Use of Ultrasonic Tomography in the Evaluation of Timber Structures

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Abstract
Ultrasonic tomography has been used in civil engineering to evaluate the integrity of structural concrete members. There is much less information about its application to timber structures even though there are a large number of constructions made of wood with historic value. Unlike concrete, timber is not an isotropic construction material, and therefore the elastic properties in different directions may play an important role when an ultrasonic tomography is performed. This work presents results of a laboratory study in which some wood elements at various levels of structural integrity were analyzed using ultrasound tomography based on an algorithm developed for common isotropic construction materials. The results indicate that it is possible to detect internal flaws in timber structures, however, in order to locate them precisely it is necessary to consider the orthotropic behavior of wood. Considerations on mathematical issues related to ultrasonic tomography for orthotropic materials are then presented.

Keywords: Computed tomography, ultrasonic testing, civil engineering, cultural heritage, timber structures, inspection

1. Introduction

The ultrasonic pulse velocity method has been used in civil engineering in the inspection of structural members for many years [1]. Variations in the ultrasonic pulse velocity within the structural member may help to identify regions with non-homogeneities such as poor consolidated regions in concrete structures or termite infested regions in timber structures. Recently, ultrasonic tomography has also been associated to evaluate the integrity of concrete members with several successful applications being reported [2-5]. However, there is much less information about the application of ultrasonic tomography to timber structures even though there are a large number of constructions made of wood with historic value.

In order to evaluate the integrity of a timber structural member, a truly non-destructive test is required since any even minor damage should be avoided [6]. Among the various methods available, the ultrasonic pulse velocity method only needs simple affordable equipment, and thus is one of the most used nowadays. In order to locate a possible flaw within the structure, a large number of ultrasound readings is necessary. Ultrasonic tomography uses these ultrasound readings to generate images of transverse sections of the structural member.

Although there have been some reports of ultrasonic tomography applications in trees [7-9], the mathematical aspects related to the application of ultrasonic tomography for orthotropic materials has been less explored. Unlike concrete, timber is not an isotropic construction material, and therefore the elastic properties in different directions may play an important role when an ultrasonic tomography is performed.

Most of the reports available on the use of ultrasonic tomography in wood elements deals with application of commercial software already developed. This work, on the other hand, has the purpose to present and to discuss the mathematical fundamentals to be followed when a tomography software to be used for orthotropic material is being developed.
An ultrasound tomography software based on an algorithm developed for an isotropic material was used in a laboratory study in which several timber structures at various levels of structural integrity were analyzed. The results indicated that it is possible to detect internal flaws in timber structures; however, in order to locate them precisely it is necessary to consider the orthotropic behavior of wood in the ultrasonic tomography software. Considerations on mathematical issues related to ultrasonic tomography for orthotropic materials are then presented.

2. Tomography

In 1917, an Austrian mathematician named Johann Radon showed that an exact representation of an object can be obtained from a complete set of its projections. This mathematical process called The Radon Transform has become the basis for X-ray tomography [10], being also used in geophysics [11-12]. This latter application used stress wave velocities in solid materials, and thus can be also used in the inspection of construction materials.

Initially, the section to be analyzed is divided in \( n \) elements, with the transducers placed at several locations according to Figure 1. This division yields several ray paths from the ultrasound emitter to the receiver transducers. Each ray path travels through certain elements at varying distances. The total recorded travel time reflects the average velocity from the emitter to the receiver transducers, which for each ultrasound reading is given by the summation presented in Eq. 1.

\[
T_i = \sum_{j=1}^{n} \frac{dL_{ji}}{V_j} = \sum_{j=1}^{n} p_j * dL_{ji} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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\cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cd -
\( P \): column vector of length \( n \) that records the slowness of each element \( j \);

\( T \): column vector of length \( m \) that records the total travel time of each reading \( i \).

Tomography imaging requires solving the slowness vector \( P \), given that the travel time vector \( T \) and the matrix \( D \) are known. This solution needs a special method, since the number of equations is usually different than the number of unknowns and matrix \( D \) is usually a rectangular matrix. Furthermore, there may be some equations that are linear dependent which may lead to a lack of uniqueness problem. The Cimmino Method, also known as Simultaneous Iterative Reconstruction Technique (SIRT), is able to yield a solution without needing to get the inverse matrix or either the whole matrix \( D \). A deep study on that matter [13] has shown that the best way to solve such problem is by using the Optimized Cimmino’s method, as proposed by Jackson and Tweeton [12], presented in Equation 3.

\[
P_n^{(k)} = P_n^{(k-1)} + W_{m,n}^T \left[ T_m - D_{m,n} * P_n^{(k-1)} \right]
\]

where:

- \( k \): is the actual iterative number;
- \( m \): is the total number of equations;
- \( n \): is the total number of unknowns;
- \( P_n^{(k)} \): the slowness vector that records the obtained values in step \( k \);
- \( W_{m,n} \): a special matrix given Equation 4.

\[
w_{ij} = \frac{d_{ij}}{N_j * \sum_{k=1}^{m} (d_{ik})^2}
\]

where:

- \( N_j \): number of equation in which \( j \) é different than zero;
- \( d_{ij} \): element of matrix \( D \).

For isotropic materials in section without strong heterogeneities, the ray paths can be assumed as straight lines, since the elastic constants do not depend on the direction of propagation. Thus, matrix \( D \) can be easily calculated.

An ultrasonic pulse velocity tomography software was developed to be initially applied to isotropic materials. Therefore, when this software is used to assess the level of integrity of a timber element, any consideration of the dependence of ray paths on the angle between them and the radial or tangential axes was not taken into account. This study will evaluate whether this consideration affects the result obtained by comparing tomographic images in controlled situations.

### 3. Experimental Program

Initially, a section of 9.6 cm width of a *Pinus elliottii* tree with an approximate diameter of 37.0 cm was cut to a square section of 20 cm of sides, as shown in Figure 2. The excess material was used to measure the moisture content of the wood. A value of 22.8% was recorded.

Ultrasound readings, according to Figure 3, were performed with a commercial ultrasound equipment using 30 kHz exponential transducers. A 2.5 cm size mesh was chosen, which yielded a total of 64 elements. The ultrasound transducers were placed at the middle of each
face element, as also shown in Figure 3. A total of 128 readings was then necessary to be processed by the tomography software.

In order to simulate different integrity levels, some mesh elements were cut out from the wood sample. Thus, three integrity levels were analyzed. In the first one, the sample was remained untouched. In the second level, one element (2.5 by 2.5 cm) was cut out, while in the third level, four elements (5.0 by 5.0 cm) were cut out, as shown in Figure 4. All cuts were performed parallel to the wood fibers.
4. Results

All 128 readings were performed for each level of integrity. These readings together with the geometry of the wood sample and the chosen mesh were inserted in the tomography software developed. The obtained images are presented in Figures 5 to 7 for each level of integrity tested.

![Tomographic image of integrity level I (UPV in m/s)](image1)

Figure 5. Tomographic image of integrity level I (UPV in m/s)

![Tomographic image of integrity level II (UPV in m/s)](image2)

Figure 6. Tomographic image of integrity level II (UPV in m/s)

![Tomographic image of integrity level III (UPV in m/s)](image3)

Figure 7. Tomographic image of integrity level III (UPV in m/s)

4. Analysis and Discussion

Figure 5 shows a relatively homogeneous section, as it should be expect for this level I of integrity; nevertheless, an increase in the ultrasonic pulse velocity in the middle of the section was observed. For level II of integrity, when only one element was cut out, it can be noticed in Figure 6 a small area of lower velocities in the upper right corner, close to the cut element. For level III of integrity, Figure 7 shows a much broader area of lower velocities indicating some lack of homogeneity in the region. However, there also some regions with higher velocities that had not appeared in the other images.
Since the tomography software used could only process isotropic materials, the higher velocity areas in the center elements in Figure 5 could be related to the assumed ray paths travelling in a straight line which would travel close to the radial direction of the fibers in the wood element. On the other hand, the ray paths that cross elements near the border travel close to the tangential direction of the fibers. It is known that the UPV in the radial direction is greater than in the tangential direction of the fibers in wood elements. This argument can be better seen in Figure 8, where the assumed straight line paths are shown together with the pattern of wood fibers.

![Figure 8. Ray paths travelling the central and the border elements](image)

Therefore, it can be noticed that the consideration of orthotropic behavior is necessary when an ultrasonic tomography software is being developed to be applied in the inspection of a timber structure. As represented by the aforementioned mathematical fundamentals, such consideration involves a modification of the software developed, which is currently being performed.

A possible approach to deal with the orthotropic behavior of the wood element would be to consider a correction factor to be applied to each reading. This correction factor could be calculated considering that the image presented in Figure 5 should yield a homogeneous section with UPV value of around 1400 m/s, representing the average value between UPV in the tangential and radial directions. This correction factor, calculated by Equation 5, was then added to each recorded reading.

\[
C_i = \frac{\sum_{j=1}^{n} dL_{ji}}{1400T_{1i}} \tag{5}
\]

where:

- \( C_i \): is the correction factor for reading \( i \);
- \( T_{1i} \): is the time travel for reading \( i \) at integrity level I.

Figures 9 to 11 present the corrected tomographic images obtained by applying the correction factor of Equation 5. It can be seen that the application of such a correction factor improved somewhat the location of the flaws; however it was not possible to precisely identify them. Therefore, it is concluded that in order to use ultrasonic tomography in timber structures it is imperative to consider its orthotropic behavior.
For orthotropic materials, such as wood, the ray paths depend on the angle $\theta$ between the ray path and the radial or tangential axes, as shown in Figure 12. Furthermore, the ray path may not travel as a straight line within an element; however, the actual path may be considered of several unknown straight lines connecting different points, each of them with a different angle $\theta$, as also shown in Figure 12. Equation 1, therefore, must be modified considering the possibility of several connections in each element, as presented in Equation 6.

It can be seen that the consideration of orthotropic material yields a much more complex system of equations to be solved. The orthotropic behavior is currently being implemented in the tomography software already developed.
Figure 12 – Possible ultrasound paths in a wood sample

\[ T = \sum_{j=1}^{n} \sum_{\alpha=1}^{c} p_{ja}(\theta) * dL_{ja} \] (6)

where:
- \( p_{ja} \): wave slowness of connection \( a \) in element \( j \) (function of angle \( \theta \));
- \( dL_{ja} \): travel distance of connection \( a \) in element \( j \);
- \( c \): total number of connections in element \( j \).

5. Conclusions

This work presented a study of the application of ultrasonic tomography in timber elements subjected to different integrity levels. The software developed was based on isotropic behavior in which the elastic constants of the material do not depend on the direction of the fibers. The results indicate that it is possible to detect internal flaws in timber structures, however, in order to locate them precisely it is necessary to consider the orthotropic behavior of wood in the development of the ultrasonic tomography software.

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