GRADING AND LOAD CARRYING CAPACITY DETERMINATION OF OLD TIMBER BEAMS

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1. INTRODUCTION

In old wood buildings, the structural members are solid sections that are normally produced from a single tree. Large sizes of solid timber members are not readily available nowadays. If large size members are needed, glulam members are used.

The grading rules used at present are designed for small size timbers. The application of these rules to large size timber is difficult, and a high percentage of these pieces would be rejected if the same rules are applied. But in reality, large size timber beams have been in use and have been functioning well in service.

The objetives of this study were: (1) to develop a procedure for obtaining geometric and mechanical properties of large size, old timber beams. and (2) to use the information collected to establish simple grading rules or methods to characterize the mechanical properties of structural members in-situ.

The practical implication of the study is to develop methods of determining mechanical properties *in-situ* for existing structural members. Information of this nature would be essential to develop a maintenance schedule for restoration of old wood buildings made of large sizes timber members.

A significant amount of time was spent to get as much information as possible to characterize the mechanical properties of the beams. Graphical and numerical information were recorded in beam "cards". A complete analysis of the data will be performed in the future.

2. METHODS

2.1 Compilation of Informations of Each Piece

First, the beams were inspected and the ones that were damaged severely were rejected. Three approaches followed to characterize the mechanical properties of the beams: (1) ultrasonic method, (2) mechanical testing, and (3) visual grading. Moisture content and specific weight of sample pieces were also measured.

Before any of the above methods were applied, a significant amount of information about the general characteristics of the pieces, such as dimensions, permanent deflections, natural defects (knots, checks and shakes, slope of grain, wanes, annual rings) were measured.

Wood **Beams:**

The beams were obtained from two old buildings in the province of Madrid. The beams were classified into two groups hereafter referred to as Group A and Group B.

Group A consisted of 20 floor joists having an approximate cross-section of 13 cm x 18 cm, and were 4 to 5 m long. These joists were procured from a 130 years old building in Madrid City (the old center).

Group B consisted of 14 roof rafters having an approximate cross-section of 12 cm x 16 cm and were 4 m long. These rafters were procured from a building in the center of Vallecas, Madrid province. The building is estimated to be 80 to 90 years old.

Reference:

The sides of the joists and rafters (hereafter referred to as beams) were marked 1 to 4, number 1 being the bottom or the support plane. The edge of a straight glulam beam was used as a reference plane and all knot and check measurements along the beams were measured with respect to the reference plane shown in Figure 1. The y_1 and y_2 measurements in Figure 1 were measured with respect to the reference plane Measurements of y_1 and y_2 were made every 30 cm.

Permanent Deflection:

Permanent deflections were measured in the middle 2.70 to 3.60 m segment of each beam for Group A but was impossible to do so for Group B because of their irregularities. The span to deflection ratios obtained from the measurement are given in Table 1

As shown in Table 1, only 4 of the 17 beams had a deflection larger than 11360. The maximum bending stress in service due to permanent loads was estimated to be between 55 and 59 kg/cm^2.

Knots:

Knots in each side or face of the beams were measured with respect to the reference. As shown in Figure 2, x refers to the distance from the center of the knot to the reference point, and y refers to the distance from the center of the knot to the reference plane. Other knot dimensions taken include diameter (ϕ) when circular, and d_1, d_2 and (Figure 2) if elliptical.

Checks and Shakes:

Checks and shakes in each face of the beams were measured and recorded. In essence they were considered as one single. The length (l), width (a), and depth (p) of shakes and their location on nine beam were measured (Fig. 3).

Wanes:

Wanes in each face of the beams were measured every 30 cm length. The dimensions of each wane and its location on the beam were recorded. Measurements relative to wanes are shown in Fig. 4.

Slope of Grain

Slope of grain was calculated using the deviation of the shakes and checks. Slopes were calculated as the tangent of the angle, $(y_2-y_2)/l$, (Fig. 3).

Rate of Growth:

Average thickness of annual rings was determined according to the Economic Commission for Europe (ECE) Recommended Standards for stress grading of structural coniferous sawn timber. Average thickness was 1.8 mm for Group A and 2.4 mm for Group B.

2.2. Visual Grading

Grading Rules:

The beams were visually graded according to the Economic Commission for Europe (ECE) recommended standards for stress grading of structural coniferous sawn timber (U.N. Economic Commission for Europe, 1982). This Standard distinguishes three grades S10 S8 and S6 of sawn timber. Knot evaluation was based on the concept of Knot Area Ratio (KAR). Other standard or grading rules will be considered in the future.

Grading Parameters:

The following defects were considered for visually grading the beams:

Knots - the total and margin KAR were calculated according to the ECE recommended standard including KAR projections of those knots that were within a distance of less than or equal to the depth of the beam, in the section of rupture. Graphic representation of knot projections were performed for the rupture section of each beam (Fig. 5).

Checks and Shakes - an average length of checks and shakes was considered.

Slope of grain - calculated from the slope and checks and shakes.

Wanes - the wanes near the rupture section were evaluated by taking the ratio of wane length to width or depth of the cross section.

Average thickness of annual rings - this parameter was also considered in the visual grading procedure.

Grading Criteria:

Two grading criteria were employed. One criteria (Criteria 1) considers the strict application of the ECE recommended grading rules, whereas the second criteria (Criteria 2) treats wanes as knots.

The following characteristics were considered in the visual grading of the members:

A.1. Knots -total KAR (ratio of the sum of projected cross-sectional area of knots and total cross-sectional area of the piece, KT), and margin KAR (ratio of the sum of projected cross-sectional area of knots or portions of knots in the margin section and the cross sectional area of the margin, KM). Margin is defined as the areas adjoining the edges of the cross-section with occupies one-quarter of the total cross-sectional area of the piece. Definitions sketches of total KAR and margin KAR are shown in Figure 5.

A.2. Knots-total KAR (KT') and margin KAR (KM') similar to A.1 but treating the areas occupied by wanes as areas of knots.

B. Checks and shakes

C. Slope of grain

D. Wanes

E. Rate of growth

Criteria 1 considers A.1, B, C, D and E, while Criteria 2 considers A.2, B, C and E. Assigned grades include: S10, S8, S6 and SX (where, SX is assigned to those pieces that did not satisfy the requirements for the lowest grade). Table 2 summarizes the results of the visual grading procedure.

2.3 Ultrasonic Method

Ultrasonic methods have been in use to evaluate load carrying capacity of timber structures in service. Ultrasonic methods are used to determine the dynamic elastic modulus of timber. The procedure followed in this study was the same as that used for structural members in-situ.

Equipment:

The equipment used was Steinkamp-ultrasonic Tester BP V. Scale of measurement ranges from 0.1 to 9999.9 s. The testing spikes were conical shape stainless steel ends. The conical shape ends allow impulse emission in a concentrate way without using a special connecting device. The frecuency of the ultrasonic wave ranges between 40 to 50 KHz. The transducer was made of lead titanate-circonate.

Wave Velocity Meacurernentc:

Wave velocity measurements were performed (1) perpendicular to the grain, and (2) parallel to the grain.

Wave velocity measurements perpendicular to the grain: In these measurements, the spikes were aligned as shown in Figure 6. This procedure is called the direct method. Wave velocity measurements were taken at three points, marked as 1,2 and 3 in Figure 6, at a distance of x = 130 cm for Group A, and 120 cm for Group B from the origin of the reference point. This section will be referred to, hereafter, as the initial section.

The outer positions, 1 and 3, in Figure 6, were 3 cm from the ends and position 2 was in the middle. The wave velocity perpendicular to the grain was calculated as the average value of the wave velocities at the three positions.

Wave velocity measurements parallel (almost) to the grain: the spikes were not quite aligned in this measurement. This procedure is referred to as the semi-direct method. Six different readings were taken between the initial section, where x = 130 cm for Group A, and 120 cm for GroLp B, and the final section, where x = 240 cm for Group A, and 220 cm for Group B, within the third middle section of each piece. The spikes were placed 100 to 11Ocm apart at an angle (α) 6 to 7° from the axis of the piece (Fig. 7). The ultrasonic wave velocity of a beam parallel to the grain was taken as the average of the six wave velocities.

The dynamic modulus of elasticity was calculated (without correction for Poisson coefficient) using the following expression:

$$E_d = v^{2*} d$$

were, E_d = dynamic modulus of elasticity (N/m^2)

v = ultrasonic wave velocity (mls)

d = density of material (kg/m^3).

The density oithe material was obtained from a small piece taken outfrom the beam cross-section. The dvnamic modulus of elasticity are given in Table 3.

2.4 Mechanical Tecting

Two bending tests were performed on each piece in order to obtain the longitudinal modulus of elasticity, shear modulus and modulus rupture. The pieces were tested according to the procedures outlined in the "Timber Structures - Solid Timber and Glued Laminated Timber - Determination of Some Phisycal and Mechanical Properties" pr EN 408 (1991).

Test **1. Apparent** Modulus of **Elasticity**

The first test was a non-destructive test to determine the apparent modulus of elasticity in bending (E_{ap}). The specimen was supported over a central span length of l_1 (l_1 = 92 cm for Group A, and 84 cm for Group B). A concentrated force was applied at the middle point. The distance between supports (l_1) was approximately equal to 5d, where d was the depth of the beam, as recommended in the Standard. One of the supports was located a distance of l_2 from de end of the beam (l_2 = 139 cm for the Group A, and 128 cm for Group B). The test set up used for determining the apparent modulus of elasticity is shown in Figure 8.

Test **2.** Modulus of Elasticity and Modulus of **Rupture**

In this test, the specimen was supported over a span of l, where, l was 3.30 m for Group A, and 3.00 m For Group B. Two concentrated forces were applied at third points of the span. The slenderness value in each Group was l_1 = 18d, as recommended in the Standard (d = depth of beam). The set up for this testing procedure is shown in Figure 9.

Relative deflections were measured at the middle third of the piece where shear force is equal to zero. Therefore, "true" modulus of elaticity (E), with no influence of shear could be determined.

To determine the modulus of rupture (σ), the load was increased until the beam was ruptured. The mode of rupture was graphically recorded. Once the "true" and apparent modulus of elasticity were obtained, the shear modulus (G) was calculated. The results of the mechanical test are given in Table 4. The shear modulus was calculated frorn the expression

$$G = Kg * d^2 / (l_1^2 * (1/Eap - 1/E))$$

where, kg = constant depending on the shape of the cross section (for a rectangular section, kg = 1.2).

d = depth of beam

l_1 = length at which deflection was measured

E_{ap} = apparent modulus of elasticity

E = "true" modulus of elastiticy

If E_{ap} is greater than E, G will be negative which is meaningless. Theoretically, E should be greater than E_{ap} because both values are obtained from deflection measurements in the same portion of the beam, and in the test for E_{ap} (Test 1), the shear deflection reduces the apparent modulus elasticity whereas in the test for E (Test 2), shear is equal to zero,

In this study, however, some test results show that E is lower than E_{ap} and this ratio EIG is very variable. The apparent reason for this reverse case is that knots or natural defects, are not necessarily uniformly distributed along the portion where deflections are measured. Secondly, the bending moment in the section of interest is not constant for the case in Test 1 but is constant for Test 2. Therefore, defects could have more impact in Test 2 (measurements for E) than in Test 1 (measurements for E_{ap}) because of the bending moment distribution in the bearn.

Moicture Content

Moisture content of each beam was obtained according to the procedures outlined in the pr. EN 408, a European standard being developed based on the ISO 8375. A 4 cm thick slide was cut out from the cross-section next to the rupture area of the beam and was kiln dried at 103± 2°C until a constant weight was obtained. The average moisture content obtained was 9.72% for Group A, and 9.92% for Group B.

Specific **Weight**

Specific weight was obtained from a rectangular 4 cm thick piece cut out from each beam close to the rupture area. The pieces were free from knots and resin pockets. The pieces were cut out almost parallel to the radial and tangencial directions of the wood. The results are given in Table 3.

3. RESULTS AND DISCUSSION

3.1 Visual Grading

Three grades, S10, S8 and S6, were considered. The fourth "grade", was assigned to the pieces that were rejected by the ECE rules. Two grading procedures were employed. Procedure 1 considers all the grading parameters including knots, checks, wanes, slope of grain and rate of growth. Procedure 2 considers only total and margin KAR of knots. Both criteria were applied to see the difference in results when a slrict application of the grading rules and when only knots were used as the basis for grading. A strict application of the grading rules rejected a high percentage of the test speciments in Group B mainly because of higher existence of wanes. This grading rule is perhaps inadequate to be used for grading gross cross-section timber. Table 5 summarizes the resulted grades and the number of pieces (N) assigned to each grade.

3.2. Linear Regression **Analysis**

Linear regression analysis was performed for the following test data:

(1) Group (A+B): Data from Group A and B were combined together for this analysis. The sample size was 28. The data associated with some test problems or beams known to be broken before the test were excluded from the analysis. The rejected test pieces were no 14 and 15 from Group A and no 3, 4, 11 and 12 from Group B

(2) Group A: The sample size for this analysis was 18

(3) Group B: The sample size for this analysis was 10

The following variables were included in the analysis

E = modulus of elasticity obtained from the mechanical test

G = shear modulus obtained from the mechanical test

E/G = E to G ratio

o = modulus of rupture

d = specific weight at known moisture content

E_d = dynamic modulus of elasticity

KT = total KAR of the rupture section

KM = margin KAR of the rupture section

KT^1 = total KAR but considering wane areas as knot areas at lhe rupture seclion

KM^1 = margin KAR but considering wane areas as knot areas at the rupture section

The correlation coefficients between the variables are given in Taole 6. The mean, standard deviation and the coefficient of variation of E to G ratios were calculated and the results are given in Table 7.

The correlation coefficient between modulus of elasticity (E) and modulus of rupture (σ) was 0.76 for Group A, but dropped to 0.42 for Group B probably because of the higher dimensional irregularities with the iatter. The mean value of the ratio of E to G was 16 (Table 7), and showed high variability.

There is strong relationship between specific weight and mechanical properties of small clear wood specimen. But this relationship was not evident for the structural size members in this study probably because of higher influence of knots and other natural characterislics on slrength than specific weight.

There were higher correlation between mechanical properties when grading was based on real knots than when area of wanes were also considered as knots. When only knots are considered, lhe effects of local deviation of grain around knots on mechanical properties were included but these effects does not exist when area of wanes are assumed as area of knots

The correlation between KAR and modulus of rupture was higher than that between KAR and modulus of elasticity. This may be because the considered KAR values were limited to the rupture section whereas modulus of elasticity depends on lhe KAR of the *entire* section of lhe *middle* third of the beam under test, The correlation between the mechanical properties and KAR was small for Group B, however.

4. Ultrasonic Method

The main advantage in using ultrasonic methods for characterizing timber is its ease of taking measurements in-situ provided lhat test specimens are accesible irom three sides.

The major inconvenience in using the method is the difficulty in calculating the density of members in-situ. Density is required to calculate the dynamic modulus of elasticity. The relation between modulus of elasticity and density is linear but the relation between modulucof elasticity and velocity is squared. Therefore, il would be reasonably acceptable to use density values from the literature.

The correlation coefficient between the dynamic modulus of elasticity obtained using the ultrasonic method (E) and the elastic modulus determined by non-destuctive testing (E) was 0.61 for Group A. Similarly, the correlation between E and modulus of rupture (o) was 0.59 (Table 6). The correlation between E_d and E dropped to 0.41 for Group B. This discrepancy may be due to the higher size irregularities of this Group.

Identical ultrasonic measurements were also taken when the beams were under load and no significant difference was observed compared to the results obtained when the beams were tested without load.

5. SUMMARY

Thirty four timber beams (20 floor joists, 13 x 18 cm in cross-section, and 14 roof rafters, 12 x 16 cm in cross-section) that were 90 to 130 years old were graded using (1) visual grading rules, (2) ultrasonic application, and (3) non-destuctive testing. Before any of the grading procedures were applied, complete and accurate measurements of dimensions and natural characteristics of each piece were taken. A data base of each piece was established for future analyses.

The beams were visually graded according to the grading rules recommended by the Economic Commissions for Europe (ECE, 1982) referred to as the KAR system. The dynamic modulus of elasticity (E_d) was calcuiated from ultrasonic wave velocity measurements. Modulus of elasticity (E), shear modulus (G) and modulus of rupture (o) were calculated from load-deflection characteristics. Correlations coefficients were obtained between KAR and σ (0.55 to 0.63, E_d and σ (0.59), and E and σ (0.76) for Group A. Futher analysis of the data and more accurate visual grading methods will be explored in the future.

6. FUTURE WORK:

Future work will focus on:

(1) Microscopic identification and characterization of the pieces.

(2) Establish relationship between mechanical properties and ultrasonic measurements of small clear specimens

(3) Determination of the effect of density on modulus of elasticity calculated using the ultrasonic method.

(4) Establish grading procedure based on the mechanical properties obtained from test results and then deducing the natural characteristics of each group (reverse aproach).

(5) Computer simulation of load carrying capacity of floor joists.

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