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# Combining NDT and visual strength grading to assess ancient timber beams stiffness to evaluate strengthening interventions suitability

**Alberto Cavalli[1], Marco Togni[2]**

**Abstract** Ancient timber beams strengthening is sometimes required by current safety standards, to sustain a safe working load or in order to reduce bending deflection. One of the fundamental information that structural engineers need to know to strengthen structural wooden elements is actual MOE. Through a settled procedure, outlined by a special Italian Standard (UNI 11119:2004) for the diagnosis of ancient timber members, mechanical properties can be assessed. The aim of this work is to evaluate if combining visual strength grading and NDT data might give a better MOE assessment. According to UNI 11119 all the grading characteristics values were recorded and 13 old timber beams of Fir wood (*Abies alba* Mill.) were graded. Beams were tested through Pilodyn 6J in order to assess wood density. Afterwards dynamic and static MOE values were respectively estimated by means of NDTs (longitudinal and bending vibration, stress wave transmission time) and mechanical tests. Possible MOE assessment improvements obtained combining data from visual strength grading and NDTs is showed.

**Keywords** *Abies alba*, visual grading, restoration, NDT, UNI 11119, MOE assessment

## 1. INTRODUCTION

Historical buildings pertinent to cultural heritage needs constant maintenance and the inside timber structures sometimes are under restoration. When the structure needs to be strengthen (e.g. for the change of use) the selection of the appropriate strengthening strategies depends mainly on the smart assessment of the material mechanical properties. It is important to note that the main problem to verify the timber structure (principally floors), is the design for the *Serviceability Limit States* instead of the *Ultimate Limit States*; it can be said that among the mechanical properties, the stiffness of timber members is the actual limiting factor for an accurate and easy design. Each strengthening solution needs an accurate evaluation of the actual stiffness to avoid wrong settings of the restoration design. The two main strategies which may be followed by experts in order to carry on a complete assessment of ancient timber beams are: the visual approach, a fundamental *prerequisite*, and the NDT approach, for better mechanical properties estimation. The idea to combine the data collected from visual grading with the values obtained by means of NDTs is well known. Ceccotti and Togni (1996) studied 12 old timber beams and combined the data (slope of grain, knot area ratio and ring width) collected applying the standard DIN 4074-1:1989 with dynamic MOEs in order to improve the timber bending strength prediction. More recently Blaß and Frese (2004) combined visual and machine strength grading techniques for the classification of structural timber and García et al. (2007)

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combined longitudinal ultrasound velocity with density and knots incidence to predict global modulus of elasticity and timber strength. In this research, thirteen beams of Fir wood (*Abies alba* Mill.) were graded: simulating the on-site condition and the potential accessibility of the faces, the visual features have been collected as follows: dimension of knots, average and local slope of the grain, actual effective load bearing cross section (excepted the decayed/damaged portions), wanes and ring shake extensions. Every other kind of strength effectiveness defects has been noted and described. Each beam has been coupled with its visual strength grade and rough data have been used separately and in combination with NDTs.

## 2. MATERIALS AND METHODS

### 2.1. Beams sample

Thirteen old beams were rescued from different ancient buildings from the Florentine area. The most recent one was beyond 70 years old, none of them were considered historically or architecturally relevant, so the research use of the collected beams was well accepted. The beams are very different for cross section area and length. This heterogeneity is useful in order to identify predictive models able to fit different beams dimensional properties. On the other hands variable length to depth ratio influence the dynamic tests results. The lowest span to depth ratio value is higher than ten which is an acceptable limit for flexural vibration test (Brancheriau 2002) and for stress wave transmission time test (Andrews 2002). The beams were stored in a covered place outside for 8 years and inside a warehouse for one year before the tests started. Moisture content (MC) has been measured by means of a digital recording moisture meter, a radio frequency device, to evaluate MC by the wood capacitance. For the all beams, the average MC measured was around 11.5%, so no adjustments were proposed either for stiffness value or density, due to the proximity MC=12% and uncertainty about the real average moisture content of the whole cross section.

### 2.2 Visual strength grading

The visual approach is the main strategy for the assessment of timber beams, in particular it is the first step for the on-site evaluation on historical buildings (Bonamini 1995 , Bonamini et al. 2001, Kasal 2004) because it is the proper (and less expensive) way to evaluate the most important features of ancient timber elements: a) original defects of the wood: ring shake, wanes, checks, slope of grain (*SoG*), knot incidence (*KI* - calculated as the minimum knot diameter to depth/width ratio); b) decay and/or damage; c) previous interventions identification; d) each sign which can be related to qualities potentially affecting the structural behaviour of the member.
Since 2004 the Italian standard UNI 11119, first in Europe, regulates on site inspection and visual strength grading by an appropriate rule studied for ancient timber members, to define the mechanical performances of each structural member. The standard was formulated to proceed step by step to the inspection procedures, especially calibrated for the on-site operations, from the description of the existing conditions to the inspection report. It has been proved to be an effective tool to achieve a complete analysis (Mannucci et al. 2011, Macchioni et al. 2011).

### 2.3 Mechanical tests

Laboratory tests were performed according to the standard EN 408:2010 in order to determinate local and global MOEs ($E_{m,l}$ and $E_{m,g}$ respectively).

### 2.4 Dynamic MOEs

For all dynamic MOEs determination, the beams were supported at their theoretical nodal points (0,224 of the length for fundamental vibration mode in flexural vibration) in order to reduce the influence of boundary condition on vibration mode. To reduce the contact surface between supports and wood, two fixed steel cylinders were used as supports. All the dynamic tests were carried out using coaxial piezoelectric accelerometers connected to a notebook and, for the stress wave transmission time determination, to a digital storage oscilloscope.

*2.4.1.Flexural vibration*

Vibration was induced by a hammer impact and collected by an accelerometer connected to a notebook pc. Resonance frequency was determined by FFT analysis using GS Spectrum Analyser software. Dynamic flexural MOE ($E_f$) was calculated using Equation 1 (Giordano 1981) for the beams supported at their theoretical nodes (zero vibration points). Only the fundamental vibration mode was used.

$$E_f = \rho \left( \frac{f_m l^2}{\sqrt{\frac{I}{A}} 3{,}5608} \right)^2 \tag{1}$$

$E_f$ = dynamic flexural MOE [MPa], $\rho$ = density [kg/m$^3$], $fm$ = fundamental vibration frequency [kHz], $l$ = beam length [m], $I$ = moment of inertia [mm$^4$], $A$ = cross section area [m$^2$].

*2.4.2.Longitudinal vibration*

An accelerometer was fixed at one end and the other one was stimulated with hammer impact. Vibration frequency was recorded and dynamical MOE was determined according to Equation 2 proposed by Kollman and Krench (1960).

$$E_l = 4\rho l^2 f_m^2 \tag{2}$$

$El$ = dynamic longitudinal MOE [MPa], $\rho$ = density [kg/m$^3$], $f_m$ = fundamental vibration frequency [kHz], $l$ = beam length [m].

*2.4.3.Stress wave transmission time*

Two accelerometers were fixed on the beams ends and the beams were excited by a hammer impact. The accelerometers were connected to an oscilloscope and the one nearer the hit end starts up a microsecond counter while the second one stops it, thus providing the time for the impact stress wave from the first to the second accelerometer. The velocity of stress wave was determined simply dividing the length of the beam by the time of flight of stress wave. Dynamical modulus of elasticity was determined according to equation 3 (Kolsky 1963):

$$E_{sw} = \rho v^2 \tag{3}$$

$E_{sw}$ = dynamic stress wave MOE [MPa], $\rho$ = density [kg/m$^3$], $v$ = stress wave velocity [km/s].

### 2.5. Hardness test

Density is fairly good related to the main wood mechanical properties but its on site direct measurement is not always possible and its assessment presents some technical problems: sometimes excessive complexity or "destructiveness", as the screw pull out test or specimen extraction, not compatible with ancient beams, pertaining cultural heritage. The NDT chosen to evaluate the density and minimise damage was the wood hardness test by the well know device Pilodyn 6J single shot (Hoffmeyer 1978, Ross et al. 1991). On the other hand the Pilodyn results must be used taking into account some limits (only external density assessment, difficult to identify exactly the anatomical direction on site). This dynamic test for hardness was performed on all the beams faces, repeated every 800 mm, taking care that the direction of the pin was perpendicular to the growth rings, to avoid the application of an adjustment factor (Görlacher et al. 1987).

## 3. RESULTS AND DISCUSSION

## 3.1. Visual grading

Each beam was graded according to the UNI 11119 (Table 1) on the base of all the collected defects. Also the MOE values (extracted from UNI 11119, appendix A – Informative) were reported in Table 1. While the grade has been assigned according to the worst defect, among the all defects considered by the standard, we examined more in detail slope of grain (*SoG*) and the knot incidence (*KI*), that are the most important MOE (and MOR) influencing parameters. Through this simplified grading only two beams are graded in the third grade, five in the second and six in the first one.

## 3.2. Physical and mechanical properties

The main properties of the beams are summarized in Table 1. The Coefficients of variation are very close to the values determined on small and clear specimens standardly tested and reported in the "Annual book of ASTM Standards" (2002). For the Italian Fir density, Giordano (1981) reports an average value of 440 kg/m$^3$ at a MC range between 12-15% that is similar to the value measured for the beams sample. According to Piazza and Riggio (2008) the average MOE values reported by the standard can be significantly different from the measured ones: comparing the data reported in Table 1 the static MOEs average value is approximately 55% lower than the one reported by the UNI 11119.

**Table 1** – Visual strength grading , NDTs values, physical and mechanical properties.

| *Beam* | *UNI 11119* | *Simplified grading* | *MOE UNI 11119* | $E_{m,l}$ | $E_{m,g}$ | $\rho$ | $E_f$ | $E_l$ | $E_{sw}$ | *Pilodyn* |
|---|---|---|---|---|---|---|---|---|---|---|
| *n°* | *Grade* | *Grade* | *[MPa]* | [MPa] | [MPa] | [kg/m$^3$] | [MPa] | [MPa] | [MPa] | [mm] |
| *1* | II | I | 13000 | 12754 | 10071 | 477 | 12030 | 14679 | 17637 | 10.5 |
| *2* | III | II | 12000 | 9620 | 8311 | 490 | 9518 | 12496 | 14832 | 12.1 |
| *3* | III | I | 13000 | 10682 | 9640 | 431 | 11544 | 14249 | 14453 | 12.4 |
| *4* | III | I | 13000 | 8652 | 7952 | 407 | 8825 | 12227 | 13117 | 12.5 |
| *5* | III | I | 13000 | 10576 | 9622 | 445 | 10711 | 12880 | 15749 | 12.1 |
| *6* | III | I | 13000 | 6749 | 4386 | 351 | 6806 | 9023 | 11583 | 20.0 |
| *7* | III | III | 11000 | 8717 | 6043 | 382 | 5739 | 6630 | 6295 | 16.7 |
| *8* | II | II | 12000 | 4901 | 4610 | 364 | 5034 | 8565 | 6883 | 17.9 |
| *9* | III | III | 11000 | 5669 | 4050 | 425 | 5855 | 8781 | 8307 | 14.7 |
| *10* | III | I | 13000 | 10756 | 7706 | 481 | 11439 | 14451 | 18377 | 13.1 |
| *11* | III | II | 12000 | 7711 | 5094 | 399 | 6706 | 9303 | 11850 | 17.3 |
| *12* | II | II | 12000 | 7157 | 6109 | 343 | 6046 | 8758 | 8934 | 18.1 |
| *13* | III | II | 12000 | 8031 | 6564 | 371 | 8323 | 10963 | 11601 | 18.2 |
| *average* | - | - | - | 8613 | 6935 | 413 | 8352 | 11000 | 12278 | 15.0 |
| *min* | - | - | - | 4901 | 4050 | 343 | 5034 | 6630 | 6295 | 10.5 |
| *max* | - | - | - | 12754 | 10071 | 490 | 12030 | 14679 | 18377 | 20.0 |
| *CV [%]* | - | - | - | 26 | 30 | 12 | 30 | 24 | 32 | 21.0 |

## 3.3. Non destructive tests

Dynamics MOE and Pilodyn depth penetration data are presented in Table 1. As observed by several authors investigating various NDTs and species (Bell et al. 1954, Smulski 1991, Lin et al. 2007), the average dynamics MOE values are higher than the static ones. The difference of 12% between $E_l$ and $E_{sw}$ was explained by Andrews (2002) who compared the acoustic speed measures obtained by resonance test and the stress wave time of flight methods, applied on the same specimens. He found that, especially for high depth-length ratio specimens, some energy travels faster than the main wave front, determining an overestimation of the velocity up to 25% in the case of stress wave method.

### 3.4. Simple linear regressions

In order to compare linear models with various explanatory variable numbers, adjusted coefficient of determination ($R^2_{adj}$) has been adopted (Equation 4). Residuals normality distribution and homoscedasticity were checked respectively by statistical tests and residual plots analysis.

$$R^2_{adj}=1-(1-R^2)\frac{n-1}{n-p-1} \qquad (4)$$

$R^2_{adj}$ values for simple linear regressions are reported in Table 2 with relative significance levels used in this research (p<0,01 (***); 0,01< p<0,05 (**); 0,05< p<0,1 (*)). Only few researches were conducted on ancient timber elements of large cross section to evaluate the reliability of the dynamic tests for the MOE/MOR assessment. The results for the single regressions reported in these researches appear to be controversial with various coefficients of determination ($R^2$) values: Ceccotti and Togni (1996) found a very high $R^2$ value between $E_{sw}$ - $E_{m,l}$ (0.85) and $E_f$ - $E_{m,l}$ (0.83); contrary, Capecchi (2002) found a fairly good value between $E_f$ - $E_{m,l}$ (0.65) and Branco et al. (2010) reported a very poor relationship between $E_{sw}$ - $E_{m,l}$ (0.36). For new elements with large section Íñiguez et al. (2008) and Casado et al. (2010) found similar $R^2$ at almost 0.77 for $E_l$ - $E_{m,l}$. The correlation found by this study between $E_f$ - $E_{m,l}$ is very close to the value reported by Ceccotti and Togni (1996), taking into account that the values reported in Table 2 are $R^2_{adj}$ that is always smaller than a simple $R^2$. The $E_f$ value results as a better single predictor for the static MOEs with high correlation (at almost 0.8*** in each case). Pilodyn penetration deep shows a very good correlation with density, the $R^2_{adj}$ value of 0.77 is in agreement with the determination coefficient from different studies on softwood elements of large cross section: 0.74 (Ceccotti and Togni 1996); 0.81 (Branco et al. 2008); 0.61 (Íñiguez et al. 2010). The stiffness of a timber element is largely affected by the global properties of wood (likes density and *SoG*) and less affected by localized defects like knots (Hanhijärvi et al. 2005). This assumption appears to be supported by the data that shows good relationship between static MOEs and both density and *SoG*, while the relationship between *KI* and static MOEs is poor and characterized by low or null significance levels, like the value reported by García et al. (2007). Looking at the *KI* column in the Table 2, it seems that *KI* affect both the vibrating modes and the time of flight of stress waves, but they do not affect the static MOEs.

### 3.5. MOE assessment combining NDTs and visual parameters

As already described, the *KI* and the *SoG* are the most important defects that lead the MOE reduction. In Table 3 these two defects were combined in various way with NDT values. Moreover, for comparison purpose, the density value was used in the same way. $R^2_{adj}$, significance levels and mean absolute percentage error (MAPE) were reported: MAPE was used as estimator of the model accuracy. $R^2_{adj}$ and MAPE improvement was obtained combining only one parameter (*KI* or *SoG*) or both the parameters to the NDT values. Using $E_f$ in addition with other parameters, the best results for both $R^2_{adj}$ and MAPE values were achieved. Adding visual data to the models which includes $E_f$, a consistent $R^2_{adj}$ improvement was obtained only for $E_{m,l}$. Generally, we can observe that for the models that explain $E_{m,l}$ the higher $R^2_{adj}$ values was obtained combining both visual parameters (*KI* and *SoG*) with dynamics MOE. For the models that explain $E_{m,g}$, the highest $R^2_{adj}$ values were obtained simply adding *SoG* to the dynamical MOE values. As expected we can observe that *SoG* is the most important parameter obtained by visual grading for $R^2_{adj}$ improvements, but in several cases adding *KI* could be useful in order to increase the model accuracy. Combining visual parameters with $E_f$ or $E_l$ permit to obtain very good or high $R^2_{adj}$ values for all the static MOEs determined. Less correlated models were obtained using $E_{sw}$ but still usable especially for $E_{m,l}$ explanation.

**Table 2** – $R^2_{adj}$ values for simple regressions and relative significance levels.

| | $E_{m,g}$ | $E_f$ | $E_l$ | $E_{sw}$ | $\rho$ | *Pilodyn* | *SoG* | *KI* |
|---|---|---|---|---|---|---|---|---|
| $E_{m,l}$ | 0.83*** | 0.82*** | 0.63*** | 0.66*** | 0.49*** | 0.56*** | 0.45*** | 0.03 |
| $E_{m,g}$ | | 0.80*** | 0.70*** | 0.56*** | 0.40*** | 0.67*** | 0.44*** | 0.22* |
| $E_f$ | | | 0.94*** | 0.87*** | 0.56*** | 0.60*** | 0.37** | 0.30** |
| $E_l$ | | | | 0.87*** | 0.55*** | 0.61*** | 0.26** | 0.46*** |
| $E_{sw}$ | | | | | 0.56*** | 0.45*** | 0.28** | 0.31*** |
| $\rho$ | | | | | | 0.77*** | -0.00 | -0.01 |
| *Pilodyn* | | | | | | | 0.08 | 0.15 |
| *SoG* | | | | | | | | 0.11 |

**Table 3** – Static MOEs prediction by linear regression models combining static MOEs, NDT, *KI* and *SoG* values: $R^2_{adj}$, relative significance levels and MAPE values (in brackets).

| | | $E_f$ | $E_l$ | $E_{sw}$ | *Pilodyn* | $\rho$ |
|---|---|---|---|---|---|---|
| $E_{m,l}$ | | 0.82*** (8.6) | 0.63*** (11.8) | 0.66*** (11.6) | 0.56*** (15.4) | 0.49*** (15.5) |
| | *KI* | 0.89*** (7.5) | 0.74*** (11.2) | 0.69*** (12.2) | 0.52** (15.4) | 0.47** (14.9) |
| | *SoG* | 0.83*** (7,8) | 0.70*** (9.9) | 0.71*** (9.2) | 0.74*** (8.8) | 0.77*** (8.8) |
| | *KI* + *SoG* | 0.91*** (5.8) | 0.85*** (8.2) | 0.77*** (9.0) | 0.75*** (9.1) | 0.75*** (8.5) |
| $E_{m,g}$ | | 0.80*** (12.3) | 0.70*** (15.0) | 0.56*** (17.6) | 0.67*** (14.4) | 0.4*** (21.0) |
| | *KI* | 0.78*** (12.3) | 0.69*** (14.9) | 0.52*** (17.4) | 0.66*** (14.0) | 0.50** 18.2) |
| | *SoG* | 0.81*** (10.6) | 0.75*** (11.0) | 0.62*** (13.7) | 0.82*** (10.3) | 0.68*** (13.5) |
| | *KI* + *SoG* | 0.79*** (10.7) | 0.75*** (10.2) | 0.58*** (13.6) | 0.81*** (9.8) | 0.68*** (12.3) |

### 3.6. On site stiffness assessment

Strengthening interventions are often carried out directly on site, so also the NDTs and the visual strength grading is performed in the same conditions. The NDTs are not always of easy on site realization: flexural vibration test requires specific boundary conditions, for longitudinal vibration test the timber ends should be accessible and the density values are indispensable for the dynamic MOE values estimation. Moreover in load bearing structures not all the faces of the elements can be easily inspected in every condition. For the Italian UNI 11119 the on site visual inspection can be carried out if at least three faces are completely accessible. In order to simulate these particular conditions the most interesting models are reported in Table 4. These models use only the parameters collected on three faces (noted *3f* - the worst value measured among the edges and the intrados) and the stress wave transmission time velocity that can be easily obtainable on site. Good $R^2_{adj}$ values were obtained simply combining *Pilodyn_3f* and *v*. Considerable improvements are possible in the case of $E_{m,l}$ estimation (adding *KI_3f* and *SoG_3f*) and for $E_{m,g}$ estimation (adding *SoG_3f*): high $R^2_{adj}$ and good MAPE values, very good $R^2_{adj}$ and reasonable MAPE values respectively.

## 4. CONCLUSIONS

Taking into account the limited numbers of tested beams, the following conclusions can be summarized:

– the information collected applying the Italian standard UNI 11119 are useful for the general assessment of the beams and to improve the $E_{m,l}$ and $E_{m,g}$ prediction (if combined with NDTs), otherwise the indicative MOE values reported by the standard (Appendix A) are not reliable for an accurate strengthening intervention plan, and potentially unsafe.

– Among linear regressions, the $E_f$ and the $E_l$ are the best single predictors for the static MOEs: $R^2_{adj}$ is approximately 0.80 between $E_f$ and static MOEs and 0.70 between $E_l$ and $E_{m,g}$.

– Combining the data obtained from the visual strength grading (*SoG* and *KI*) and NDT values, consistent improvements of MOEs estimation are obtained. The use of $E_f$ combined to *KI* and *SoG* gives a very high $R^2_{adj}$ values of 0.91 and very accurate $E_{m,l}$ estimation (MAPE=5.8).

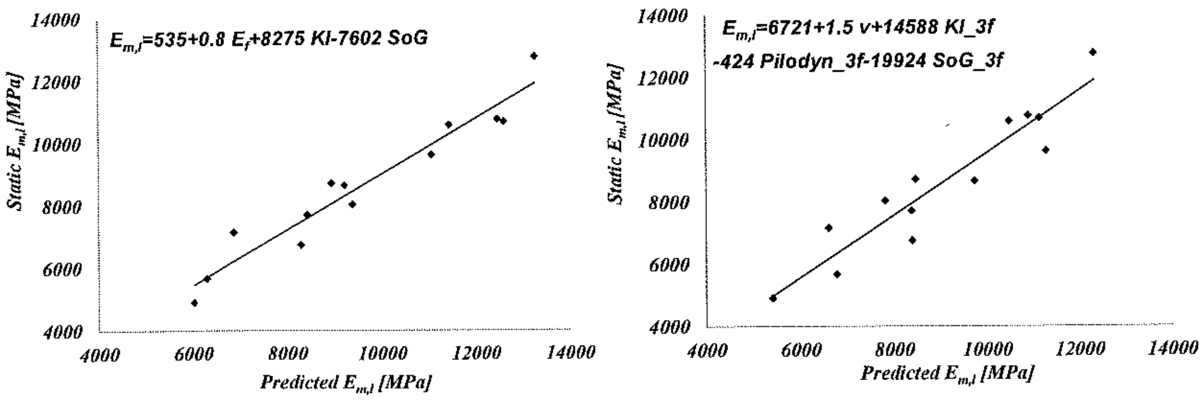
– When the operating conditions limit both the beams accessibility and the evaluation of $E_f$ and $E_l$, an alternative model can be fruitfully adopted for the MOEs assessment. This model is based on the use of stress wave transmission time velocities, Pilodyn values, *KI* and *SoG* and it provides a very good $R^2_{adj}$ values (0.83 and 0.76 for $E_{m,l}$ and $E_{m,g}$ respectively).

– Pilodyn results as a very good tool for the density estimation and the density remain a key factor for the static MOEs assessment.

**Table 4** – Static MOEs prediction by linear regression models combining NDT, *KI_3f* and *SoG_3f* values: $R^2_{adj}$, relative significance levels and MAPE values (in brackets).

| | | *v + Pilodyn_3f* | | | *v + Pilodyn_3f* |
|---|---|---|---|---|---|
| | | 0.63*** (11.4) | | | 0.71*** (13.9) |
| $E_{m,l}$ | *KI_3f* | 0.71*** (10.8) | $E_{m,g}$ | *KI_3f* | 0.68*** (13.8) |
| | *SoG_3f* | 0.69*** (9.4) | | *SoG_3f* | 0.76*** (13.1) |
| | *KI_3f + SoG_3f* | 0.83*** (7.6) | | *KI_3f + SoG_3f* | 0.74*** (13.1) |

**Figure 1** – (left): observed vs predicted $E_{m,l}$ values combining $E_f$, *SoG* and *KI* values (all faces accessible); (right): observed vs predicted $E_{m,l}$ values combining *v*, *Pilodyn*, *SoG* and *KI* values (only three faces accessible).



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