Strength grading of timber in historic structures – methodology and practical application

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ABSTRACT

The retrofitting and redevelopment of existing structures is of great economic and social importance. A comprehensive assessment of the building's condition is an absolute prerequisite for professional interventions in existing load-bearing structures that do not damage the substance. The assessment of the existing load-bearing capacity is an essential part. The combination of visual and non-/semi-destructive testing methods has proven to be a promising approach. Basic requirements are already included in the drafts of international codes. However, concrete specifications for practical implementation are still missing. This paper presents a method for in situ strength grading. In addition to the basic methodological approach and definite specifications for its implementation, the practical application is presented using the example of tests in the laboratory and in situ.

KEYWORDS: historic timber structures, strength grading, ultrasonic time-of-flight measurement

INTRODUCTION – CURRENT STANDARDS FOR THE ASSESSMENT OF EXISTING TIMBER STRUCTURES

The redevelopment, preservation and future use of existing structures is of increasing economic, ecological and social importance. In order to ensure professional, substance-careful and economic interventions in existing constructions, a comprehensive assessment of the building condition is required. In the recent past, the latter has increasingly become the focus of research and standardization. For example, Italy, Switzerland and Austria published national codes for the assessment of existing structures - especially timber structures - in the period 2004-2013 (see [1]).

In 2015, the Joint Research Centre of the European Union published a first draft of a unified guideline for the assessment of existing structures, which is in line with the regulations of the Eurocodes (see [1, 2]). At the same time, the COST action IE0601 "WoodCultHer" developed a guideline for the assessment of the structural condition of historic timber structures (see [3]). The basic requirements of both guidelines have since been transferred into European standards (see [4, 5]). The essential procedure includes not only the assessment of the structural geometry, the present loads and influences and any possible damage, but also the determination of the existing material quality. However, the currently available international codes [4, 5] only specify general requirements. The material quality should usually be determined using the strength grading methods developed for new timber.

However the strict application of these methods is usually not possible in-situ (see [6]). In practice, therefore, in-situ strength grading is rarely carried out and then only visually and to a limited extent. Usually, the material capacity is only estimated and static calculations are carried out assuming an average load-bearing capacity. A reliable assessment of the material quality is thus not possible. Therefore, alternative approaches are necessary. The combination of a visual examination and non-destructive/semi-destructive testing methods is currently the general consensus (see [4, 5, 7]). However, concrete specifications for the application of an in-situ strength grading are still not available in the existing regulations.

METHODOLOGY FOR THE IN-SITU STRENGTH GRADING

From 2017 to 2021, a systematic study on the strength grading of timber members in existing structures was carried out at BTU/Cottbus, Germany in cooperation with HNEE & VHÖB/Eberswalde, Germany (see [8]). The aim was to develop a methodology for in situ strength grading based on the combined use of visual grading and selected NDTs/SDTs. For this purpose, approximately 900 specimen made from new spruce, pine and oak timber were examined in comparative material tests. These tests included the following test methods (for a detailed description of the applied methods see [9]).

- visual grading according to DIN 4074-1/-5 [10, 11],
- ultrasonic time-of-flight measurement with the Sylvatest Trio measuring device,
- determination of density on cuboid specimen, core drill samples and with the penetration depth method (test device: “wood pecker wood test hammer”)
- and destructive bending tests according to EN 408 [12].

On this basis, two methods for in situ strength grading have been investigated. The first approach was a grading procedure based on the ultrasonic time-of-flight measurement with limiting values for the grading criterion “ultrasonic velocity” (see [8, 9]). The sorting yield showed a significant improvement compared to visual sorting - especially in the strength classes C30/D30 according to EN 338 [13] and higher. However, the accordance between the estimation of the material quality and the load-bearing capacity determined in destructive tests was still comparatively low. The reason for this is, on the one hand, the relatively low correlation between the ultrasonic velocity and the strength and stiffness properties. On the other hand, the ultrasonic pulse time-of-flight measurement does not include the effects of relevant features that influence the load-bearing capacity - such as knots, slope of grain and cracks. From this it can be concluded that ultrasonic time-of-flight measurement is suitable in principle for strength grading, but should not be used alone.

As an alternative approach, the applicability of so-called grading parameters was investigated. These grading parameters are already used for the machine grading of new construction timber. However, the applicable European standards currently only take into account the natural frequency and the density (see [14]). Furthermore, the investigations by the authors have shown that the direct inclusion of the essential visually measurable growth characteristics is necessary for an accurate estimation of the material quality. Therefore, based on the results of the comparative material tests, grading parameters were derived using a multi-variate regression model.

This model enabled the simultaneous evaluation of the measurement results of several non- and semi-destructive test methods. Specifically, the visually measurable growth characteristics like knots, slope of grain and cracks as well as the measurement results of the ultrasonic time-of-flight measurement, the density calculated from the penetration depth and determined on drill core samples were included in the analysis. With regard to the ultrasonic time-of-flight measurement, the transmitted electrical stress as an indicator for the signal attenuation and the dynamic modulus of elasticity were taken into account in addition to the measured ultrasonic velocity. The bending strength and the static modulus of elasticity served as target values.

In order to take the particularities of existing structures and the possible implementation of adjusted analysis methods into account the regression model was set up as a multi-level system (see Figure 1). The extent of the measurements and examinations to be carried out on-site depends on the state of preservation of the components or constructions, their degree of stress and importance for the entire structure, as well as on the conservation value. In general, less extensive investigations are required for subordinate structural components. The main structure and critical components, on the other hand, require a more detailed investigation. This offers the possibility to precisely plan and carry out the necessary investigations in situ. Depending on the extent of the knowledge gained from the strength grading, various adjustments of the verification methods can be made (see [15]).

Strength Grading Level SGL 3 – apparatus-supported visual strength grading

- *Determination of Knot-Area-Ratio, slope of grain and depth of cracks (A/FN/R)*
- *Ultrasonic time-of-flight measurment (v/U)*
- *Extraction of core drill samples for density determination (ρ_{BK}/E_{dyn})*
- *Adjusted verification methods can be used*
- *Scope of Application: Members and constructions with high loads, extensive damages and/or high conservative value*

Strength Grading Level SGL 2 – apparatus-supported visual strength grading

Strength Grading Level SGL 2a	Strength Grading Level SGL 2b
- *Determination of Knot-Area-Ratio, slope of grain and depth of cracks (A/FN/R)* - *Ultrasonic time-of-flight measurment (v/U)*	- *Determination of Knot-Area-Ratio, slope of grain and depth of cracks (A/FN/R)* - *Ultrasonic time-of-flight measurment (v/U)* - *Penetration depth measurement (ρ_{TP}/E_{dyn})*

- *Adjusted verification methods can be used*
- *Scope of Application: Members and constructions with average loads, average damages and/or without conservative value*

Strength Grading Level SGL 1 – visual strength grading

- *Determination of Knot-Area-Ratio, slope of grain and depth of cracks (A/FN/R)*
- *Adjusted verification methods can be used*
- *Scope of Application: Members and constructions with low or average loads, limited or average damages and/or without conservative value*

Strength Grading Level SGL 0 – no strength grading

- *Determination of the overall condition, damage and deformation*

Figure 1: Schematic depiction of the methodology for in situ strength grading

RESULTS

The application of the in situ strength grading methodology to the sample material made from new construction timber showed that the material quality can be reliably estimated. The accordance between the assignment to the strength classes according to EN 338 [13] based on the developed grading method as well as based on the destructive bending tests was (86 ... 96) %.

In addition to the investigations described above, the strength grading methodology was applied in comparative material test on sample material from historical, partially deconstructed timber structures (see [16, 17] and Figures 2 & 3). In the course of this, it was determined that minor adjustments to the methodology are necessary with regard to the consideration of the load-bearing capacity-reducing growth and component characteristics.

Figure 2: Fichtenberg Oberschule, Berlin/Germany – left: exterior view; right: view on the historic roof construktion

Figure 3: Castle Friedenstein, Gotha/Germany – left: aerial view; right: view on the examined ceiling construction

The tests carried out on historic timber components showed that, regardless of the size of the features, their position in the component is also decisive for the load-bearing capacity. Knots, smaller defects, limited organic damage and superficial indentations and notches caused premature failure even if they were relatively small, provided they were located in the loaded area. If these circumstances are not taken into account, the agreement between the estimated and test-determined material quality is only (64 ... 79) %. About (10 ... 30) % of the components were overestimated.

In order to eliminate this deficit, the accuracy of the strength grading methodology was adjusted by means of correction factors. The use of a global factor in the range of k_{IP} = (0.80...0.95) resulted in a reduction of the overestimation to approx. (0 ... 23) %. At the same time the proportion of underestimated samples increased to approx. (5 ... 79) %. This does not represent an improvement in the accuracy and reliability of the results. Using a correction factor k_{vis} = (0.85...0.90) related to the individual case resulted in an overestimation of (7 ... 10) %. The agreement between the estimated and test-determined material quality was (78...85) %. This is acceptable from an engineering point of view. The application of the factor k_{vis} is recommended for components that have local weak points (i.e. predetermined breaking points) that are not included in the calculation of the grading parameter due to their characteristics or size. This is necessary, for example, in the case of knot accumulations, strong crack formation and unfavourable fibre inclinations in the tensile area - especially in the highly stressed component sections, knots and knot accumulations in the area of load introduction, local cross-section weakenings (e.g. cuts/cervicals/etc.), and superficial damage to the edge fibres (e.g. axe notches).

Overall, the application of the proposed grading methodology represents a significant improvement compared to an exclusively visual grading. The examined sample material taken from historic timber structures was underestimated by (61 ... 69) % with regard to its material quality by an exclusively visual grading. Only (23 ... 28) % were assigned to the same strength class as on the basis of the destructive bending tests. This can result in considerable load-bearing capacity deficits, which in practice can lead to an unrealistic evaluation of the construction and thus to unprofessional, less substance-careful and uneconomical interventions in the existing constructions. This deficit can be significantly reduced by applying the proposed methodology for in situ strength grading. In the investigated constructions, reserves in the range of (17 ... 67) % related to the characteristic bending strength and (7 ... 27) % with regard to the mean value of the modulus of elasticity were found. The application of the proposed grading methodology is thus a significant improvement over the current practice in the assessment of present material quality in existing timber structures.

CONCLUSION

The study shows that the method for in situ strength grading derived from tests on new structural timber is suitable for the practical application. This conclusion is confirmed by the laboratory tests on wooden components from historical constructions. The existing uncertainties were considerably reduced with the help of additional safety factors, which take the influence of individual growth and structural characteristics on the fracture behaviour into account. The remaining uncertainties are acceptable from an engineering point of view. This is especially the case under consideration of the load-bearing reserves that can be determined and used in the assessment of the structural stability and for the planning of redevelopment measures.

However, the results also show that the grading process requires expertise in the load-bearing and fracture behaviour of timber members in order to evaluate the measurable parameters according to their structural position.

The results of the presented study are currently used to draft the framework for an application guideline. The implementation of the proposed method into the currently existing standards for the assessment of existing timber structures [4, 5] as part of a detailed on-site survey is possible.

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