The Effect of Length on Stress-Wave Velocity in Long Pieces of Salzmann Pine from Existing Structures

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Abstract

The use of non-destructive techniques (NDT) to estimate physical-mechanical timber properties is an effective way of assessing and conservation of built heritage. Some research works have applied NDTs in different species with different piece's dimensions and have showed good correlations between timber properties and the Time-of-Flight (ToF) with portable stress-wave devices. Nevertheless, there are certain parameters that need to be studied deeper, such as the effect of the pieces' dimensions on the ToF estimation.Usually, timber structures of existing buildings in Spain present large cross-section pieces as well as a cross-section variation along the piece. Frequently, in-situ assessments accessibility to structural members is complicated and measurements may only be made on 1 or 2 surfaces of the piece. The test material used in this research study consisted of 21 structural timber pieces (rafters) with 150x200 mm^2 in average cross-section and 9.53 to 11.00 m in length of Salzmann pine species (*Pinus nigra* Arnold ssp. *salzmannii* (Dunal) Franco). The material comes from an existing structure built in 1768 (Royal Coliseum of Charles III in Aranjuez, Madrid, Spain).In this work, the ToF has been obtained from end to end and in different lengths ranging from 0.5 to 10.5 m at one edge of the piece and also their corresponding transmission velocities. In addition, stress velocity has been determined based on both the ToF corrected with time lag and the ToF in intermediate sections to avoid the local effect of the initial wave path.

Keywords: non-destructive testing, stress waves, length effect, Salzmann pine.

Introduction

Acoustic methods applied to structural timber have demonstrated to be an effective tool in the estimation of mechanical properties. These methods allow an accurate estimation of dynamic modulus of elasticity (MOE_{dyn}) in timber from existing structures as well as in new buildings. Their application in the *in-situ* assessments have a great potential both for grading structural timber members and to predict their mechanical behaviour (Arriaga et al. 2017; Branco et al. 2017). This plays a critical key in the conservation of built heritage. Nevertheless, there are several parameters that affect acoustic readings, such as moisture content, temperature, member's dimensions, and the devices used (Gonçalves and Leme 2008; Llana et al. 2014, 2018; Osuna-Sequera et al. 2017).

In *in-situ* assessments, the accessibility to all surfaces of the pieces is often complicated or sometimes even impossible. Therefore, the determination of dimensions of the pieces and its influence on the measurements must be taken into account when planning the sampling areas. Some research works have studied the effect of geometry of the pieces using acoustic methods (Bucur and Böhnke 1994; Bartholomeu et al. 2003; Oliveira et al. 2006; Osuna-Sequera et al. 2017).

The aim of this work is to study the effect of length on acoustic measurements with stress waves in pieces from a historic building as well as to compare the acoustic parameters obtained by applying different measurement methods.

Materials and method

Material

The tested material are ten rafters from the Royal Coliseum of Charles III in Aranjuez, Madrid, Spain, designed by the French architect Jaime Marquet and built in 1768. The wood species was identified as Salzmann pine (*Pinus nigra* ssp. *salzmannii* (Dunal) Franco) by the Forest Timber Industries Laboratory of the Universidad Politécnica de Madrid and the Structural Timber Laboratory of INIA-CIFOR (National Agricultural Research Institute), Madrid, Spain. These pieces with 150x200x11000 mm^3 nominal dimensions have already been studied in previous works (Osuna-Sequera et al. 2017, 2019 a; 2019 b).

Device

The MicroSecond Timer (MST) (Fakopp, Sopron, Hungary): It is an impact-induced stress wave timing device that allows to measure the ToF using two spike sensors (transmitter and receiver) and obtain an accuracy of 1 µs. The excitation is generated by a blow of a 100-gram hammer.

Time-of-Flight and wave velocity

The ToF is timed from the wave is generated by the hammer hitting the transmitter until it reaches the receiver. The wave stress velocity (V) in m s^{-1} is obtained from the Equation 1 according to the following parameters: length between the sensors (L) and ToF.

$$V = \frac{L}{ToF} \tag{1}$$

Sensor positioning

The ToF was obtained by positioning the sensors in two configurations:

- End-to-end measurement: Sensors were positioned perpendicularly on the ends. Two end-to-end measurements have been made: an upper measurement located at one third of the height, h, and a lower measurement positioned at two thirds of h, both on the vertical axis of the section as shown in Fig. 1a.

- Surface measurement: The two sensors are positioned at the same piece surface with 45º above the horizontal axis, Fig. 1b, c. This positioning of the sensors may be the most suitable in an *in-situ* assessment, due to the limited access to one of three faces of the piece, where the ends are hidden and inaccessible. 11 cross-sections (numbered from 0 to 10) were marked in each piece at 1 m intervals, leaving 20 cm margin at each end, Fig. 1. In addition, when the receiver was positioned in the cross section 0, the measurements were denominated ascendants, Fig 1b. On the other hand, when the receiver was positioned in the cross section 10, the measurements were denominated descendants, Fig 1c.

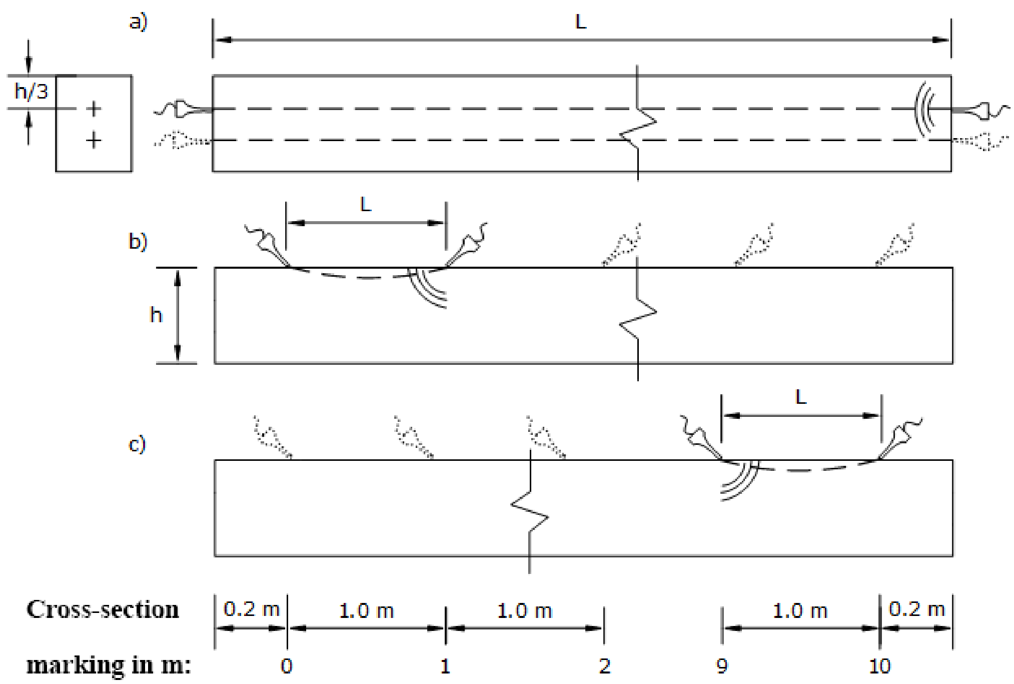

Figure 1. Details of the marking of the pieces, end-to-end (a) and surface (b) measurement.

Wave velocity determination

Wave velocity was obtained following several criteria. The end-to-end velocity (V_0) was determined from the average value of upper and lower ToF measurements in each piece, Equation (1), Fig 1a. The global surface velocity ($V_{s,\,glo}$) was obtained from the coefficient b of Equation (2), which is the slope of the linear correlation between ToF and L for each piece.

$$\mathrm{ToF} = a + b \cdot L \tag{2}$$

Where a and b are the coefficients of linear regression between ascendant or descendant ToF_i and L_i. The inverse value of b is the $V_{s,\,glo}$ ascendant or descendant, which represents the Time Lag (tL).

The ascendant surface velocity ($V_{s,\,asc,\,i}$) was obtained for each L with the method referred in Fig. 1b and, similarly, descendant surface velocity ($V_{s,\,des,\,i}$) was calculated using the method referred in Fig. 1c.

The local velocity ($V_{i\text{-}j}$) was obtained from the increment of ToF and L between two surface measurements, Fig. 2, in order to remove the errors of measurement produced in the output and arrival of the wave, Equation (3). In this work, the local velocity was calculated from 3 to 8 m ($V_{3\text{-}8}$) according to Equation (3) with the TTO from the ascendant measurement with the aim of simplifying the results.

$$V_{i-j} = \frac{L_j - L_i}{TTO_j - TTO_i} \tag{3}$$

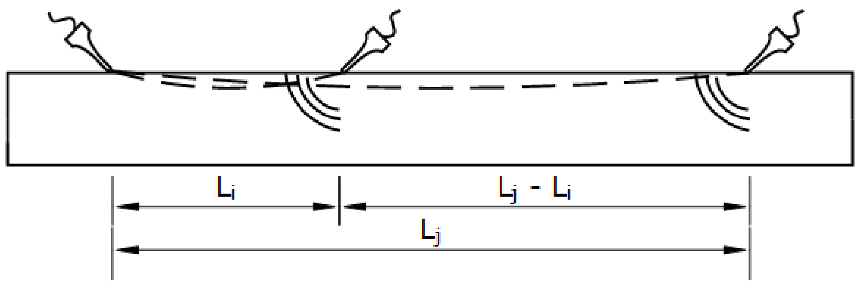

Figure 2. Details of local velocity measurement.

Results and discussion

End-to-end velocity

Table 1 shows the results of the end-to-end velocities in m s^{-1} and the distance between the sensors in m for each piece.

Table 1. End-to-end velocities using MST device and distance between sensors.

Piece Nº	L [m]	V_0 [m s^{-1}]
1	10.83	5189
2	10.90	4903
3	10.89	4728
4	10.90	5290
5	10.38	4823
6	9.69	4532
7	9.53	5009
8	10.89	4730
9	10.77	4498
10	10.24	5176

The average V_0 of the batch is 4888 m s^{-1} with 6% of coefficient of variation (CoV) and an average length between sensors of 10.50 m. Arriaga et al. (2017) showed a mean V_0 value of 5229 m s^{-1} with 6% CoV in 30 sawn Salzmann pine timber pieces with MST and a 4 m sensor length. In a previous work, Osuna-Sequera et al. (2019 a) presented an average V_0 of 4858 m s^{-1} and CoV of 5% measured in the same pieces at this work but this time using Sylvatest Duo (SYL) (CBS-CBT, France-Switzerland) device. Comparing both devices, the ratio between MST and SYL average V_0 is 1.006, which means that V_0 obtained with MST and SYL have similar results in this case. The ratio between MST and SYL V_0 average is 1.031 using the results of Arriaga et al. (2017) in 30 4 m sawn Salzmann pine timber pieces.

Surface velocity

Global ascendant and descendant surface velocities

The $V_{s,\,glo}$ ascendant and descendant obtained from Equation 2 are showed in Fig. 3.

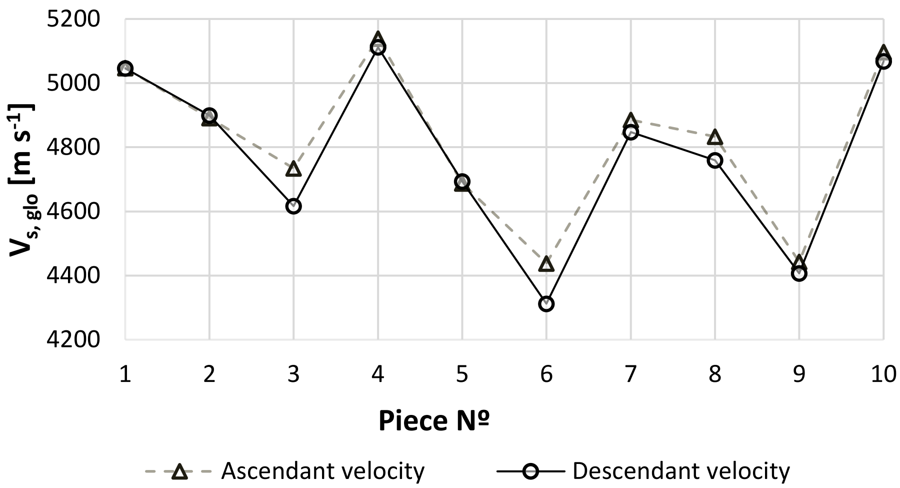

Figure 3. Ascendant and descendant apparent surface velocities in each piece with MST.

The results of taking the measurements in ascendant or descendant direction, show similar values with a maximun and minimum difference of 126 and -7.4 µs. Nevertheless, the tL presents different values depending on the direction, being higher in descendant way. A linear regression was carried out between both $V_{s,\,glo}$ with a coefficient of determination $r^2 = 0.98$ and a standard error (StE) 40.5 m s^{-1}. In a previous work, Osuna-Sequera et al. (2019 a) revealed a similar behaviour with ultrasounds. It can be concluded that there is not a significant effect with stress-wave measurement depending on the direction of measurement. In order to simplify the explanation, in the following analysis only the ascendant velocity $V_{s,\,asc,\,i}$ will be considered.

In this work, the ratio between V_0 and $V_{s,\,glo}$ presents an average value of 1.014, with a linear regression with $r^2 = 0.92$ and StE 84 m s^{-1}. Arriaga et al. (2017) presented a relation between V_o and $V_{s,\,glo}$ of 1.010 in 30 sawn Salzmann pine pieces with dimensions 90x140x4000 mm^3. This reinforces the idea that there is a fixed proportion between both measurements depending on the device used.

Ascendant and descendant surface velocities

In order to analyze the effect of length in stress-waves transmission velocity along the piece, relative velocities were calculated as a quotient between $V_{s,\,asc,\,i}$ and $V_{s,\,glo}$ in each piece, Fig. 4.

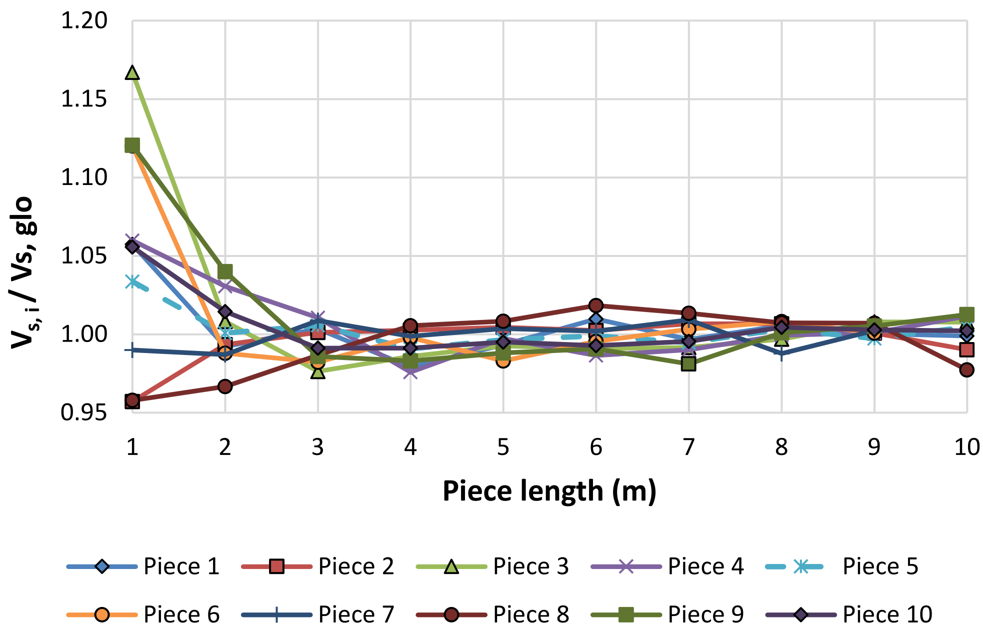

Figure 4. Relative velocities depending on the piece length, $V_{s,\,i}$ / $V_{s,\,glo}$.

The tendency to the value 1.00 observed in Fig. 4 is clearer when the distance between the sensors is higher. From 2 to 10 m of L, the ratio between $V_{s,\,asc,\,i}$ and $V_{s,\,glo}$ is equal or less than 1.040, and from 3 to 10 m equal or less than 1.020. Approximately, this ratio keeps constant from 2 m L. This variation is smaller in short distances than results obtained with SYL in Osuna-Sequera et al. (2019 a).

Local velocity

Local velocity ($V_{i\text{-}j}$) was analyzed from 3 to 8 m ($V_{3\text{-}8}$). Fig. 5 shows the values of velocity obtained for V_0, $V_{s,\,glo}$ and $V_{3\text{-}8}$ in m s^{-1} for each piece.

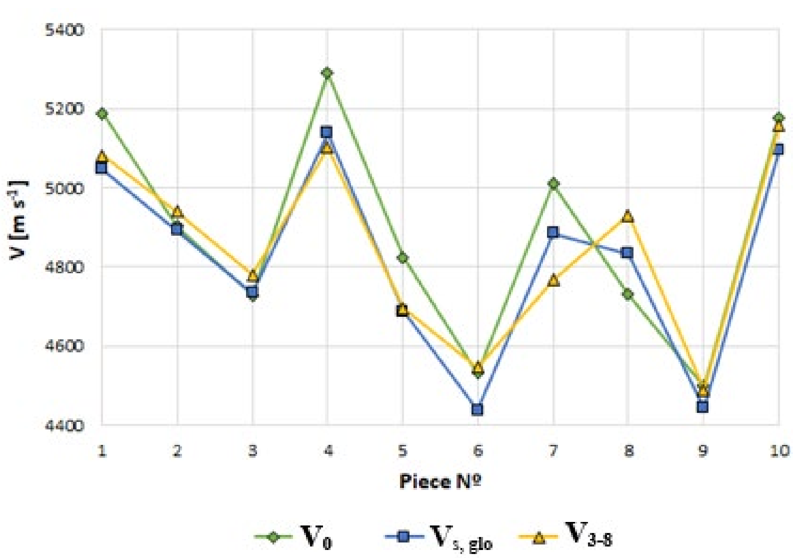

Figure 5. End-to-end velocity (V_0), Global surface velocity ($V_{s,\,glo}$), Local velocity ($V_{3\text{-}8}$) comparison for each piece.

Fig. 5 shows very similar values among the three velocities represented. V_0 values seems to be slightly higher than $V_{s, glo}$ in almost all pieces (except in piece Nº 8) with an average ratio of 1.014. The linear regression between $V_{s, glo}$ and V_{3-8} presented a $r^2 = 0.93$ and StE = 70.4 m s^{-1}. It may be possible to estimate $V_{s, glo}$ with a local measurement from 3 to 8 m with a high accuracy. Comparing the results obtained with other previous works, Osuna-Sequera et al. (2019 a) presented a relationship between V_0 and the other velocities, $V_{s, glo}$ and V_{3-8}, more differentiated with SYL, where V_0 was clearly higher. Nevertheless, as discussed in the previous section *"Global ascendant and descendant surface velocities"*, Arriaga et al. (2017) presented a ratio between surface velocities and end-to-end velocities measured with SYL of 1.045 and with MST of 1.010. In the present work, the average ratio between V_0 and $V_{s, glo}$ was 1.014. As this MST ratio is lower than in SYL, the end-to-end velocity may not as distinguish from the other two.

Conclusions

The surface velocity obtained measuring in both directions presents similar values. It can be concluded that the measurement of velocity with the stress-wave method is not affected by the direction of grown of the tree. Nevertheless, the time lag has different values in each case, being higher in descendant way, which will be studied in future works.

Surface velocities obtained with 1 m sensor distance showed a maximum difference between the ascendant surface velocity and the global surface velocity of 17%. From 2 m sensor distance to 10 m, the maximum difference was 4%.

The average end-to-end velocity presented a slighter higher value (1.41%) than global surface velocity. End-to-end velocity was not corrected with the tL, whereas the global surface velocity was corrected. As consequence of tL correction, it is considered the global surface velocity as the most representative.

The linear regression between the global surface velocity and the local velocity between 3 and 8 m showed that could be a simple way to obtain an accurate approximation to global surface velocity with only two surface measurements. Furthermore, the local velocity avoids the tL correction and the effect of the output and arrival of the wave.

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