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Reducing the effect of wave dispersion in a timber pole based on transversely isotropic material modelling

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HIGHLIGHTS

- Wave propagation in timber pole is solved considering it as anisotropic material.
- An experimental set up is proposed for the condition assessment of timber pole.
- Dispersion is more while considering timber as an anisotropic material.
- Reducing the effect of wave dispersion in utility timber pole is discussed.

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ABSTRACT

Round timbers are used for telecommunication and power distribution networks, jetties, piles, short span bridges etc. To assess the condition of these cylindrical shape timber structures, bulk and elementary wave theory are usually used. Even though guided wave can represents the actual wave behaviour, a great deal complexity exists to model stress wave propagation within an orthotropic media, such as timber. In this paper, timber is modelled as transversely isotropic material without compromising the accuracy to a great extent. Dispersion curves and mode shapes are used to propose an experimental set up in terms of the input frequency and bandwidth of the signal, the orientation of the sensor and the distance between the sensors in order to reduce the effect of the dispersion in the output signal. Some example based on the simulated signal is also discussed to evaluate the proposed experimental set up.

1. Introduction

Utility poles represent a significant part of Australia's infrastructure as well as globally. According to Nguyen et al. [1], there are nearly 7 million utility poles in the current Australian network, around 5 million of which are timber poles and used for distribution of power and communication. The utility pole industry in Australia spends about $40–50 million annually on the maintenance and asset management to avoid the failure of the utility lines. Each year, about 30,000 electricity poles are replaced in the eastern states of Australia, despite the fact that up to 80% of these poles are still in a very good serviceable condition. In terms of timber bridges, current estimation reveals that around 27,000 of the total 40,000 bridges are made of timber, 85% of which are in local government areas, with the other 15% owned by State Road and Rail authorities [2]. Most of them are in excess of 50 years old and are in a degraded or structurally weakened condition. Nonetheless, these bridges are highly valued for the purpose of transportation and also for their social and historical significance.

It is, therefore, of great importance to carry out research on timber columnar structures such as poles and pile for evaluation of their in-service conditions including their embedment lengths. To serve this purpose, different types of non-destructive tests (NDT) have been developed during the last decades to evaluate the embedment depth and the quality of materials of embedded structures. Some of these methods have also been utilised for timber piles or poles. However, the extent of knowledge developed on non-destructive tests for timber piles is far from adequate and the effectiveness and reliability of current NDTs are questionable due to uncertainty on materials, structures and the environment. Moreover, as determination of the length of a pole depends on the characteristics of stress wave including wave modes, wave frequencies and velocities, hence, analysing the wave properties

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and the analytical solution of this problem become equally important.

Most of the available stress wave based method can be divided into two categories, one is based on bulk longitudinal wave theory and elementary beam theory (also called conventional surface reflection techniques) and the other one is based on guided wave (GW) theory. Fu et al. [3] determined the embedment length of the timber piles in bridge structures considering bulk longitudinal wave propagation. He introduced some factors to consider the effect of moistures and continuous dry and wet condition for the bridge piers. However, the frequency range considered here is very low which is related to long wavelength and thus, is incapable of detecting smaller damage. Chen and Kim [4], Holt et al. [5] assessed the condition of the installed timber piles by flexural wave propagation using Short Kernel method (SKM) where the velocity of the wave is determined from the experiment tests directly and no comparison is made against any theory. Also, it has been found that the accuracy of SKM varies notably for different tests [6,7]. Ross et al. [8] conducted an extensive analysis on the condition assessment of timber materials where the effect of ring orientation, decay, moisture content and temperature in timber materials were taken into account. Nevertheless, the analysis are based on pitch catch method which cannot be directly applied to timber poles/piles material due to the fact that reflection is the most important parameter for the NDE of piles/poles. Ross and Pellerin [9] also used the pulse echo techniques for the non-destructive evaluation of structural members, however, bulk longitudinal wave theory was considered for this purpose. Therefore, most of the work on timber structures are based on non-dispersive assumption of wave propagation.

The GW equations are used mainly for isotropic materials. The wave propagation in foundation structures considering both non-dispersive and GW propagation are described in [10–13], and it is showed that in the low frequency band, bulk longitudinal wave velocity and elementary beam theory based flexural wave velocity are very similar as GW propagation. Wang and Chang [14] compared the experimental flexural wave velocity against the theoretical velocity derived from GW approach. However, this work was limited to concrete piles and also in the low frequency range where bulk longitudinal wave or flexural wave based on elementary beam theory and GW theory act similar. Popovics [15] also established that the predominant waves in concrete slabs excited by impact echo method are related to low frequencies of the lowest branch of GW. Chao [16] and Finno et al. [13] also reached the same conclusion for concrete piles and drilled shafts. Finno et al. [13] showed that the upper limit of the frequency band varies from 250 Hz to 1000 Hz for 4 m to 1 m diameter concrete piles, respectively. Chao [16] identified a 7% cross section notch in a prototype concrete pile using longitudinal GWs whereas a defect size of more than 30% of the cross sectional area of a pile can only be detected by conventional surface wave methods [17]. Finno and Chao [18] used the high frequency content for detecting smaller damage using GW theory which is limited to isotropic material only. Moreover, mobility curve was used in a number of research in order to determine the location of defect which is found to be not very clear for timber materials in the real field tests [7].

Therefore, it is important to consider GW theory for the detailed and accurate NDE of timber materials. And the guided wave theory for isotropic material cannot directly be used for the analysis of anisotropic material [19]. Although the GW theory are derived for orthotropic cylindrical structures [20–23], it is not been extensively used for the analysis of timber materials. The reasons are related to a number of factors, such as, the diversity in the timber materials is broad; also, the fibre orientation of the grain causes variation in GW propagation. Additionally, for the GW propagation in high frequency, the diameter–frequency product of the timber poles/piles are considered as thick waveguide and thus, it is very difficult to solve the GW equation. However, high frequency may need to be induced in the experiment in order to get shorter wavelength to detect smaller damage. Accordingly, to simplify the model, it is reported that timber can be considered as transversely isotropic material with a little compromise which can improve the GW propagation in a timber pole to a great extent [6,24]. The theories of transversely isotropic material can be found in [25–29].

The solution of GW theory of transversely isotropic material is complex in terms of finding out its roots for wavenumbers. Some of the widely used analytical methods are stiffness methods [30,31], global matrix methods [32], etc. Both these methods are accurate for plate like structures, layered material and thin cylindrical waveguides. In contrast to these analytical approaches, some purely numerical methods have been developed to obtain the dispersion curves. Among them, the semi analytical finite element method (SAFE) [33] and the scaled boundary finite element (SBFEM) [34] are very universal to use and also accurate. The solution for anisotropic cylindrical waveguide by SAFE can be found in [35,36] where hollow cylinder or laminated composites of very thin cross section are considered. To solve the dispersion curves, there are three software that can be found at this stage, namely, PCDisp [37], Disperse [38] and GUIGUW [39]. Only the demo version of GUIGUW is available now which uses SAFE method whereas Disperse uses global matrix method. PCDisp is a MATLAB written code developed for an isotropic material.

In the present study, GW equation is solved using Disperse in order to get the insight of the guided wave propagation in timber pole/piles where timber is considered as transversely isotropic material. As high frequency is the point of interest in this research due to detect any size of damage, it has been find out that the dispersion in the high frequency is unavoidable in the signal which make it difficult to extract the feature, and therefore, the condition assessment of the timber materials become challenging. In this work, focus is made on reducing the effect of dispersion by analysing energy velocity curve, normalised displacement profile and simulated signal which are derived from GW theory with a view to propose an effective experimental set up for the NDT of timber poles.

2. Wave theories

Wave propagation in timber follows the constitutive equation and Newton's law of motion. The dispersion and spectral relations are derived from these equations which give the inside of wave propagation. The constitutive equation in this article is described for transversely isotropic material and the derived equation for spectral relation, dispersion relation and displacement equations are also presented for discussing the inside of wave propagation.

2.1. The compliance matrix

The constitutive equation reflects the basic difference of compliance and stiffness matrix of an isotropic and anisotropic material. In anisotropic media, the compliance matrix [S] is used more often to define the stress (σ) strain (ε) relationship compared to the stiffness matrix [C]. The compliance matrix is defined as:

$$[\varepsilon] = [S][\sigma]. \tag{1}$$

In the cylindrical coordinate system (r–θ–z), the three elastic moduli in three orthogonal directions can be denoted as E_r, E_θ and E_z. If the six Poisson's ratios are denoted by $\nu_{\theta r}$, $\nu_{r\theta}$, ν_{rz}, $\nu_{\theta z}$, ν_{zr} and $\nu_{z\theta}$, the stiffness and compliance matrices of an orthotropic or transversely isotropic material are defined by Eqs. (2) and (3)