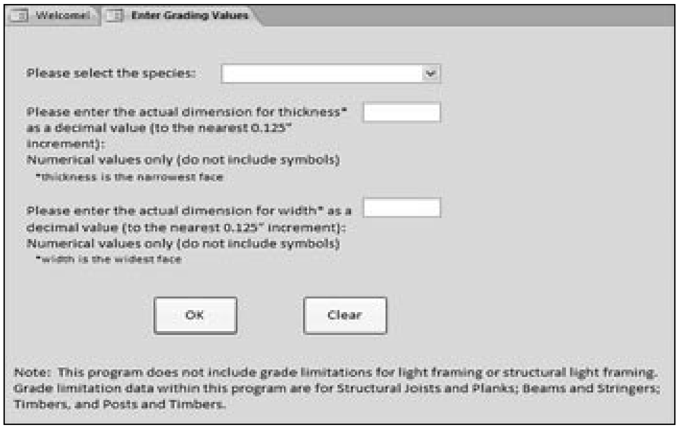

Fig. 2. The input screen for the wood-grading program.

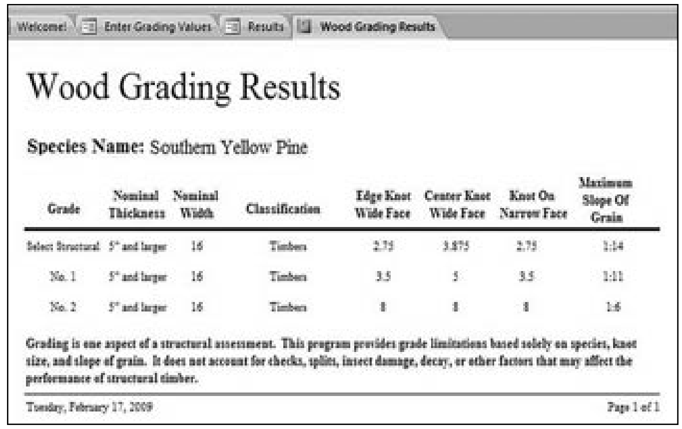

Fig. 3. The results screen for the wood-grading program, showing data for a southern yellow pine, 8-inch-by-15.75-inch timber.

failure. The result of assuming a species and/or grade is often an overly conservative estimate of the design values followed by unnecessary replacement, repair, and retrofit decisions along with associated unnecessary project costs and the loss of historic fabric.

Determining the appropriate species and grade, however, is not sufficient for assessing the serviceability of wood elements within a historic structure: it is also essential to know the condition of the timber being graded. Deterioration due to decay or insect attack, member failure, mechanical damage, alterations, and other conditions can adversely affect the performance of structural timbers, even though they may appear to meet the requirements for a particular grade. Therefore, a detailed wood condition assessment is an essential first step that must be conducted prior to the use of this wood-grading protocol.

There are three primary reasons to conduct a wood inspection: concerns about moisture and its effects, deterioration (both physical and biological), and a need to know material properties. Wood behavior is highly variable, and it is important to understand this variability in historic structures. There are numerous references that provide information on the various components of a wood condition assessment, including one of the *Practice Points* published in the *APT Bulletin*.[3]

History of Wood Investigation and the Development of Standards

Early investigations of wood properties. Evidence of timber construction has been found in many of the earliest human societies. It is this history and familiarity with timber that allowed for the building of some of the world's most magnificent structures — such as Hōryū Gakumonji, Ikaruga, Nara Prefecture, Japan; the roof trusses of Palazzo Vecchio in Florence, Italy; and the Urnes stave church in Sogn og Fjordane, Norway — centuries before the strength properties of wood were well understood and documented. Despite the fact that only tradition and experience governed timber-construction methodology until the late nineteenth century, many structures built prior to the late nineteenth century still stand today.

While some research into the properties of wood was conducted as early as 372 to 287 B.C.E., more specific investigations of the properties of building materials did not occur until the seventeenth and eighteenth centuries. These experiments, by Galileo, Musschenbroek, Buffon, and others, examined tensile strength, load duration, and failures.[4]

Early work in the U.S. In the late nineteenth century scientists began to conduct tests designed to provide data on properties of wood for use in buildings. Until this time no design values had been published, nor were there building codes to govern construction. Although generally unknown today, this research, conducted between 1894 and 1912, provided the means of designing with timber based on an understanding of material performance.[5]

In 1895 Filibert Roth and B. E. Fernow published *Forest Service Bulletin No. 10,* which detailed the influence of weight and moisture content on the strength of clear wood specimens and summarized much of the available knowledge on wood behavior.[6] That same year the American International Association of Railway Superintendents of Bridges and Buildings Committee presented a report that also included a summary of data on wood properties and behavior.[7] These data led to recommendations made by the railway committee, some of which foreshadowed modern design and grading rules.

Beginning in the late 1800s and continuing into the early 1900s, a concerted effort to systematically extend this knowledge through well-designed testing programs was made by the U.S. Division of Forestry (under B. E. Fernow) and several universities, including Washington University, Yale, Purdue, and the University of California at Berkeley.

In the early 1900s W. K. Hatt, who was in charge of the timber-testing program at Purdue University, designed a program to test both small, clear specimens and larger wood members, addressing a controversy that had been brewing for years. *Forest Service Circular 38* was an attempt to summarize existing data and standardize programs among the various testing laboratories.[8] At the same time Arthur Talbot was

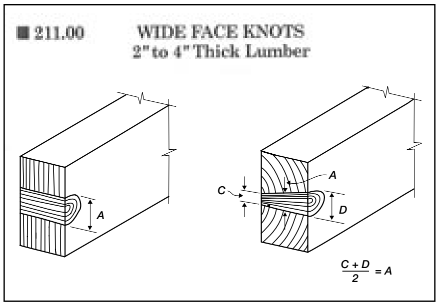

Fig. 4. Instructions for measuring knots on 2-inch- to 4-inch-thick lumber, which includes structural joists and planks. Courtesy of Western Wood Products Association.

working on testing timber beams at the University of Illinois Engineering Experiment Station. Talbot conducted horizontal shear tests on large timbers and small samples cut from the larger timbers to determine correlative values.[9] He also examined the strength-limiting properties of knots, shake, and cross grain, as well as moisture content and the effect of seasoning.

As data on both small clear specimens and large timber beams began to accumulate, researchers began to look at lesser wood properties, behavior, and relationships. For instance, McGarvey Cline and Harry Tiemann conducted research on the effect of load rates on the strength and stiffness of wood, while Rolf Thelen investigated the testing of green and partially seasoned timbers.[10]

Consolidation of the testing results conducted before 1910 into grading criteria began when Cline and Heim produced *Forest Service Bulletin 108*, a complete summary of the full-sized testing program that became an important reference for subsequent grading rules.[11] The bulletin identified the strength of beams tested in bending and compression, both parallel and perpendicular to grain, as a function of their characteristics (moisture content, splits, knots, etc.).

By the early 1900s the discrepancy between test results for small clear samples and full-size members was becoming problematic. In order to correlate the data from both types of tests, researchers began to focus on so-called "defects," such as knots, splits, checks, shake, and cross grain, which seemed to limit the stress properties of full-size members. This focus, along with the development of strength ratios that were based on results of both types of tests, provided the historical data that led to modern grading standards based on visual characteristics and mechanical tests.

Early development of standards in the U.S. Standards and grading rules in the U.S. were not published until the early twentieth century. The American Society for Testing and Materials (ASTM), formed in 1898, marked the beginning of formal standards for testing that would ultimately lead to today's standards.[12] In 1905 the Committee on Standard Specifications for the Grading of Structural Timber was formed. The committee, initially designated Committee Q, changed to its current form, Committee D7, in 1910.

While Committee D7 was organizing the development of grading rules, the U.S. Forest Service (USFS) was investigating how the rules might work in practice. In 1915 H. S. Betts defined a set of potential grading rules developed by the USFS, based in part on the work of Cline and Heim and others. In 1922 ASTM tentatively approved *ASTM D143,* "Standard Methods of Testing Small Clear Specimens of Timber," which was formally established as a standard in 1927 (ASTM D143-27). A similar standard for testing full-sized timbers, ASTM D198-27, was established the same year.[13]

In 1922, while ASTM was drafting the standards for testing, the Central Committee on Lumbers Standards in the Department of Commerce (now the American Lumber Standards Committee [ALSC]), was formed.[14] In 1924 the ALSC produced *Simplified Practice Recommendation No. 16,* the first national standard for lumber sizes and grades. This standard focused on nomenclature, the visual properties of wood members, and standardization of sizes. It did not include any information on allowable design values.[15]

Information on allowable design values was first published as USDA Forest Products Laboratory Circular 295, *Basic Grading Rules and Working Stresses for Structural Timbers.*[16] This circular outlined a system of grading similar to the current one, with four grades of lumber, which were limited to 88, 75, 62, and 50 percent of the strength ratios of clear wood.[17] This system for grading and allowable design values contained information on numerous species but was shown without regard for width or thickness. A companion paper, USDA FPL Circular 296, *Standard Grading Specifications for Yard Lumber,* contained recommendations on sizes and moisture-content adjustments.[18]

ASTM continued to promulgate and improve numerous standards that are the basis for modern grading and strength values for lumber and timber. The most important standards for grading of structural wood members in historic structures are:

- *ASTM D2555,* "Standard Methods for Establishing Clear Wood Strength Values." This standard was developed to provide an "authoritative compilation of clear wood strength values for commercially important species" and marked the first use of the fifth percentile for deriving allowable wood properties.[19]
- *ASTM D245,* "Standard Methods for Establishing Structural Grades for Visually Graded Lumber." Based on the work of Newlin and Johnson, this standard focused on a means of selecting material for strength values.[20]

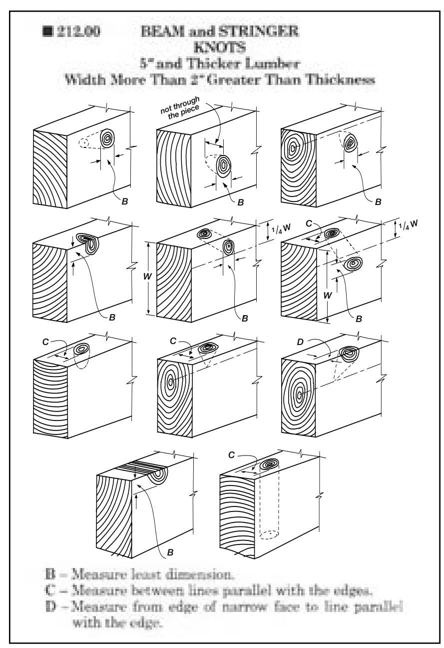

Fig. 5. Instructions for measuring knots on beams and stringers. Courtesy of Western Wood Products Association.

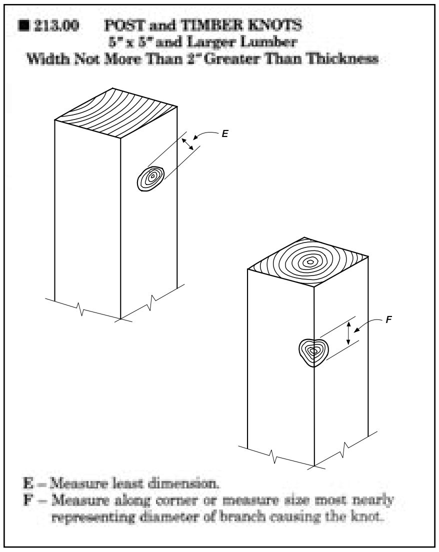

Fig. 6. Instructions for measuring knots on posts and timbers. Courtesy of Western Wood Products Association.

Beginning in 1915 code-writing organizations were formed to address the need for building standards to safeguard public health and safety. With the advent of building codes, additional research led to numerous publications that discussed early grading procedures and material properties, much of which may still be applicable to historic structures.[21]

During the 1940s there was an interest in expanding design values to dimension lumber. Standards for stress grading of lumber became less restrictive, and grades were developed for lumber with less than a 50-percent strength ratio to that of clear wood.[22] This work culminated in recommendations by the National Lumber Manufacturers Association in 1944 known as the *National Design Specification for Stress-Grade Lumber and Its Fastenings*. This document has evolved into the *National Design Specification for Wood Construction*.[23]

During the 1950s and 1960s the most important debate in lumber standards was about the unification of size standards, a problem since the early nineteenth century. This problem was eventually resolved in the 1970s, when the *American Lumber Standard (ALS)* was revised as *Voluntary Product Standard PS20-70*.[24] *PS20-70* made substantive changes in lumber grading and marketing and established an independent board of review to enforce grading and grade-marking portions of the standard. The board of review continues its work today and has authority to certify grading agencies and approve lumber design values promulgated by regional agencies in accordance with ASTM standards.[25]

Grading of lumber and timbers in historic structures. Some of the issues associated with assigning structural values to old lumber were published in 1954.[26] Rather than simply address design stresses, the publications emphasized the significance of wood deterioration, moisture, and connections, as well as the reuse of lumber from demolished buildings, a topic that is currently being researched by the U.S. Forest Products Laboratory.[27] Understanding how recycled lumber behaves is important but does not address how wood members can be graded in an existing building where they have come to behave as a system.

The means to grade in-situ wood members are well defined but are, in general, not well known. In addition to the information given above, several summary reports can help the engineer or architect.[28] Despite these efforts, the methodology for determining grade values for timbers in historic structures has remained ambiguous. The problem of assigning grade values to timbers in historic structures so that they comply with existing building-code requirements is not unique to the U.S. and can be viewed as a preservation issue with international implications.[29]

Use of the Grading Program for Lumber in Historic Buildings

The following grading protocol provides the means for architects or engineers to use the current grading rules to make an informed decision about allowable design values for wood members in historic buildings. The application of the grading protocol includes reviewing and understanding the historic development of wood grading, codes, and standards as outlined in the report *A Grading Protocol for Structural Lumber and Timber in Historic Structures;* it also includes the application of a basic in-situ wood-grading methodology and a query-based wood-grading database program, the Wood Database Grading Query Version 1.0, referred to here as the grading program. Full instructions on the use of the wood-grading program are included in the above grading protocol. The report and the wood-grading program are available for free download at www.ncptt.org and www.apti.org.

It is important to remember that the wood-grading protocol is just one part of a structural assessment. The grading program determines the grade based on the wood species and dimensions of the element and provides limitations for knot size, knot location, and slope of grain. Knots and slope of grain are the most common and most limiting of lumber defects, but there are other defects, such as splits, checks, damage from insects, and deterioration due to moisture intrusion and/or wood-decay fungi, that can significantly impact the grade of a member.[30] Seasoning checks, which are separations between wood fibers that do not fully penetrate the width or thickness of a member, are common in structural timbers and rarely affect performance. Splits are separations of wood fibers that extend completely through the width or thickness of a wood member. Short splits typically do not affect the performance of a wood member, but the engineer should evaluate long splits if there are concerns about shear strength in beams or buckling in columns.

Prior to using the wood-grading protocol (including the wood-grading program), a complete wood condition assessment should be conducted to determine the presence and/or significance of any other grade-limiting defects. If significant grade-limiting defects other than knot size and/or slope of grain are identified, the grading protocol and wood-grading program should not be used; in such cases it may be necessary to seek the advice of a consultant with expertise in in-situ wood grading and condition assessment.

The wood-grading program (Wood Database Grading Query Version 1.0). The grading program is intended for use by engineers or architects when assessing structural adequacy of historic buildings. The program was developed using Microsoft Access 2003. Comput-

Table 1. Nominal Size Categories by Classification (Member Type)

Classification (Type of Member)	Species Included	Nominal Thickness Category	Width to Thickness Relationship
Structural Joists and Planks	All	2" to 4"	None. However, thickness must be between 2" and 4"
Timbers	Southern Yellow Pine	5" and Larger	None. However, width and thickness must be 5" or greater
Posts and Timbers	Douglas Fir, Northern Red Oak, White Oak, Eastern White Pine	5" and Larger	Width must be no more than 2" greater than thickness
Beams and Stringers	Douglas Fir, Northern Red Oak, White Oak, Eastern White Pine	5" and Larger	Width must be more than 2" greater than thickness

ers with Microsoft 2003 or later can access the program, although display and security settings may be slightly altered. It is essential that the species of the wood members and their dimensions be known prior to using the wood-grading program. This information is entered into a simple input screen (Fig. 2). Entering this information will generate an output table that can be used to assign a grade to the wood members (Fig. 3).

Wood species. To determine the correct species for use in the grading program, a sample of each type of structural member under consideration must be removed and sent for analysis. Generally, the same wood species is used for identical framing members, such as joists or rafters; however, species may vary between framing-member groups. Samples should be taken for every framing-member group under scrutiny and then sent either to a consultant for analysis for a fee or to a public or government agency, such as the U.S. Forest Products Laboratory Center for Wood Anatomy Research, for free species analysis. The wood species available within the grading program are:

- Southern yellow pine
- Douglas fir
- Northern red oak
- White oak
- Eastern white pine

Many species have similar grading standards, but the output data of the grading program differ slightly depending upon the selected species. These differences can be significant for the resulting grade and allowable-design values, so the correct species must be established.

Output data for the wood-grading program can also vary based on the function of the wood members. Their function, identified in the wood-grading program as the Classification, is determined by species and width-to-thickness ratio (Table 1). Therefore, width and thickness dimensions of the wood members in question must be known in order to run the grading program.

Knots and their measurement. Knots are generally considered the most significant of the numerous strength-limiting defects occurring in lumber. Three major strength-reducing effects arise from the presence of a knot: part of the board cross section is reduced as harder, denser, but structurally weaker knotwood takes the place of the regular wood fibers; a stress concentration and subsequent reduction in capacity is induced by the material inhomogeneity of the knot surrounded by the rest of the board; and lastly the growth pattern of the trunk is disrupted by the branch causing the knot, which results in considerable distortion of the grain angle around the knot.[31] This distortion can allow for the development of tensile stresses perpendicular to the grain and the formation of checks and microfractures as the wood dries.[32]

Since the location of the knot has an impact on member strength, there are three knot-size limitations based on location. Centerline knots, located on the wide face of an element, have the least impact on grade and therefore have the largest allowable knot size. Edge knots on the wide face generally increase localized tensile stresses and therefore have smaller knot-size limitations. The same holds true for knots on the narrow face of an element. For some smaller elements (2 to 4 inches in thickness), knots on the narrow face are considered to be identical to edge knots on the wide face. While the location of a knot along the length of a bending member (within the middle third of the length or in the outer thirds) also affects the performance of a beam, this placement was not taken into account in order to simplify field measurements. This factor results in a conservative limitation on knot size for the outer third of beams.

The measurement of knots varies depending upon the species, size, and function of the element containing the knot (Figs. 4 through 6). For example, knot measurement on columns under axial loads is different than knot measurement on beams and joists in bending. The following excerpt provides an example of methods of knot measurement for various classifications of lumber and timbers.

From *Western Lumber Grading Rules* 05:

210.00 Knots

In all Framing lumber 4" and less in thickness, the size of a knot on a wide face is determined by its average dimension as in a line across the width of the piece. The size of knots on wide faces maybe increased proportionately from the size permitted at the edge to the size permitted at the centerline. Knots appearing on narrow faces are limited to the same displacement as knots specified at edges of wide faces. Knots in Beams and Stringers and Posts and Timbers are measured differently than knots in 4" and thinner material. Examples of these measurement methods are shown in Sections 212.00 and 213.00 [33]

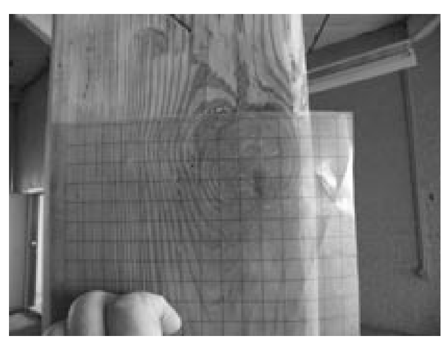

Fig. 7. The use of a 1/2-inch grid on acetate for measuring a knot on a post and timber. This knot is 1 3/4 inches in diameter.

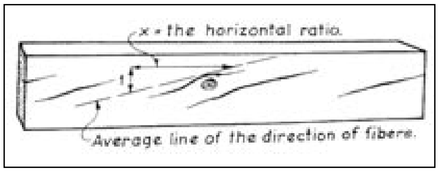

Fig. 8. Diagram showing measurement of slope of grain. Courtesy of WCLIB, Standard No. 17.

Knots can be quantified using an acetate sheet with a 1/2-inch grid to facilitate measurement (Fig. 7). For beams and stringers the grid should be placed parallel to the edge of the timber, and the knot dimension measured parallel to the long axis of the timber. For posts and timbers the grid should be aligned across the narrowest face of the knot, and the knot should be measured between parallel lines edge to edge, from the most distinct point of grain deviation. In other words the acetate grid may not be parallel to the edge of posts and timbers as it is for beams and stringers. Occasionally, knots have very distinct boundaries, but this is often not the case, and the measurement of knots can be rather subjective. Differential drying of the denser knotwood often causes knots to become raised from the normal surface of a timber; hence, knots on painted timbers often telegraph through the painted surfaces and are visible for measurement. Also, radial checks may be useful in defining the knot boundary, as they will not extend into the surrounding wood.

Slope of grain and its measurement. One reason knots have such impact on the strength capacity is that a distorted grain angle occurs as the tree grows around the branch. When logs are milled into lumber, the areas of distorted grain can be cut so that segments of grain "run out" at one or several locations along a board's length, rather than extend parallel along the entire length of the board. The same effect can occur if the board is milled at an angle that is not parallel to the grain or if the entire log is twisted due to spiral growth patterns in the tree. Areas of cross grain, or where the grain runs out, create deviations in the way stresses are transmitted throughout the piece and concentrate stresses where the wood fibers have been discontinued, significantly weakening the element.

Slope of grain is generally measured as a ratio of rise to run, that is, the number of inches the grain slopes within a given distance that is parallel to the long axis of the member (generally from 6 to 20 inches) (Fig. 8). Typically, slope of grain must extend for 10 inches or more to be considered a grade-limiting defect. Only the most severe slope of grain needs to be checked. Localized grain deviation around a knot should not be measured to determine slope of grain.

To measure slope of grain, an acetate sheet with a printed 1/2-inch grid is needed (Fig. 9). The length of the area that appears to have significant slope of grain should be measured first from an axis parallel to the long axis of the member. If the length of the slope of grain area exceeds 10 inches, then the acetate grid can be used to establish the rise-over-run ratio. To do so, one edge of the acetate grid must be aligned parallel to the long axis of the member. The total number of inches for the rise can be determined along the vertical axis by counting from the lowest point of the rise to the highest point of the rise (or wherever the grain crosses the edge of the acetate sheet). The total number of inches in the run can be determined along the horizontal axis by counting across from the lowest point of the rise to the highest point of the rise (or wherever the grain crosses the edge of the acetate sheet). This ratio can then be reduced to represent the actual slope of grain over a given length to determine the appropriate grade.

Since seasoning (drying) checks in timber generally follow the slope of grain, determining the slope of grain on painted timbers can be achieved relatively easily by examining drying checks.

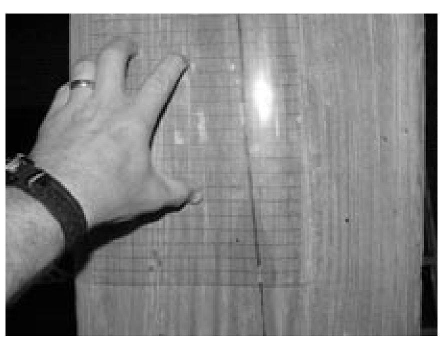

Fig. 9. The use of a 1/2-inch grid on acetate for measuring slope of grain.

All visible faces of the timber should be examined for slope of grain, as not all faces will exhibit the same extent of the slope of grain. While not always conclusive, usually this approach correlates closely with results achieved using laboratory methods for measuring slope of grain that are not practical for field use.

Summary

The purpose of the wood-grading protocol is not to make every engineer or architect a certified lumber grader but rather to provide a simple tool with sufficient supporting documentation to facilitate the decision-making process concerning the structural capacity of wood members in historic buildings. Application of the grading protocol can also significantly reduce budget expenditures for historic-preservation projects by saving historic fabric or eliminating the need for costly upgrades. This grading protocol should be an essential tool for any structural assessment of lumber and timber.

Disclaimer

This article describes information contained in a wood-grading protocol that has been produced based on publicly available information. Some of that information comes from grading rules promulgated by various trade associations or grades identified within the National Design Specification for Wood Construction. None of the trade associations that produced the grading data or the American Wood & Paper Association is responsible for the production of the report or program associated with this article. The National Center for Preservation Technology and Training and the Association for Preservation Technology International, while providing either financial or administrative support, are not responsible for the content or use of the information. It is the responsibility of any user of this protocol to understand the information being provided and accept sole responsibility for its use.

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